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İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

**EJECTION FROM RAPIDLY DEPRESSURIZED VESSELS
CONTAINING BUBBLY-LIQUID TWO-PHASE FLUID**

Ph.D. THESIS

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P R E F A C E

The research students prospectuses of the elitist Oxobridge universities contain this statement ; "We expect our students carry out their research with the minimum of detailed supervision". This peace of study, although not as a result of my choosing, well satisfies the quoted aim but with such a high cost that I rather not contemplate.

Although he repeatedly acknowledged the level of his contributions by the phrase 'you are the expert' that I still not dare to accept , I would like to offer my sincere thanks to Dr.J.W.CLEAVER of the University of Liverpool (UK) as I believe he did his best, never the less as the supervisor of this study, though only for the first half of the long period I spent there.

I am very much indebted to my university and especially to my dear teacher, Prof.Dr. Hasan Fehmi YAZICI, not the least for his patience of putting up with my being so late in putting this study on paper. I also very much thank to my dear teacher Prof.Dr.Cahit ÖZGÜR for his frequent stimulations that helped to prevent my not so much improbable total break with the subject.

The long years that passed by with this study with long off periods took so much from me that I prefer to forget but I feel responsible to give at least two simple but probably all inclusive indication on the extent of the programming side of the study ;

* In spite of my belief and practice that the computational problems has to be first solved on the study papers and programme listing and output away from the computing environment and the preparation of many sophisticated command usage programme that did all the repetitive and time consuming work , at least 10K hours was spend in front of terminals connected to really fast mainframe computers.

* Though, from the start, as much conservationist as possible a strategy was followed that is never a new version printout was requested before it is really required and the output file sizes were carefully controlled ; if all printout that requested from the beginning were put on each other, there would be a pile of at least three meters tall which may well be only a quarter of what otherwise it might be.

The only reason for the presentation of this study in English is that it was rooted up in the land of that language. I tried to do my best to write as clearly as possible and the word processor did the spelling checks , but certainly there still are some mistakes and I would like to apologize for them beforehand.

İstanbul, June 1993

Şükrü BALTA

C O N T E N T S

NOMENCLATURE	XI
SUBSCRIPTS	XIII
SUPERSCRIPTS	XIV
GRAPHICS ABBREVIATIONS	XIV
ABBREVIATIONS	XV
LIST OF FIGURES	XVI
LIST OF TABLES	XIIX
ABSTRACT	XX
ÖZET (ABSTRACT IN TURKISH)	XXI

CHAPTER 1. INTRODUCTION	1
-------------------------------	---

1.1. The Two-Phase Flow Concept	1
1.2. Parameters of Two-Phase Mixtures and Flows ...	4
1.3. Restrictions and Assumptions	4
1.3.1. Shape of the Vessel	4
1.3.2. Physical Conditions of the Mixture	4
1.3.3. Physical Conditions of the Phasic Fluids	5
1.3.4. Physical Conditions of the Bubbles	5
1.3.5. Initial Conditions	5
1.4. The Cases	6
1.4.1. Non-Full Vessel Case	6
1.4.2. Full Vessel Cases	6
1.4.3. The Sub - Cases	7
1.5. Scope of Applicability	8

CHAPTER 2. GOVERNING EQUATIONS OF ONE DIMENSIONAL BUBBLY - LIQUID TWO - PHASE FLOWS	9
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2.1. The Principals of Approach	9
2.2. Limiting Conditions and Assumptions	10
2.3. Separated - Flow Concept	11
2.4. Phasic Conservation Equations	11

2.5.	The Arranged Phasic Equations	13
2.6.	The Governing Equations	15
2.7.	The Bernoulli Equation	16
CHAPTER 3. METHOD OF CHARACTERISTICS EQUATIONS OF BUBBLY - LIQUID TWO - PHASE MIXTURES		18
3.1.	Summary of the Numerical Methods	18
3.1.1.	Wave Tracing	18
3.1.2.	Finite Difference Methods	19
3.1.3.	Lumped Control Volumes Method	19
3.2.	Characteristic Equations	19
3.3.	Characteristic Equations of the EVET Model ...	22
3.4.	The Speed Differences Ratio Approach	23
3.5.	True Characteristic Directions	25
3.6.	The Stability Criteria	26
3.7.	Characteristic Equations of the Gas	27
CHAPTER 4. FLOW OF BUBBLY LIQUIDS THROUGH EXPULSION ELEMENTS AND THE CRITICAL PRESSURE RATIO		28
4.1.	Introduction	28
4.2.	Principal Works of the Subject	28
4.3.	Main Concepts and Definitions	29
4.3.1.	The Expulsion Element Concept	29
4.3.2.	The Flow Coefficients	29
4.3.3.	Back - Flow Case Treatment	30
4.3.4.	Undeveloped Flow Stage Treatment	30
4.3.5.	Formats of the Time Dependant Variables	31
4.3.6.	Principal Def. of the Expulsion Element	32
4.3.7.	Assumptions and Applicability	32
4.4.	The Theoretical Speed of Expulsion	33
4.5.	The Theoretical Mass Flow Rate	34
4.6.	The Critical Pressure Ratio (CPR)	35
4.7.	Simplified and Practical CPR Equations	36
4.7.1.	Isothermal Equilibrium Speed of Expulsion	36

4.7.2. Sonic Speed of Expulsion	36
4.7.3. Isothermal Equilibrium Critical Pressure Ratio	37
4.7.4. Practical Considerations on CPR Calculations .	37
4.8. Usability of the Rate of Flow Equations	38
CHAPTER 5. SHOCK - WAVES IN BUBBLY - LIQUID MIXTURES	39
5.1. The Origins of the Shock Fronts in the Problem	39
5.2. Shock Front Creation due to Instant Change of the type of the Expelled Fluid	40
5.3. Def. of Character and the Notation Convention	41
5.4. Literature Review	42
5.5. The Assumptions and Restrictions	43
5.6. The Ways of Approach	44
5.6.1. The Principle Method : Rankine Hugoniot Eqns .	44
5.6.2. The Secondary Methods	44
5.7. The Rankine - Hugoniot Shock Equations	45
5.8. Basic Shock Relations	47
5.9. Summary of the Basic SF Cases	48
5.9.1. Ordinary Fronts	48
5.9.2. Reflection at the Closed End	49
5.9.3. Reflection at the Open End	50
5.10. Non - Full to Full Vessel Transformation	51
5.11. Programming for the SF Calculations	51
CHAPTER 6. SPEED OF WAVE PROPAGATION IN BUBBLY LIQUIDS ..	53
6.1. The Restrictions and Assumptions	53
6.2. Principal Works of the Subject	53
6.3. The Principal Formats	54
6.4. The Practical Formats	56
6.5. Non - Uniform Flow Case	57
6.6. Some Named Definitions	58
6.7. Eigenvalue Problem Approach	59
6.8. The Routine FSWP ; Speed of Wave Propagation .	61

CHAPTER 7. NUMERICAL APPROACH TO THE " MC "	62
7.1. General Considerations	62
7.2. Principal Points of the MC Application	63
7.3. Characteristic Grid Forms	63
7.3.1. Ordinary Points	64
7.3.2. The End Points	65
7.3.3. The Contact Surface (CS) Point	66
7.3.4. Points Near the Contact Surface	67
7.3.5. Points Near the Shock Front	68
CHAPTER 8. THE PROGRAMME ; CONCEPTS & CHARACTERISTICS ..	69
8.1. General Calculation Strategy	69
8.2. Correct MC Calculation Measures	70
8.3. Fail - Free Run Measures	70
8.3.1. Initial Expulsion Stage	70
8.3.2. The SF Calculation Stage	71
8.3.3. General Failure Prevention Measures	71
8.4. Resources Saving Measures	72
8.4.1. Decreased Run - Time Measures	72
8.4.2. Decreased Size and Modularization	73
8.4.3. Easy Error Tracing (Debugging) Measures	74
8.5. Quality Improvement Measures	74
8.5.1. Accuracy Improvement Measures	74
8.5.2. Comparative Study Facilities	75
8.5.3. Structure of the Mixture Functions Use	75
8.5.4. Shape of the Vessel Function Use	76
8.5.5. Area of the Vessel Function Use	76
8.5.6. Expendability and Adoptability	76
8.6. Intelligibility Improvement Measures	76
8.6.1. Intelligible Programme Measures	77
8.6.2. Intelligible Output Measures	77
8.6.3. Dimensional Versus Non - Dimensional Format ..	77
8.7. Portability Measures	78
8.7.1. Fully Standard Language	78
8.7.2. Independence of Library Availability	78

8.8.	The Input File	79
8.8.1.	General Description of the Data Files	79
8.8.2.	Content of the Data Files	79
8.8.3.	Format of the Data Files	80
8.9.	The Output Files	80
8.9.1.	General Description	81
8.9.2.	The Format and the Content	82
8.9.3.	The Output Arrays Listing Files	82
CHAPTER 9. THE GRAPHICS		83
9.1.	Introduction	83
9.2.	The Ghost Graphics Library	83
9.3.	General Character of the Graphics Output	84
9.4.	Graphical Information Parameters	85
CHAPTER 10. CONCLUSION		86
10.1.	The Results	86
10.1.1.	The Full Vessel Case	86
10.1.2.	The Non - Full Vessel Case	89
10.2.	Checking the Results	91
10.3.	Recommendations	93
10.3.1.	Recommendations for Improved Accuracy	93
10.3.2.	Recommendations for Further Investigations ...	94
10.3.3.	Recommendations for Enlargements	95
REFERENCES		96
APPENDIX A. MULTI - PHASE FLOW QUANTITIES		102
A.1.	Definition of the Non-Dimensional Quantities	102
A.2.	Definition Equations Between the Non - Dimensional Quantities	102
A.3.	Relations Between the Non-Dimensional Quantities .	103
A.4.	Slip Ratio Equations	103
A.5.	Relations Between the Specific Mass Quantities ...	104

APPENDIX B. PRINCIPAL RELATIONS	105
B.1. Pressure Field Equations	105
B.2. Void Fraction - Pressure Relations	105
B.3. Mixture Density and Pressure Head Relations	106
B.4. Specific Mass Quantities and Pressure Relations ..	106
B.5. Implicit Balance Equation for a Small Bubble	107
B.6. Pressure Ratio Equations	107
B.7. Basic Shock Front Equations	108
APPENDIX C. RELATED KNOWLEDGE	110
C.1. Thermodynamic Behaviour of Gas Bubbles In a Liquid	110
C.2. Slip and Relative Acceleration Ratios	112
C.3. Quasi-Steady-State Expansion and Expulsion	113
C.4. Equation of Radial Motion of a Bubble in a Liquid	114
C.5. Bubbly-Liquid Two-Phase Flow Wall Friction Coef. .	115
APPENDIX D. GEOMETRY OF THE VESSEL	117
D.1. General Conditions of Shape	117
D.2. The Conditions Imposed	117
D.3. Definition of the Shape of the Vessel	117
APPENDIX E. SAMPLE SET OF MC EQUATIONS AND A CALCULATION FORMAT	118
E.1. MC Equations ; Ordinary Points In the Mixture	119
E.2. MC Equations ; Contact Surface Point	121
E.3. MC Solution ; Ordinary Points In the Mixture	123
APPENDIX F. THE DATA FILES	126
F. 1. Division of the Data Into Function Based Groups ..	126
F. 2. The Compact Field of Usage Information Format	127
F. 3. Description of the Main and the Method of Characteristics Data In Function Bases Groups	128

F. 4. Description of the Shock Fronts and Special SF-MC Calculations Related Data In Function Based Groups	139
F. 5. Description of the Graphics Work Data In Function Based Groups	142
F. 6. Index of All Data In All Input Files	143
F. 7. Index of All Names Specific to the Output Files ..	145
APPENDIX G. DESCRIPTION OF THE ROUTINES	146
G.1. Classification of the Main Jobs of the Routines The Job Classification Numbers (JCNs)	146
G.2. Listing the Routines in JCN Order	151
G.3. Index of All Routines With JCN Number(s)	154
APPENDIX H. ROUTINES CALL DIAGRAMS	155
H.1. Non - Full Vessel Case Routines Call Diagram	156
H.2. Full Vessel Cases " " " " "	157
H.3. Gas Bottle Case " " " " "	158
H.4. Shock Front Calculations " " " " "	159
H.5. Graphics Drawing " " " " "	160
APPENDIX I. STATISTICS AND REQUIREMENTS	161
I.1. Statistical Information	161
I.2. COMMON Blocks Information	162
I.3. Statistical Data on SF Calculations	163
I.4. Programming Requirements	163
I.5. Library Routines Use	164
APPENDIX J. THE COMPUTERS AND THE CUP'S	165
J.1. The Computers	165
J.2. The Commands Usage Programmes	166

APPENDIX K. GRAPHICAL OUTPUT EXAMPLES 168

Graphics Abbreviations 169

Abbreviations for the Principal Data 170

Abbreviations for the Principal Results 170

K.1. The Full Vessel Case 171

K.1.1. A Full Graphics Output 171

K.1.2. Compact Outputs 176

K.1.3. The Multi Data Run Plots 179

K.2. The Non - Full Vessel Cases 187

K.2.1. The First Full Graphics Output 187

K.2.2. The Second Full Graphics Output 193

K.3. The Pressurized Gas Bottle Case Example 199

APPENDIX L. INPUT / OUTPUT FILE EXAMPLES 204

L.1. Data File of the Non-Full Vessel Case 205

L.2. Examples for the Data Lists of the MD Cases 211

L.3. Examples on the Character of the Output Files .. 212

L.4. Full Disk List of the Programs 213

CURRICULUM VITAE 214

END OF LIST OF CONTENTS.

NOMENCLATURE

a	: Area , Surface of a Bubble.	[M ²]
A	: Area , Cross - Section of the Vessel.	[M ²]
B	: $\rho = \rho(p, "B", m)$ factor for liquids. (Eqn. C.30)	[NM ⁻²]
C	: Speed of Sound.	[MS ⁻¹]
C _D	: Drag coefficient.	[0]
C _p	: Specific heat of gas at constant pressure.	[JK ⁻¹ C ⁰ -1]
C _v	: Specific heat of gas at constant volume. ..	[JK ⁻¹ C ⁰ -1]
d	: Diameter of a/the bubbles.	[M]
D	: Diameter of the vessel / at a cross-section.	[M]
D _e	: Equivalent Diameter of a cross-section area.	[M]
e	: Unit Specific Energy.	[JK ⁻¹]
	Vessel wall thickness.	[M]
E	: Specific Energy , Energy.	[J]
	Elasticity modulus of the pipe material.	[NM ⁻²]
f	: Wall (Vessel) friction coefficient.	[0]
	Frequency of the bubble oscillations.	[S ⁻¹]
F	: The friction term. (= 0.5 (f/D _e) u ²)	[MS ⁻²]
g	: Gravity.	[MS ⁻²]
h	: Enthalpy.	[JK ⁻¹]
i	: Specific Entropy.	[J ⁰ C ⁻¹]
I	: Entropy.	[JK ⁻¹ C ⁰ -1]
K	: Compressibility coefficient. / Bulk modulus. ..	[NM ⁻²]
m	: Mass of a bubble.	[K]
	Unit Mass flow rate.	[KM ⁻² S ⁻¹]
	" for the whole interfacial wall surface.	[KM ⁻¹]
	$\rho = \rho(p, B, "m")$ factor for liquids. (Eqn. C.30) ..	[0]
m	: Mass flow rate.	[KS ⁻¹]
M	: Total Mass.	[K]
	Mach Number.	[0]
n	: Gas index , Specific heats ratio.	[0]
p	: Pressure.	[NM ⁻²]
P	: Strength of an SF.	[0]
q	: Heat transfer rate.	[WM ⁻² =JM ⁻² S ⁻¹]
r	: Slip Ratio , Phasic velocities ratio [U _g /U _l].	[0]

R	: Radius of a bubble.	[M]
R_b	: The gas constant of the gas in the bubbles. [JK ⁻¹ °C ⁻¹]	
s	: Specific Entropy.	[J°C ⁻¹]
t	: Time.	[S]
t_D	: Duration of expulsion.	[S]
u	: Velocity.	[MS ⁻¹]
U	: Velocity of a front.	[MS ⁻¹]
v	: Velocity. (SF : $v = u + U $)	[MS ⁻¹]
V	: Velocity of radial pulsations of a bubble.	[MS ⁻¹]
	Valensi Number.	[0]
W	: Work , Energy.	[J=Nm]
W_e	: Weber Number.	[0]
z	: Height.	[M]
α	: Volume Ratio.	[0]
	Volume fraction of bubbles to the liquid.	
β	: Void Fraction.	[0]
	Volume fraction of bubbles to the mixture.	
Γ	: Shape of the bubbles correction factor for "r". ...	[0]
θ	: Contraction coefficient of the opening.	[0]
Λ	: Thermal diffusivity length.	[M ² S ⁻¹]
χ	: Quality , Mass Quality.	[0]
	Mass flow rate percentage of the bubbles.	
λ	: Thermal Conductivity.	[WM ⁻¹ K ⁻¹]
	Velocity coefficient. ($u_E/u_{E,T}$)	[0]
μ	: Mass Fraction (of the bubbles to the mixture).	[0]
	Dynamic Viscosity.	[NSM ⁻²]
ν	: Kinematic viscosity.	[M ² S ⁻¹]
ξ	: Pressure ratio. (p / p_E)	[0]
ρ	: Mass Density , Specific Mass.	[KM ⁻³]
σ	: Surface Tension.	[NM ⁻¹]
φ	: Area Ratio of the Opening.	[0]
	Area of the opening to the last cross-section.	[0]
τ	: Frictional stress per unit length.	[NM ⁻¹]
	Stress.	[NM ⁻²]
ω	: Angular Frequency.	[S ⁻¹]

END OF NOMENCLATURE

SUBSCRIPTS

o	: Initial state , Conditions at the beginning.
1	: Low Pressure side of SF.
2	: High " " " " " .
∞	: At or under the conditions of infinity.
ad	: Adiabatic conditions.
b	: Bubble(s). ; Gas in the bubbles.
B	: " " , Back side of the SF.
cr	: Critical conditions.
D	: Drag , Duration of expulsion , Disturbed side of SF.
e	: Equivalent (diameter).
E	: Environment , Contracted cross-section , Expulsion.
eq	: (eq1) Equilibrium -flow- conditions.
f	: Frozen - distributed phase - conditions.
F	: Front side of the SF.
g	: Gas in the bubbles.
G	: Gas phase of the mixture.
hf	: High frequency (limit) value.
HP	: High pressure side of SF.
i	: Interface ; liquid - bubble.
is	: interfacial surface.
k	: Any of the phasic components of the mixture.(l or g)
l	: Liquid.
LP	: Low pressure side of SF.
m	: Mixture.
neq	: Non - Equilibrium conditions.
o	: Opening element.
ov	: For Ordinary Value(s) (Conditions).
p	: Pseudo - Two-phase conditions , Projection , Pressure.
r	: Radial motion (of bubbles).
s	: Spherical (bubble(s)), Stratified flow, Cst. Entropy.
Th	: Teoretical value.
U	: Undisturbed side of SF.
v	: Vessel.
w	: Wall (of Vessel) , Wave.
μ	: At constant mass ratio.

SUPERSCRIPITS

$\dot{R}$: " dR / dt " for the pulsating bubbles.
* : Partial - phasic - value [$\xi_k^* = \beta_k \xi_k$].
Of / For the critical value / pressure ratio.
"." : Derivative in respect to time.

GRAPHICS ABBREVIATIONS

BV [%IV] : Void Fraction , % of Initial Value.
CEC : Precision of expulsion , Expelled / Depleted.
CEC-SF : Precision of Expulsion Calculations ; SF.
CSN : Calculation Step Number.
DEL [%MV] : Movement of the CS , % of Mean Value.
DP-E : I. Dimensionless Parameter. (Routine SENDEX)
DP-T : II. " " " " " " " "
DSN : Data Set Number in the group of data.
DT [%MV] : Time increment , % of Mean Value.
DTRT : Time increment , % of Theoretical value.
DTRT-SF : Time increment , SF , % of Theoretical Value.
DT-SF [%MV] : Time increment , SF process , % of Mean Value.
HM [%HV] : Height of mixture level , % of Vessel Height.
MCES [%IV] : Mass of Contents Expelled , % of Initial Value.
MCES-SF [%MV] : Mass of Contents Expelled , SF , % of Mean V.
MCE-S/G [%MV] : Mass of Content Expelled, Gas, % of Mean Value.
MG [%IV] : Mass of Gas expelled , % of Initial Value.
PBVF : Final Void Fraction , % of Initial Value.
PCAL : Precision of Calcs., overall, up to a time.
PCE [%FV] : Per. of Contents Expelled , % of Full Value.
PHM-S : Height of mixture level , % of full value.
PLE [%IV] : Per. of Liquid Expelled , % of Initial Value.
PR-T : Pressure at the Top of the Vessel [Atm].
RJME : Ratio, Total number of steps to the nodes.
RPLE : Percentage of Liquid Expelled , % of QSS Value.
T [%DE] : Time , % of the duration of expulsion.
T-GE [%DE-GE] : Time , in gas expulsion as % of its duration.
T-SF [%DE-SF] : Time , in SF phenomena as % of its duration.

ABBREVIATIONS

C^+	: $C^+(C+U)$ Characteristic line of the MC grid.
C^-	: $C^+(C-U)$ Characteristic line of the MC grid.
$C^\mp$	: $C^+(C\mp U)$ Characteristic lines of the MC grid.
C_u	: $C(u)$ / the particle path characteristic.
CE	: Closed End.
CPR	: Critical Pressure Ratio.
CS	: Contact Surface of the gas and the mixture.
Cst.	: Constant.
EVETEP	: Equal Velocity & E. Temperature & E. Pressure.
FV	: Full Vessel Case.
FVMD	: Full Vessel Multi Data Case.
FVMDS	: Full Vessel Multi Data Special Case.
FVS	: Full Vessel Special Case.
GB	: Gas Bottle Case.
GHOST	: GHOST Graphics Library.
ICD	: Initial Calculation Data Run Case.
IO	: Instant Opening.
IWF	: Initial wave Front.
MC	: Method of Characteristics.
NAG	: NAG Mathematical Calculations Library.
NFV	: Non-Full Vessel Case.
OAL	: Output Arrays Listing.
OE	: Open End.
OF	: Output File(s).
OP	: Ordinary Points.
PR	: Pressure Ratio.
QSS	: Quasi-Steady State.
R	: Routine of the programme.
SF	: Shock Front.
SWP	: Speed of Wave Propagation.
TCO	: Time Constant (Duration) of Opening.
Z	: Adiabatic Behaviour Ratio. ($p_o / \rho_{g_o}^n$)

LIST OF FIGURES

1-1	Spectrum of Two-Phase Flows	2
1-2	Gas-Liquid Two-Phase Flows	2
1-3	Vertical-Upward Liquid-Gas Flow Patterns	3
1-4	Horizontal Liquid-Gas Flow Patterns	3
4-1	Opening Cross-Section and last MC Calculation Node	32
5-1	Transformation from Moving to Stationary SF	41
5-2	Transformation of Left Running Ordinary Fronts	48
5-3	Transformation of Right Running Ordinary Fronts ...	48
5-4	Transformation of Approaching Closed-End Front	49
5-5	Transformation of Departing Closed-End Front	49
5-6	Transformation of Approaching Open-End Front	50
5-7	Transformation of Departing Open-End Front	50
6-1	Stagnating Wave Front	57
7-1	MC Grid for Ordinary Points ; Subsonic Flow Case ..	64
7-2	MC Grid for Ordinary Points ; Sonic Flow Case	64
7-3	MC Grid for Ordinary Points ; The Gas Region	65
7-4	MC Grid for the Open End Point	65
7-5	MC Grid for the Closed End Point	66
7-6	MC Grid for the Contact Surface Point	66
7-7	MC Grid for the Points Near the Contact Surface ...	67
7-8	MC Grid for the Points Near the Shock Front	68
10-1	Interaction Between Main Full Vessel Case Params. .	88
10-2	NFV Case Time History Output of Ref. [57]	92
C-1	QSS Calculations ; NSFV Case , PLE - PR_0 Plot	113
C-2	QSS Calculations ; NFV Case , $[PM_0]_{CR}$ - PR_0 Plot .	113

List of Figures (Cont.)

K-1	List of Main Data And Results of the FV Case Ex. . .	171
K-2	First Detailed Plot Page of the FV Case Example ...	172
K-3	Second Detailed Plot Page of the FV Case Example ..	173
K-4	Pressure History Plot of the FV Case Example	174
K-5	Multi Parameter Plot of the FV Case Example	175
K-6	First of the Compact FV Case Examples	176
K-7	Second of the Compact FV Case Examples	177
K-8	Third of the Compact FV Case Examples	178
K-9	First Page of the FV - MD Case Plots	179
K-10	Second Page of the FV - MD Case Plots	180
K-11	Third Page of the FV - MD Case Plots	181
K-12	Forth Page of the FV - MD Case Plots	182
K-13	Fifth Page of the FV - MD Case Plots	183
K-14	Sixth Page of the FV - MD Case Plots	184
K-15	Seventh Page of the FV - MD Case Plots	185
K-16	Eighth Page of the FV - MD Case Plots	186
K-17	List of Main Data and Results ; First NFV Example .	187
K-18	First Detailed Plots Page ; First NFV Example	188
K-19	Second Detailed Plots Page ; First NFV Example	189
K-20	Third Detailed Plots Page ; First NFV Example	190
K-21	Pressure History Plot ; First NFV Example	191
K-22	Multi Parameter Plot ; First NFV Example	192
K-23	List of Main Data and Results ; Second NFV Example	193
K-24	First Detailed Plots Page ; Second NFV Example	194
K-25	Second Detailed Plots Page ; Second NFV Example ...	195
K-26	Third Detailed Plots Page ; Second NFV Example	196
K-27	Pressure History Plot ; Second NFV Example	197
K-28	Multi Parameter Plot ; Second NFV Example	198
K-29	List of Main Data and Results of the GB Example ...	199
K-30	Fist Detailed Plots Page of the GB Example	200
K-31	Second Detailed Plots Page of the GB Example	201
K-32	Principal Pressure History Plot of the GB Example .	202
K-33	Multi Parameter Plot of the GB Example	203

END OF LIST OF FIGURES

LIST OF TABLES

8-1 Principal Points of Modularization of the Programme .	73
8-2 Principal Intelligibility Information on the OF's. ..	77
8-3 Data Files of the Cases	79
8-4 Input / Output Channels Information	80
8-5 The Characteristic Steps of the Output Files	81
8-6 The Characteristic Nodes of the Output Files	81
8-7 Format and the Content of the Output Files	82
9-1 Parameters and the Plots of the Graphics Output	85
C-1 Behaviour of Gas Bubbles in Liquids in Terms of Characteristic Lengths	111
C-2 Behaviour of Gas Bubbles in Liquids in Terms of Characteristic Times	111
C-3 The Slip Effect Criteria with Valensi Number	112
F-1 Grouping of the Main and MC Calculations Data	126
F-2 Grouping the Shock Front Calculations Related Data ..	127
F-3 Grouping of the Graphics Drawing Related Data	127
F-4 Index of All Data with Inf. Reference Numbers	144
F-5 Index of All Names Specific to Output Files	145
G-1 Classification of the Main Jobs of the Routines The "JCN" - Job Classification Numbers - Listing	150
G-2 Listing of the Routines Called in "JCN" Order	153
G-3 Index of All Routines with "JCN" Numbers	154
H-1 Routines Call Diagrams Combinations	155
H-2 Non-Full Vessel Case MC Calculations Routines Call Diagram	156
H-3 Full Vessel Cases MC Calculations Routines Call Diagram	157
H-4 Gas Bottle Case MC Calculations Routines Call Diagram	158
H-5 Shock Front Calculations Routines Call Diagram	159
H-6 Graphics Drawing Routines Call Diagram	160

List of Tables (Cont.)

I-1 Total File Statistics of the Program	161
I-2 Sizes and the Functions of the Program Parts	161
I-3 Statistical Information of the COMMON Blocks	162
I-4 Characteristics of the COMMON Blocks	162
I-5 Statistical Data on the SF calculations	163
I-6 Components of the Machine Size Requirements	163
I-7 Compiler Requirements of the Programme	164
J-1 A Short Comparison of the Computers Used	165
J-2 Time Spent With the Computers Used	166
J-3 List of the Jobs of the Command Usage Programs	167
J-4 Statistics on the Command Usage Programs	
L-1 Order of the Data In the Data Files.	204

END OF LIST OF TABLES

EJECTION FROM RAPIDLY DEPRESSURIZED VESSELS CONTAINING BUBBLY-LIQUID TWO-PHASE FLUID

Şükrü BALTA

An important consideration in the design of large pressure vessels containing bubbly liquid two-phase fluid in the process industries, is the assessment of the time history of the internal pressure, the void fraction distribution and the amount of discharge immediately following a sudden failure, such as a fracture on its body or the operation of an emergency relief system with nearly instant bursting characteristics, due to excess pressure built up.

Application of the best known numerical method for the calculation of transient thermo-fluid dynamic problems; the Method of Characteristics is recalled, but as one of the extreme cases that involve a bubbly liquid two - phase mixture and a gas medium with a free interface and highly transient process barely taking a second.

The program can tackle the problem even for the very extreme conditions in respect to any of the parameters involved and still produce consistent results and it does not involve any short cut that exploit the ability of the MC of smoothing the adverse effects of errors; it uses a proper third -particle path- characteristic for the void fraction distribution and creates a shock front with fitting strength when required at the non-full to full vessel transformation due to the strong throttling effect. Although the case ignores all transfer effects, the programme with its very modular structure would allow to enlarge the field of application to processes that involve heat and mass transfer, such as sub-cooled and overheated liquids; and easily, at least for the full vessel cases.

Main results of the program may be summarized as below for the two characteristic cases of Full Vessel and the Non-Full Vessel.

* For moderate conditions, sudden discharge of bubbly liquids from full pressurized vessels is no more a disorderly process than the ideal gas expulsion under equivalent conditions and whatever the initial conditions are, the pressure history can never have a peak anywhere near the initial pressure at the top, that is no excess pressure built up - hammering effect - can occur that may worsen the emergency conditions, especially in the case of pipe like vessels.

* The effect of strong throttling at the Non-Full Vessel to Full Vessel transformation stage very much asserts itself on the time history of pressure change in the case of sudden discharge of bubbly liquids from initially non-full pressurized vessels, but still; under normal conditions, the highest pressure peak, the first peak of the instant of transformation, can only reach about half of the initial pressure or may be just slightly higher; that is, not the value of the peak pressure itself but the speed of its creation may need to be taken into account as the principal design parameter.

Ö Z E T

GAZ KABARCIKLI SIVI İKİ FAZLI AKIŞKAN TANKLARINDAN ANİ BASINÇ DÜŞÜŞÜ YARATARAK FİŞKİRMA

Proses endüstrilerinde sıkça kullanılan, gaz kabarcıklı sıvı i-ki fazlı karışımlarının bulundurulduğu , tamamen veya kısmen dolu ba-sınçlı kapların dizaynında , kap gövdesinde hasar oluşturabilecek ba-sınç artışı durumlarında , ani olarak devreye giren ve düşük basınçlı ortama açılan bir diyafram şeklindeki emniyet açıklığı yolu ile , ani olarak tahliye nedeni ile oluşabilecek basınç değişimlerinin , zaman içindeki gelişiminin belirlenmesi oldukça önemlidir. Benzer durumlar, basınçlı halde tek fazlı yapıya sahip oldukları halde düşük basınçlı ortamlara, gaz kabarcıklı iki fazlı karışımlar halinde tahliye olabi-len, aşırı soğutulmuş (krojenik) ve aşırı ısıtılmış akışkanlar halin-de de geçerlidir. Nükleer enerji endüstrisinde çok önemli yeri olan olan Soğutucu Akışkan Kaybı Kazaları [LOCA] incelemeleri de konu üze-rindeki çalışmaların faydalı olabileceği alanlardandır.

Problemin sınır şartları aşağıdaki şekilde belirlenebilir.

- * İçindeki akış tek boyutlu kabul edilebilecek, eksenel simetrik ve uzunluk çap oranı 1'den oldukça büyük basınçlı kaplar.
- * Sıvı sürekli faz içinde , eksenel kesit üzerinde homojen dağıl-mış yaygın faz halinde, küresel kabul edilebilen gaz kabarcıkları.
- * Isıl ve kimyasal denge ; fazlar arasında veya kap cidarlarından ısı veya kütle transferi yok sayılabiliyor.
- * Gaz kabarcıklarının hacimsel konsantrasyonu ve ortalama çapları kap eksenini boyunca doğrusal veya düzgün bir şekilde değişebiliyor.
- * Olayın bütün safhalarında homojen karışım kabulü yapabilmeye o-lanak sağlayacak oranda düşük başlangıç hacimsel konsantrasyonu.
- * Yüzey gerilimi etkisinin ihmal edilemeyeceği derecede küçük ol-mayan; küresel, yalnız bir ideal gaz ihtiva eden , önemli oranda sıvı buharı bulundurmayan gaz kabarcıkları.
- * Sıvı fazın ısı kapasitesi gaz fazından çok büyük ; gazdaki sıcaklık değişimlerinin sıvı faza etkisi yok sayılabilir.
- * Gaz fazın ısı davranışı izoterm kabul edilebiliyor.

İki fazlı akışkanların davranış denklemleri için , çok sağlam temellere dayanan , tartışmasız bir teori bulunmamaktadır. Çalışmada, uygulamalı araştırmalarda en yaygın olarak kullanılan ve Ayırık Akış kavramı ile tanımlanan ; faz konsantrasyonları ile yazılan akış denklemlerinin her iki faz için de geçerli olduğunu ve bunların bir ara-ya getirilmesi ile , iki fazlı karışımın hareket denklemlerinin elde edilebileceğini kabul eden teori esas alınmıştır. Faz değeri kavramı iki temel büyüklük olan özgül kütle ve basınça uygulanmaktadır.

$$\left. \begin{array}{l} \rho_j^* = \beta_j \rho_j \\ \rho_j^* = \beta_j \rho_j \quad (p_s = p_g = p) \end{array} \right\} \begin{array}{l} j = g : \quad \beta_g = \beta \quad (\text{Gaz}) \\ j = s : \quad \beta_s = 1 - \beta \quad (\text{Sıvı}) \end{array}$$

Tek fazlı hal akış denklemlerinin, kapsamlı genel şekilleri ile ele alınması ; fazlar arasındaki ısı ve kütle geçişi gibi burada yok sayılan etkileri de içine alan, kapsamlı ve çok amaçlı temel denklemlerin elde edilmesini sağlamıştır. Homojen dağılmış gaz kabarcıklı sıvı iki fazlı karışımlarının ; kayma , yüzey gerilimi , ısı ve kütle geçişleri etkilerinin kolayca ayırt edilebileceği formda yazılmış temel denklemleri aşağıda verilmiştir.

Denklemlerdeki, çok yaygın olarak kullanılmayan sembol ve indislerin anlamları aşağıda özet şekilde verilmiştir.

r : Faz kayması oranı (U_g / U_s). ; C : Ses hızı.
R : Kabarcıkların ortalama yarıçapı. ; m : Kütle geçişi.
τ : Viskoz sürtme gerilmeleri. ; q : Isı geçişi.
İndisler : k : Karışım / s : Sıvı faz / g : Gaz faz.
a : Faz Arakesitleri. d : Kap Duvarları.

Enerjinin korunumu denklemi ;

$$\frac{D p_k}{D t} + [1 + (r-1) \beta] \rho_k C_k^2 \frac{\partial u_k}{\partial x} - \left[1 - (1-\beta) \frac{\rho_k C_k^2}{\rho_s C_s^2} \right] \frac{2 \sigma}{R} = \rho_k C_k^2 V_1$$

$$V_1 = V_1^* - [1 + (r-1) \beta] \frac{u_k}{A} \frac{dA}{dx} ; V_{j=s/g} = \frac{(q_{dj} + q_{aj}) + (\tau_{dj} + 2\tau_{aj}) u_j}{\beta_k \rho_k A}$$

$$V_1^* = \left[\frac{1}{\rho_g} - \frac{1}{\rho_s} \right] \frac{m_{ag}}{A} - \left[V_g \frac{\beta}{\rho_g} \frac{\partial \rho_g}{\partial h_g} + V_s \frac{1-\beta}{\rho_s} \frac{\partial \rho_s}{\partial h_s} \right]$$

Akış denklemi ;

$$[r \rho_k - (r-1) (1-\beta) \rho_s] \frac{Du_k}{Dt} + \frac{\partial p_k}{\partial x} - \beta \frac{2 \sigma}{R^2} \frac{dR}{dx} = V_2$$

$$V_2 = -g \rho_k \frac{Dz}{Dx} - \frac{(\tau_{dg} + \tau_{ds}) + (\tau_{ag} + \tau_{as})}{A}$$

Süreklilik - konsantrasyon dağılımı denklemi ;

$$\frac{1}{\beta (1-\beta)} \frac{D\beta}{Dt} + \left[\frac{1}{\rho_g C_g^2} - \frac{1}{\rho_s C_s^2} \right] \frac{Dp_k}{Dt} - B = V_3$$

$$B = \frac{r-1}{u_k} \left[\frac{Du_k}{Dt} - \frac{du_k}{dt} \right] + \frac{1}{\rho_g C_g^2} \frac{2\sigma}{R^2}$$

$$V_3 = - (r-1) \frac{u_k}{A} \frac{dA}{dx} + \frac{1}{\beta(1-\beta)} \frac{\rho_k}{\rho_g \rho_s} \frac{m_{ag}}{A} - \left[\frac{V_g}{\rho_g} \frac{\partial \rho_g}{\partial h_g} - \frac{V_s}{\rho_s} \frac{\partial \rho_s}{\partial h_s} \right]$$

Hareket denklemleri , "hiperbolik" tip kısmi dd'lerdir ; bu da çözümün Karakteristikler Yöntemi (KY) ile aranmasının uygun olacağını gösterir. Ayrıca, olayın anlık sürecindeki bütün fiziksel değişimleri adım adım izleyebilmek ve eş zamanlı durum tablolarını kolaylıkla hazırlanabilmesi için KY'nin kullanılması hemen hemen zorunludur. Yöntem, açıklık ve fiziksel gerçeklik özellikleri dolayısı ile, geçiçi rejimli olayların incelenmesinde çok tercih edilir. Özellikle süreksizlik yüzeylerinin bulunması halinde çok önemli kayıt tutma ve iletme sorunları yaratması yöntemin en olumsuz yanıdır. Yöntem , sorun kaynaklarından çokca bulunmasına rağmen (iki hareketli düzgünsüzlük yüzeyi : gaz-sıvı arakesiti ve şok cephesi) tam başarı ile uygulanmıştır.

Genel hareket denklemlerinden elde edilen Karakteristik Denklemler ; çalışmada kabul edilen Eşit Hız - Eşit Sıcaklık [EVET] modeline göre sadeleştirildiğinde, programda kullanılan aşağıdaki basit format elde edilmektedir. İki fazlı akış ortamının getirdiği ilave büyüklük, yaygın fazın hacimsel konsantrasyonu için ; bu fazın akış alanındaki yörüngelerini belirleyen bağıntısının , üçüncü bir karakteristik olarak hesaba katılmasını gerektirmiştir.

$$C^{\mp} (u \mp C) : \frac{1}{\rho_k C_k} \frac{D^{\mp} p_k}{Dt} \mp \frac{D^{\mp} u_k}{Dt} = C_k V_1 \mp \frac{1}{\rho_k} V_2$$

$$V_1 = - \frac{u_k}{A} \frac{dA}{dx} ; \quad V_2 = - g \rho_k \frac{dz}{dx} - \frac{\tau_{dg} + \tau_{ds}}{A}$$

$$C(u) : \frac{D\beta}{Dt} + \beta(1-\beta) \left[\frac{1}{\rho_g C_g^2} - \frac{1}{\rho_s C_s^2} \right] \frac{Dp_k}{Dt} = 0$$

Tamamen dolu olmayan kaplar halinde , büyük hız ile tahliye olan gaz tarafından sürüklenen iki fazlı akışkanın tahliyesi safhasında çok kuvvetli de olabilen ve bir Şok Cephesi (ŞC) oluşmasına neden olan boğulma olayı ile karşı karşıya kalınır. Zayıf boğulma durumunda, KM'nun düzensizliklerin etkisini sınırlayan ve söndüren karakterinden faydalanılarak, ŞC yaratılmadan da çözüm aranabilir ise de, güçlü

cepheler halinde bu basitleştirme , sonuca ulaşmayı tamamen önleyebilir veya çok yanıltıcı, hatalı sonuçlar verebilir. Yalnız bir adet ŞC'nin oluşması ve dolayısı ile girişim sorunlarının bulunmaması, problemi KM ile çözülebilirlik sınırları içinde tutmuştur. Araştırmalar çok ince olan cephede izoterm değişim kabulü yapılabileceğini ve sıkıştırılabilir akışkanlar dinamiğinden bilinen Rankine-Hugoniot şok denklemlerinin, gaz kabarcıklı sıvı iki fazlı akışkanları için de, hiçbir düzeltmeye gerek olmadan geçerli olduğunu göstermiştir. Rankine Denklemlerinin iki fazlı akışkan için yazılan şekli aşağıda verilmiştir ; doğruluğu artırmak için, enerji denklemi olarak, özel şartlara göre sadeleştirilmiş, Bernoulli denklemi kullanılmıştır.

$$\rho_1 v_1 = \rho_2 v_2 \quad : \quad \rho_1 (u_1 + U) = \rho_2 (u_2 + U)$$

$$p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2 \quad : \quad p_2 - p_1 = \rho_1 v_1^2 - \rho_2 v_2^2$$

$$\frac{p}{\rho} + \frac{1}{2} v^2 + e = \text{Sbt.} \quad : \quad e \approx (1-\beta) C_{v,s} T = \text{Sbt.}$$

$$\left[1 + \frac{\beta}{1-\beta} \ln \frac{p}{p_0} \right] \frac{p}{\rho_s} + \frac{u^2}{2} = \text{Sbt.}$$

Yalnız iki fazlı değil, hem yoğun hem de çok düşük ses hızlarına sahip olabilen bir akışkanla çalışmanın zorlukları, problemin çözümünü çok daha zor hale getirmiştir. Şok denklemleri, uygun olanı bulunamadığı için, hiçbir paket yazılım kullanılmadan , ama özellikle iki fazlı ortamdan kaynaklanan güçlükler nedeni ile, çok zorlukla çözülebilmektedir. Data dosyasıda, ŞC hesaplarına yönelik pekçok parametre bulunmakta ise de, sınır değerler ile çalışıldığında bile bunların yalnız temel birkaç tanesi üzerinde düşünmek yeterli olmaktadır.

Gaz kabarcıklı sıvı iki fazlı akışkanı, gaz fazın konsantrasyonuna çok bağlı olarak çok büyük aralıkta değişen ses hızlarına sahip olabilmektedir dolayısı ile bu değerlerin doğru hesaplanması oldukça önemlidir. Testler göstermiştir ki, karmaşık veya basit bütün öne sürülmüş formatların yer aldığı programda da tercih edilen aşağıdaki basit bağıntı en iyi sonucu vermektedir.

$$[\rho_k = \beta \rho_g + (1-\beta) \rho_s] \quad C_k = \sqrt{\frac{n p}{\beta \rho_k}}$$

Tahliye elemanı esas olarak bir standart eleman olarak düşünülmüştür. Teorik tahliye hızını hesaplamada , aşağıda verilen , gaz kabarcıklı sıvı iki fazlı akışkanlar için yazılmış hidrolik yük ifadesi kullanılmıştır.

$$H = \frac{1 + \mu}{\mu} z + \frac{1}{1 + \mu} \left[1 + \frac{n}{n-1} \frac{\beta}{1-\beta} \right] \frac{p}{g \rho_s} + \frac{u_k^2}{2g}$$

İzoterm davranış kabulü yapıldığında, teorik tahliye hızı için aşağıdaki bağıntı geçerli olmaktadır. D daralmış kesiti, T tepedeki en son hesap noktasını gösterir, $\xi = p_T / p_D$ ise basınç oranıdır.

$$(u_D)_{Th}^2 \approx u_A^2 + \frac{1}{1 + \mu} \frac{p_D}{\rho_s} \left[(\xi - 1) + \frac{\beta_T}{1 - \beta_T} \xi \ln \xi \right]$$

Çok küçük sayılabilecek ses hızlarının kolayca gerçekleşebildiği iki fazlı akışkan, başlangıçta genellikle ses hızı ile tahliye olur. İki fazlı akışkanın karakteri ses altı akışa dönüş şartlarını belirleyen kritik basınç oranının hesabında da kendini gösterir ve izoterm davranış ve kaymasız akış için basitleşmiş bağıntı dahi aşağıdaki karmaşık yapıda kalır.

$$(E_1 + \ln \xi_{Kr}) \xi_{Kr}^2 - E_2 \xi_{Kr} - E_3 = 0$$

$$E_1 = \frac{Z_1 - Z_2}{Z_1 Z_2} ; \quad E_2 = \frac{2 + (Z_1 - Z_3)}{Z_1 Z_2} ; \quad E_3 = \frac{1}{Z_1 Z_2^2}$$

$$Z_1 = \frac{2}{1 + \mu} ; \quad Z_2 = \frac{\beta_T}{1 - \beta_T} ; \quad Z_3 = \frac{\rho_s}{p_D} \left[u_A^2 - 2 g \Delta z \right]$$

Problemin çözümünde göz önüne alınan etkilerin ve kullanılan yöntemlerin başlıcaları aşağıda özetlenmiştir.

* Üçüncü karakteristik kullanımı ihmal edilmemiş, bunun yerine ve başlangıçta konsantrasyon dağılımı olmasına da izin vermeyen analitik yöntemler kullanılmamıştır.

* KM'nin ani değişimleri yumuşatıcı karakteri zorlanmamış ve mesela, bütün hallerde başlangıç dalga cephesi sistemi kullanılmıştır.

* Olayın en hızlı olduğu ilk anlarda, değişimlerin yumuşak olması için gerekli kısıtlamalar programa konmuştur.

* Hatasız çalışma için gerekli bütün önlemler alınmış, hata dolayısı ile geri dönüşlerde, yalnız bir önceki tam adımın bilgilerinin kullanılması için gerekli düzenlemeler yapılmıştır.

* Hataların sızmasını önlemek için, ortak işlemler bir alt programda toplanırken; aynı bazlı da olsalar ayrıntıda çok farklı olan mesela süreksizlik yüzeyli uc nokta hesapları için bağımsız alt programlar kullanılmıştır.

Özellikle, büyük ölçüde karmaşık, hacimli ve çok bilgisayar zamanı kullanabilen bir program sözkonusu olduğundan, aşağıda özetlenen iyi programcılık uygulamalarına önem verilmiştir.

* Gerekli bilgisayar zamanını azaltmak için, hesap noktası sayısı

artırmaları yalnız çok gerekli olduğunda ve gerektiği süre için yapılmıştır.

* Hataların kolay belirlenebilmesi için gerekli önlemler alınmış ve data dosyası parametreleri ile istenilen hesap adımı ve düğümü için detaylı veri dosyaları üretimi sağlanmıştır. Program, hiçbir hata bulma yardımcısına gerek göstermeyecek kadar kapsamlı hata kaynağı belirleme olanaklarına sahiptir.

Yukarıda değinilenlere ilave olarak ; programın kolay anlaşılabilirliğini artırmak , çıkış dosyalarını ve grafikleri rahat kullanılır ve gerekli bütün bilgilerle donatılmış yapmak ve kullanılan her yöntemin ve parametrenin etkisini inceleyebilmek için gereken önlemler alınmıştır. Programın portatifliği ve benzer iki fazlı akış şartlarına genişletilebilirliğini sağlamak için gerekli önlemler, dikkatle ele alınmış ve uygulanmıştır. Yalnız, programı boyutsuzlaştırma bu kapsamda düşünülmemiştir ; boyutsuzlaştırmanın program içinde yapılması, çok karmaşık yapıyı, işlemlerin fiziksel anlamlı yapılarını bozarak çok daha karmaşık hale getireceğinden hiç istenmemiştir. Çıkış dosyalarının boyutsuzlaştırılması ise özellikle grafik dosyaları için büyük ölçüde gerçekleştirilmiştir.

Gaz kabarcıklı sıvı iki fazlı akışkanı ile tamamen dolu kaplar hali, en uc sayılabilecek veriler için dahi hatasız çalışma sağlayacak kalitede çözülmüştür. Bu hallerde, tek fazlı akışlarda yeterli olan kadar , yaklaşık 10 düğüm noktası ile çalışılması çözüme ulaşmayı sağlamaktadır. Tam dolu olmayan kap hali de çok kapsamlı olarak ele alınmış ve uygulamada raslanabilecek uç değerler de tek tek göz önüne alınarak program test edilmiştir ; yine de, şok cephesi ile ilgili çok karmaşık hesaplar sözkonusu olduğundan , bazı uc değerler için ŞC hesabı parametrelerinin bir-iki tanesinde ayarlama yapmak gerekebilmektedir. Makul uc değerleri de kapsayan yüze yakın tam dolu olmayan kap hesabı, hiçbir özel önlem almadan gerçekleştirilebilmiştir.

Tam dolu kap hali, çok verili dosyalar da kullanılarak çok yönlü olarak incelenmiştir. Varılan sonuçlar aşağıdaki gibi özetlenebilmektedir; normal şartlarda - düşük basınç ve konsantrasyon - basıncın zaman içindeki değişimi; ses hızı farklılığı göz önüne alındığında, basınçlı gaz kabı halindekinden çok farklı olmamaktadır; bu da beklenilecek bir sonuçtur. Bu şartlarda tahliye edilen akışkan miktarı ise basit Sanki Daimi Akış (SDA) şartları için hesaplanandan çok az farklı olmaktadır. Tahliye edilen sıvı miktarı hemen tamamen başlangıçtaki basınca bağlıdır ; açıklığın alan oranına bağlılık artı yönde ama çok önemsiz mertebededir. Tam dolu kap halinde önemli sayılabilecek basınç sıçramaları - darbe etkisi - görülmemektedir. Bu hal için iki boyutsuz sayı geliştirilmiş ama yalnız birinde ve tam olmayan bir başarı sağlanmıştır. SDA çözümlerine olan yakınlık, sonuca bu yoldan ve çok bol sayıda ve çeşitli hallere ait sonuçlar kullanılarak yaklaşılabileceğini göstermektedir.

Tam dolu olmayan kap hali, özellikle tam dolu hal ile orantılama yapılamayacak ölçüde çok bilgisayar zamanı kullandığı için, tam dolu hal kadar çok sonuç dosyası kullanılarak değerlendirilememiş ama bu halin genel karakterini ortaya koymaya yeterli sayıda ve çeşitte veri dosyası üretilmiştir. Bu hale ait sonuçların değerlendirilmesi , aşağıda özetlenen sonuçlara yaptırmıştır ;

* Eğer kullanılacak bilgisayar zamanı yönünden yeterli rahatlıkla

davranılamamış ise ; sonuçlar , genel karakter korunsa da oldukça hatalı olarak elde edilebilmektedir.

* Kuvvetli şok cepheleri, etkilerini çok bariz bir şekilde basınç dağılımı zaman çıkışlarında göstermekte ise de, tahmin edileceği gibi başlangıç değerini aşan bir darbe basıncı gözlenmemektedir. En yüksek basınç artışı , ŞC'nin üretildiği boğulma anında olmakta ve normal olarak ilk değerin yarısını geçmemektedir.

* Olayın yaratabileceği negatif basınç şartlarının sınırlılığı, karışımın dışarı atılması olayının başlayacağı kritik karışım yüksekliği oranının Sanki Daimi Akış hali sonucuna çok yakın olduğunu göstermiştir.

ÖZETİN SONU



CHAPTER 1

INTRODUCTION

The name of the subject under investigation; "Ejection From Rapidly Depressurized Vessels Containing Bubbly-Liquid Two-Phase Fluid" is quite self explanatory but the following paragraph would help to draw the frame of interest more precisely.

" Ejection through standard or otherwise top side openings from full or lengthwise partially full, axisymmetrical, tube like vessels or pipes; holding low volume fraction, homogeneously dispersed, moderate size gas bubbles - liquid two-phase mixtures in equilibrium; as a result of nearly instant or rapid depressurization that resulting flow can be considered one dimensional and largely slip-free ."

1.1. THE TWO - PHASE FLOW CONCEPT.

Two-phase flow as a term describes interacting flow of the two of the phases - gas, liquid or solid - that the interface between the phases is influenced by the motion.

Two-phase flow concept has many familiar natural occurrences and applications in most industries. The spectrum of the two-phase flows is illustrated in Fig.1-1 [5].

The type of two - phase medium under consideration is the mixture of a liquid (the continuous phase) and an ideal gas (not liquid vapour) - the distributed phase - where the gas presents itself as uniformly distributed and not moderate size - neither too small or too large - spherical like bubbles.

As seen in Fig.1-2 [5], most natural and industrial two-phase flow examples fall into the liquid - gas mixture flow category and in a lot of industrial applications, the gas phase is created in the process as the vapour of the base liquid.

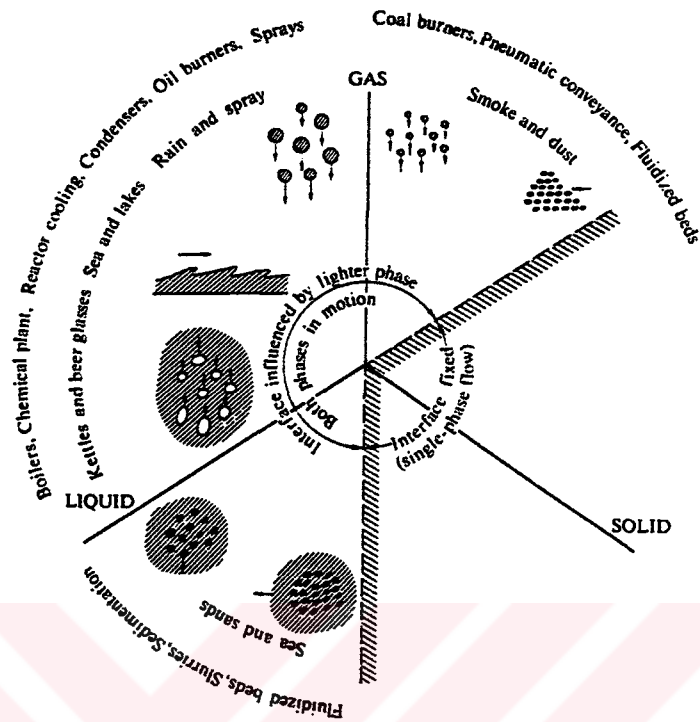


Fig. 1-1 Spectrum of Two-Phase Flows.

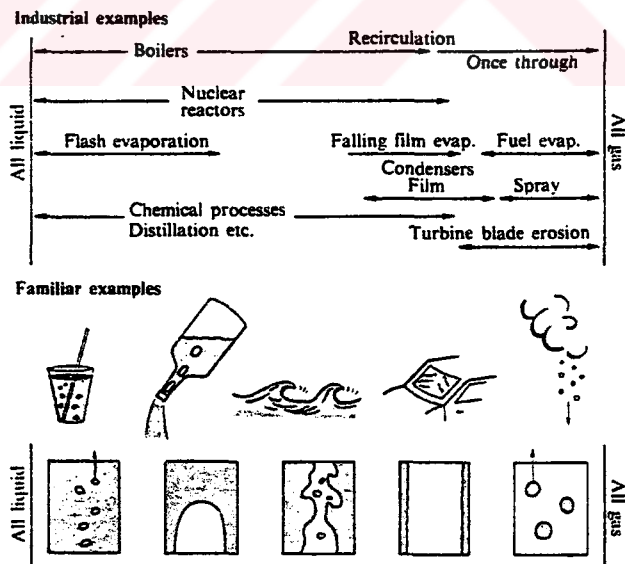


Fig. 1-2 Gas-Liquid Two-Phase Flows.

Due to their unique coupling - both being fluids and large specific mass ratio -, liquid-gas two-phase flows create very rich (the richest for any two-phase case) flow patterns, specific to the vertical upward and horizontal flow cases.

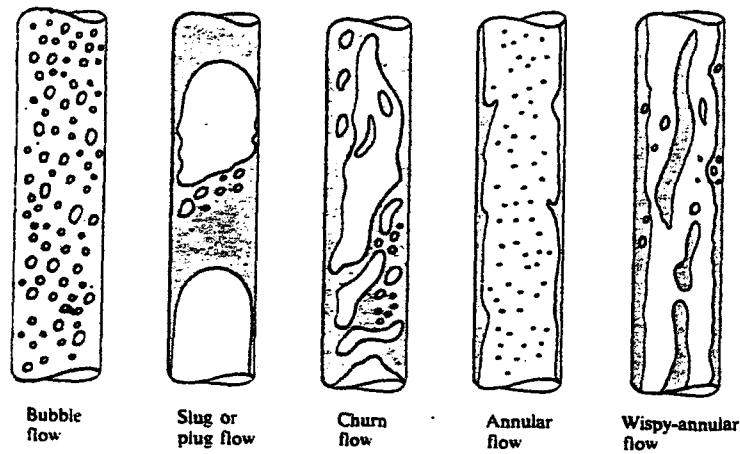


Fig. 1-3 Vertical-Upward Liquid-Gas Flow Patterns.

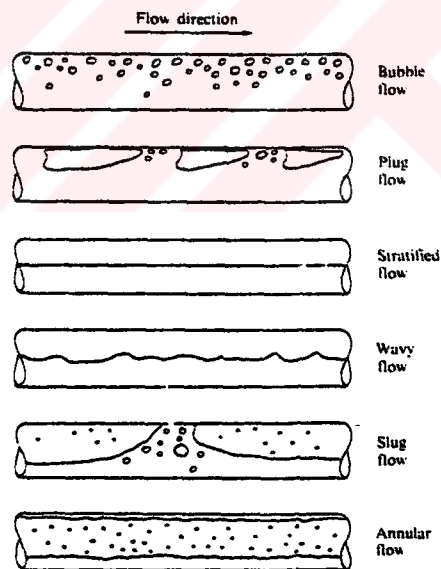


Fig. 1-4 Horizontal Liquid-Gas Flow Patterns.

Fig.1-3 and Fig.1-4 [5] depict the flow patterns of the main vertical-upward and horizontal cases ; for which the quality of the illustrations and the meaningful names assigned to them largely negates the need for explanations, for the present purpose.

1.2. PARAMETERS OF TWO-PHASE MIXTURES AND FLOWS.

Two-phase mixtures introduce two special parameters and some others as the characteristic derivatives of them, the physical properties of the phases and the flow.

Principal special parameter; *Void Fraction* or *Volumetric Concentration* $[\beta]$ represents the volume fraction of the dispersed phase - the bubbles - in the whole mixture. The other special parameter; *Slip (Ratio)* or *Holdup (Ratio)* $[r]$ is the ratio of the phasic velocity of the dispersed phase - the bubbles - to that of the continuous phase - the liquid -.

Unlike void fraction, slip ratio may justifiably be omitted, due to its very small effect and the complexities it brings, for homogeneous low acceleration flows that represent most part of the two-phase flow under consideration.

Definitions and all forms of interrelating equations of all of the non-dimensional quantities of bubbly-liquid two-phase flows are given in App.A.

1.3. RESTRICTIONS AND ASSUMPTIONS.

The boundaries of the problem under consideration are drawn through the restrictions and assumptions listed below.

1.3.1. Shape of the Vessel.

The conditions on the shape of the vessel that are listed below basically aim the maintenance of the one-dimensional flow assumption; that is on whether the vessel resembles a cylinder or a pipe or not ;

- Tube like vessel with a straight axis of symmetry.
- Aspect ratio is considerably bigger than unity.
- Cross section area changes are small and smooth.

The full list of conditions are given in App.D.

1.3.2. Physical Conditions of the Mixture.

- Liquid part forms the continuous phase and gas bubbles form the dispersed phase.

- Thermodynamic equilibrium ; thermal diffusion rates can be

omitted - but phasic temperatures may differ -.

- Chemical equilibrium ; mass diffusion rates can be omitted.
- Mixture is neither superheated nor sub-cooled ; no phase transition may take place.

1.3.3. Physical Conditions of the Phasic Fluids.

- * The liquid has moderate physical characteristics ;
 - Moderate viscosity and surface tension.
 - Moderate saturation vapour pressure.
 - Constant bulk modulus of elasticity can be assumed.
 - Classical surface tension theory can be assumed valid for all bubble radii.
- * Heat capacity of the continuous - liquid - phase is far bigger than that of the dispersed - gas - phase, that is temperature of the liquid phase can be assumed to stay constant.
- * The gas is an ideal gas and does not contain (considerable amount of) the vapour of the liquid.
 - Gas in the bubbles or in the vessel on top of the mixture obeys the perfect gas law.
 - The gas is not too soluble in the liquid; mass of the gas in bubbles stay the same.
 - Specific heat ratios of the phases stay constant.

1.3.4. Physical Conditions of the Bubbles.

- Bubbles are spherical or very nearly spherical initially and stay spherical -like- at all stages of the process.
- Size of the bubbles do not considerably differ at any cross-section and at any stage of the process.
- Bubbles are uniformly dispersed in all cross-sections and along the vessel.

1.3.5. Initial Conditions.

- Mean void fraction is low enough at all stages of the process that allows homogeneous mixture assumption to be made.
- Initial mean bubble radius is neither too high nor too low that is special emphasis need not be paid to the surface tension effect.
- Initial pressures are not too high. Too high pressures

jeopardize most of the assumptions above and due to specific gravity ratios near unity, make the employed methods quite useless.

- Smooth or linear void fraction and bubble size distributions along the vessel ; no buoyancy coagulation at the top.

- There is no heat transfer through the vessel walls in either direction, that is the processes can be assumed adiabatic.

1.4. THE CASES.

The Program, due to varying requirements and additional aims mentioned below, was associated with six more or less different cases and their data files.

The Full Vessel cases mentioned below are of the sub-cases of the principal case of the Non-Full Vessel case, but at least for the sake of having clearer input files, they are preferred to be treated as separate cases.

1.4.1. Non-Full Vessel (NFV) Case.

NFV case considers partially full vessels and is the main and obviously the most complex case of all which uses all routines of the programme (excluding the ones for the graphics).

1.4.2. The Full Vessel Cases.

The basic Full Vessel case is the principal sub-case and corresponds to most of the industrial applications of the subject. There are also two Multi Data File - Full Vessel cases for comparative study purposes.

The full-vessel cases of the programme with independant data files are listed below in the order of their relative importance ;

- * Basic Full Vessel (FV) Case.
- * Full Vessel - Multi Data (FV-MD) Case.
- * Full Vessel - Multi Data - Special (FV-MD Sp.) Case.
- * Full Vessel - Special (FV Sp) Case.

- * Basic Full Vessel (FV) Case.

Basic FV case is for the thorough investigation of a single set of data to produce detailed and informative output on step by step calculations that can be used for development purposes.

* Full Vessel - Multi Data (FV-MD) Case.

FV-MD case allows to do full comparative study on the effects of freely chosen two of the six principal quantity listed below ;

- Initial pressure ratio (PRO)
- Final area of the opening ratio (PHIF)
- Initial volumetric void fraction (BVO)
- Initial volume averaged bubble radius (BRVO)
- Duration of opening (TCO)
- Number of calculation nodes (M)

* Full Vessel - Multi Data - Special (FV-MD Sp.) Case.

FV-MD Sp. Case is a sub case of the FV-MD case that only one of the six principal parameters is allowed to change for the most comprehensive investigations.

1.4.3. The Sub - Cases.

* Pressurized Gas Bottle (GB) Case.

The GB case is obviously the extreme end subset of the main case, but it is found worthwhile to consider it as a separate full case with specially organized output format and graphics, due to relatively ample data on the case that can be used to check the format of the basic MC calculation routines.

* Artificial Run - Time Saving Cases.

Two artificial case were created just for the sake of run-time saving at the development stages of the program which were required due to large need of resources and the relatively low capacity and restricted access to the initially used computers.

- Full Vessel - Special (FV Sp) Case.

FV Special case was created for the relatively easy development of the SF programming part that allows to create an SF of more freely determined strength by artificial and instant throttling of the flow at a pre-determined stage which removes the necessity of passing through a lot of run time consuming NFV stages for being able to create an SF.

- Initial Conditions Data (ICD) Run Cases.

ICD run cases were created for savings at the development

stages when errors occur. Information of the last full step , in the format appeared on the output file is used as the initial conditions data to save the run-time up to the error stop stage. (For the basic FV and the GB cases only.)

* Quasi - Steady Flow (QSF) Calculations Case.

QSF calculations for the Full Vessel case [App. C.3] is incorporated into the program for simple comparison purposes.

1.5. SCOPE OF APPLICABILITY.

The scope of applicability of the problem as defined with its name may be considered very limited at the first thought but in fact many types of accidents in process industries may be reduced to and investigated through the subject or may use the methods employed and its applications as a guide for case specific solutions.

Principal fields or industrial processes that the methods of investigation and / or its applications and / or the results of this study can be any of help may be summarized as below.

- * Pressurized hydrodynamic process tanks ; that,
 - Contain bubbly liquid,
 - Produce vapor bubbles when depressurized,
 - Contain -large amount of- nucleation cavities.

* Thermodynamic process tanks that for their quick depressurization the heat and mass transfer effects can be assumed unimportant.

* Pressurized and hot liquid transport lines that at sudden depressurization produces and discharges two-phase mixtures of the liquid and its vapour bubbles. This case principally recalls the " Loss Of Coolant Accident " (LOCA) investigations in the nuclear power industry.

END OF CHAPTER 1.

CHAPTER 2

GOVERNING EQUATIONS OF ONE DIMENSIONAL BUBBLY-LIQUID TWO-PHASE FLOWS

The aim is to establish the set of governing equations of the one dimensional , bubbly - liquid two - phase flows that can be employed as the theoretical bases of a practical method of a numerical solution. The theoretical basis is covered as completely as possible that allow to examine a lot more complex problems than the one on hand that involve heat and / or mass transfer through the walls of the conduit and / or phase boundaries.

2.1. THE PRINCIPLES OF APPROACH.

The subject under consideration, does not and possibly can not have a straightforward theoretical basis, that is it can only be examined through at least some assumptions over the ones usually made for the single phase flows of the phasic components.

Micro structural problems of the two-phase, two-component bubbly-liquid flows are out of the scope, that is no averaging equation will be considered. But, in a way, it has been done in the macro structure with the Separated Flow assumption, through which the single phase governing equations are put together with effectiveness factors equal to phasic concentrations. As no established theory exist for the evaluation of the relative strengths / roles of the components in any of the governing equations, the phase concentrations are assumed as the representative Effectiveness Factors.

A two-phase bubbly-liquid flow theory / model must consider

the behaviour - being a variable or a constant - of the three principal parameters of - in the order of their importance - " Velocity , Temperature and Pressure " at the phase boundaries. The most complete model is called " UVUTUP : Unequal Velocity , Temperature and Pressure " model. The eventually arrived model of the cases under consideration is the simplest one that is the " EVET : Equal Velocity - Equal Temperature " model. (*)

The EVET model is also the only model that can be approached numerically in its proper meaning as will be reasoned later.

2.2. LIMITING CONDITIONS AND ASSUMPTIONS.

The main limiting condition of one dimensional flow assumption is important only for the cases of too rapid expulsion from openings of large area ratio on vessels that may not be regarded pipe - like.

The Separated Flow model can be established for the slip flow case, but it makes the resulting equation unnecessarily complex and no comprehensive data is available for its numerical evaluation. Even for the highly accelerated flows through expulsion elements, lack of proper data prevented the inclusion of the slip effect into the numerical solution [Chap. 4].

The model, in theory, allows the employment of the unequal pressures concept, but the resulting characteristic equations would be too complex and the benefits would be minimal for not very small bubbles cases that are under consideration.

Uniform or non - uniform temperature field assumption across the phase boundaries does not effect the formulation. In this respect, the important point is the determination of the heat transfer coefficients.

Although it is ignored due to its minimal importance , the interfacial mass transfer effect too is readily allowed and can easily be incorporated into the programme as it does not effect the character of the system of equations.

(*) "EP" ; Equal Pressure part is customarily dropped as it is an obvious extention of the "EV" and the "ET" assumptions.

2.3. SEPARATED FLOW CONCEPT.

The principals of the separated flow concept and its application may be summarized as below ;

- Single phase equations written with phase concentrations are valid for both phases.
- The single phase equations of the phases may be combined to form the governing equations of the two-phase mixture.
- Partial values concept can be applied to the two of the specific quantities, namely the specific gravity and pressure, that is ;

$$\xi \left\{ \begin{array}{l} \rho \\ p \end{array} \right. \quad \xi_k = \beta_k \xi_k : \quad \begin{array}{l} k = g : \beta_g = \beta \quad ; \quad \xi_g^* = \beta \xi_g \\ k = l : \beta_l = 1-\beta \quad ; \quad \xi_l^* = (1-\beta) \xi_l \end{array} \quad (2.1)$$

2.4. PHASIC CONSERVATION EQUATIONS.

The governing equations that can be applied to both continuous and dispersed / separated phases may be listed as below for one dimensional flows ;

Equation of State ;

$$\rho_k = \rho_k (p_k , h_k) \quad (2.2)$$

Equation of Continuity ;

$$\frac{\partial}{\partial t} A \rho_k^* + \frac{\partial}{\partial x} A \rho_k^* u_k = \left(\frac{dm}{dt} \right)_{i,k} \quad (2.3)$$

Equation of the conservation of mass ;

$$\sum \left(\frac{dm}{dt} \right)_{i,k} = \left(\frac{dm}{dt} \right)_{i,g} + \left(\frac{dm}{dt} \right)_{i,l} = 0 \quad (2.4)$$

Equation of the conservation of momentum ;

$$\begin{aligned} \frac{\partial}{\partial t} A \rho_k^* u_k + \frac{\partial}{\partial x} A \rho_k^* u_k^2 + A \beta_k \frac{\partial}{\partial x} p_k &= \longrightarrow \\ \longrightarrow &= - g A \rho_k^* \frac{dz}{dx} - \tau_{wk} - \tau_{ik} - \left(\frac{dm}{dt} \right)_{i,k} \left(\frac{du}{dt} \right)_k \end{aligned} \quad (2.5)$$

Eqn.(2.5) involves an uncertainty : $\beta_k \frac{\partial}{\partial x} p_k / \frac{\partial}{\partial x} (\beta_k \rho_k)$

Equation of the Conservation of Energy ;

$$\begin{aligned} \frac{\partial}{\partial t} A \rho_k^* \left(h_k + \frac{u_k^2}{2} \right) + \frac{\partial}{\partial x} A \rho_k^* u_k \left(h_k + \frac{u_k^2}{2} \right) - A \beta_k \frac{\partial}{\partial t} p_k &= \longrightarrow \\ \longrightarrow &= - \rho_k^* u_k \left(h_k + \frac{u_k^2}{2} \right) \frac{dA}{dx} + m_{i_k} \left(h_k + \frac{u_k^2}{2} \right) - \longrightarrow \\ &\longrightarrow - g A \rho_k^* u_k \frac{dz}{dx} + q_{w_k} + q_{i_k} + \tau_{i_k} u_{i_k} \end{aligned} \quad (2.6)$$

Where ; m_{i_k} : Interfacial Mass Transfer ;

$$m_{i_g} + m_{i_l} = 0 ; \quad m_{i_g} = m_{i_l} ; \quad m_{i_g} = - \frac{q_{i_g} - q_{i_l}}{h_g - h_l} \quad (2.7)$$

q_{i_k} : Interfacial Heat Transfer ;

$$q_{i_k} = \lambda_{i_k} (T_s - T_k) ; \quad T_s - T_k = \frac{h_{k_s} - h_k}{C_{p_k}} \quad (2.8)$$

$$\lambda_{i_k} = K_{i_k} A_i \rho_k C_{p_k} ; \quad A_i = \beta_g \beta_l A \quad (2.9)$$

q_{w_k} : Wall Heat Transfer ;

$$q_{w_k} = \beta_k q_w ; \quad q_w = q_w(x) \quad [A \text{ known function}] \quad (2.10)$$

τ_{w_k} : Wall Friction ; [App.C.5]

$$\tau_{w_k} = \rho_k^* A F ; \quad F = \left(\frac{f_k}{D_e} + f_{dl} \right) \frac{u |u|}{2} \quad (2.11)$$

$f_{dl} = f_{dl}(x)$: Distributed Loss function.

τ_{i_k} : Interfacial Friction Stresses ;

$$\tau_{i_k} = \tau_{i_{kcg}} + \tau_{i_{kid}} + \tau_{i_{kam}} + \tau_{i_{kbf}} \quad (2.12)$$

Concentration	Interfacial	Added	Bessel Force
Gradient	Drag	Mass	History
Effect	Effect	Effect	Effect

$$\tau_{i_{kcg}} = (p_{i_k} - p_k) \frac{\partial \beta_k}{\partial x} \quad (2.13)$$

$$\tau_{i_{k_{id}}} = K(\beta_k) C_D \frac{\rho_k}{d_b} u_{rk} |u_{rk}| \quad ; \quad K(\beta_k) \approx \frac{3}{4} \beta_k \quad (2.14)$$

$\tau_{i_{kam}}$: Added Mass effect ; is related with the force needed to overcome the inertia of the mass that lies in the path of the distributed phase which accelerates more than the continuous phase. Ignored due to its very small effect and the need to save run-time but can easily be incorporated into the set of equations employed.

$$\tau_{i_{kam}} = M(\beta_k) \left(\frac{\partial u_{rk}}{\partial t} + u_k \frac{\partial u_{rk}}{\partial x} \right) \quad (2.15)$$

$$M(\beta_k) \approx \frac{1}{2} \beta_k (1-\beta_k) \frac{C_D}{C_{D,s}}$$

$\tau_{i_{kbf}}$; Basset Force / History Effect is related with the momentum diffusion through growing boundary layer on the interface due to the acceleration of one phase against the other and is expressed with a very complex integral equation (Wallis [48]), and is quite ignorable due to not too important slip and acceleration effects.

Here, there is a probably inevitable dilemma that "Separated" and "Distributed-Continuous" phase concepts are in consideration at the same time ; that is "micro state" forces too are taken into consideration in the above relations.

2.5. THE ARRANGED PHASIC EQUATIONS.

The arranged, simpler to handle formats of the phasic governing equations [Eqns. (2.2) to (2.6)] can easily be obtained through simple considerations

The principal governing equation, the equation of flow ; can be obtained through simple manipulations of the continuity and the momentum equations. [Eqns. (2.3) and (2.5)]

$$\frac{Du_k}{Dt} + \frac{1}{\rho_k} \frac{\partial p_k}{\partial x} = - \frac{\tau_{wk} + \tau_{ik}}{\beta_k \rho_k A} - g \frac{dz}{dx} \quad (2.16)$$

The arranged continuity equation ;

$$\frac{1}{\rho_k} \frac{D\rho_k}{Dt} + \frac{1}{\beta_k} \frac{D\beta_k}{Dt} + \frac{\partial u_k}{\partial x} = \frac{m_{ik}}{\beta_k \rho_k A} - \frac{u_k}{A} \frac{dA}{dx} \quad (2.17)$$

The energy balance equation ;

$$\frac{Dh_k}{Dt} - \frac{1}{\rho_k} \frac{Dp_k}{Dt} = V_k \quad (2.18)$$

$$V_k = \frac{(q_{wk} + q_{ik}) + (\tau_{wk} + 2 \tau_{ik}) u_k}{\beta_k \rho_k A} \quad (2.19)$$

Speed of small perturbations relation ;

$$[\rho_k \neq \rho_k (T)] \quad \frac{1}{C_k^2} = \left[\frac{\partial \rho_k}{\partial p_k} \right]_s = \frac{\partial \rho_k}{\partial p_k} + \frac{1}{\rho_k} \frac{\partial \rho_k}{\partial h_k} \quad (2.20)$$

Eqns. (2.17) to (2.19) may be combined as below ;

$$\frac{1}{C_k^2} \frac{Dp_k}{Dt} + \frac{\rho_k}{\beta_k} \frac{D\beta_k}{Dt} + \rho_k \frac{\partial u_k}{\partial x} = \text{MHMT} - \rho_k \frac{u_k}{A} \frac{dA}{dx} \quad (2.21)$$

The "Mass , Heat and Momentum Transfer" term ; "MHMT" is ;

$$\text{MHMT} = \frac{1}{\beta_k \rho_k A} \left(\rho_k m_{ik} - [(\tau_{wk} + 2\tau_{ik})u_k + (q_{wk} + q_{ik})] \frac{\partial \rho_k}{\partial h_k} \right) \quad (2.22)$$

Phasic velocity difference and its derivatives can be extracted from the principal relations of ;

$$r = \frac{u_g}{u_l} \quad (2.23)$$

$$u_g = r u_l \quad ; \quad u_g - u_l = (r - 1) u_l$$

With the aim of keeping the equations as simple as possible , the phasic pressure difference is expressed in its most basic format ;

$$p_g - p_l = \frac{2 \sigma}{R} \quad \frac{dR}{dt^*} = \dot{R} = u_{ik} < u_k \quad (2.24)$$

where " t* " is related with the special boundary conditions of the radial pulsations of bubbles. [App.C.4]

2.6. THE GOVERNING EQUATIONS.

Governing equations of bubbly - liquid two - phase mixtures are to be created by side-by-side adding up of the corresponding phasic equations of Eqns.(2.21), (2.16) and (2.17) ; which is a straightforward work when Eqns.(2.23) and (2.24) are properly taken into account.

The mixture quantities are to be taken as of the continuous phase - liquid - ones, that is ;

$$u_m = u_l, \quad p_m = p_l, \quad \beta = \beta_g \quad (2.25)$$

It should be noted that the phasic equations takes into account of the relative concentrations of the phases that is no additional correction with regard to phasic void fractions is required.

The three governing equations are given below, in a format most easy to evaluate in respect to the limiting and special conditions. The energy conservation equation of the mixture ;

$$\frac{Dp_m}{Dt} + [1 + (r-1)\beta] \rho_m C_m^2 \frac{\partial u_m}{\partial x} - \left(1 - (1-\beta) \frac{\rho_m C_m^2}{\rho_l C_l^2} \right) \frac{2 \sigma}{R^2} \dot{R} = \rho_m C_m^2 V_1 \quad (2.26)$$

$$V_1 = V_1^* - [1 + (r-1)\beta] \frac{u_m}{A} \frac{dA}{dx} \quad (2.26A)$$

$$V_1^* = \left(\frac{1}{\rho_g} - \frac{1}{\rho_l} \right) \frac{m_{ig}}{A} - \left(V_g \frac{\beta}{\rho_g} \frac{\partial \rho_g}{\partial h_g} + V_l \frac{1-\beta}{\rho_l} \frac{\partial \rho_l}{\partial h_l} \right) \quad (2.26B)$$

$$V_k = \frac{(q_{wk} + q_{ik}) + (\tau_{wk} + 2 \tau_{ik}) u_k}{\beta_k \rho_k A} \quad (2.26C)$$

The equation of motion of the liquid ;

$$\left(r \rho_m - (r-1) (1-\beta) \rho_l \right) \frac{Du_m}{Dt} + \frac{\partial p_m}{\partial x} - \beta \frac{2 \sigma}{R^2} \frac{dR}{dx} = V_2 \quad (2.27)$$

$$V_2 = -g \rho_m \frac{dz}{dx} - \frac{(\tau_{wg} + \tau_{wl}) + (\tau_{ig} + \tau_{il})}{A} \quad (2.27A)$$

The continuity - void fraction distribution equation ;

$$\frac{1}{\beta (1-\beta)} \frac{D\beta}{Dt} + \left(\frac{1}{\rho_g C_g^2} - \frac{1}{\rho_l C_l^2} \right) \frac{Dp_m}{Dt} - B = V_3 \quad (2.28)$$

$$B = \frac{r-1}{u_m} \left(\frac{Du_m}{Dt} - \frac{du_m}{dt} \right) + \frac{1}{\rho_g C_g^2} \frac{2\sigma}{R^2} \dot{R} \quad (2.28A)$$

$$V_3 = - (r-1) \frac{u_m}{A} \frac{dA}{dx} + V_3^* \quad (2.28B)$$

$$V_3^* = \frac{1}{\beta (1-\beta)} \frac{\rho_m}{\rho_g \rho_l} \frac{m_{ig}}{A} - \left(\frac{V_g}{\rho_g} \frac{\partial \rho_g}{\partial h_g} - \frac{V_l}{\rho_l} \frac{\partial \rho_l}{\partial h_l} \right) \quad (2.28C)$$

The effects of all of the related physical quantities - the slip , surface tension , mass and heat transfer - can easily be distinguished in the simplified formats given above.

2.7. THE BERNOULLI EQUATION.

A Bernoulli type flow equation of a bubbly - liquid mixture can be quite handy for some cases like the calculation of the rate of expulsion of bubbly - liquid mixtures through openings [Chap.4].

When the steady state condition simplification is applied to Eqn.(2.27) ; after some arrangements [App.B.3], the Bernoulli equation of the bubbly - liquid mixtures given below can be found ;

$$g dz + \frac{1}{\beta} \frac{d\left(\frac{p_m}{\rho_m}\right)}{1-\frac{n}{n}} + \left(r-(r-1)(1-\beta) \frac{\rho_l}{\rho_m} \right) d\left(\frac{u_m^2}{2}\right) = Y \quad (2.29)$$

$$Y = \frac{\beta}{\rho_m} \frac{2\sigma}{R^2} dR - \frac{(\tau_{wg} + \tau_{wl}) + (\tau_{ig} + \tau_{il})}{\rho_m A} dx \quad (2.29A)$$

For the simplified case of constant mass ratio flows , the hydraulic head equation may be given as below ;

$$\hat{H} = g z + \frac{1}{1 + \frac{\mu}{r}} \left(1 + \frac{n}{n-1} \frac{\beta}{1-\beta} \right) \frac{p_m}{\rho_l} + \frac{1 + \mu}{1 + \frac{\mu}{r}} \frac{u_m^2}{2} \quad (2.30)$$

This equation may be put into an easier to handle format below ;

$$\hat{H} = \frac{1 + \mu}{1 + \frac{\mu}{r}} z + \frac{1}{1 + \mu} \left(1 + \frac{n}{n-1} \frac{\beta}{1-\beta} \right) \frac{p}{g \rho_l} + \frac{u_m^2}{2g} \quad (2.31)$$

Eq.(2.30) can be put into a format, fully compatible with the single phase Bernoulli equations of both phases ;

$$\hat{H} = g z + \frac{1 - \beta_0 \left(1 - \frac{r_0}{r} \frac{n}{n-1} \frac{\rho_{g0}}{\rho_g} \right)}{\frac{r_0}{r} \beta_0 \rho_g + (1 - \beta_0) \rho_l} p_m + \frac{1 + \mu}{1 + \frac{\mu}{r}} \frac{u_m^2}{2} \quad (2.32)$$

Simplifications for the phasic equations ;

Single phase flow : $r, r_0 = 1$

Liquid " : $\beta_0 = 0, \mu = 0$

Gas " : $\beta_0 = 1, \mu = 1$

END OF CHAPTER 2

CHAPTER 3

METHOD OF CHARACTERISTICS EQUATIONS OF THE FLOW OF BUBBLY-LIQUID TWO-PHASE MIXTURES

The governing equations of the bubbly-liquid two-phase flows, [Chap. 2.6] needless to say ; can only be solved numerically and their well known character imposes a particular numerical method, the " *Method of Characteristics* (MC) ".

Due to the complexity of programming MC equations, and especially with discontinuities (G.D.Smith [44]); some other methods too had been developed and employed in the field, especially for the investigation of transient processes and limiting conditions rather than getting a full picture of a complete process.

3.1. SUMMARY OF THE NUMERICAL METHODS.

Three numerical methods may be identified for the numerical solution of the governing equations of bubbly-liquid mixture flows ;

3.1.1. Wave Tracing.

Wave Tracing method is the oldest one and may be considered as the method of the times that the computers were either not existed or were very slow and difficult to access.

Wave Tracing method may be described as the step by step calculations - by hand or a calculator - of the MC equations in difference form on a wave mesh. Principal characteristics are ; no fixed time step, difficult to evaluate results, discontinuities and rapid physical changes are too difficult to handle, rare recent applications but not at all phased out (Fischer [15] & Ferch [14]).

3.1.2. Finite Difference Methods.

Finite difference equations format of the set of phasic conservation equations, in implicit form are considered. Rectangular mesh with fixed time step, allows cell structured easy and efficient programming. Discontinuities are very difficult to handle but possible with the techniques like explicit formulation with a pseudo-viscosity term. Phasic interaction terms needed to be modeled accurately for numerical stability (Ishii [24]).

The method is most suitable for the complex UVUT cases involving heat and mass transfer and as a result it is employed by most of the patented (and not well documented) computer codes that were developed mainly by the atomic energy industry and its regulatory authorities (Solbrig [45] & Lyczkowski [31]).

3.1.3. Lumped Control Volumes Method.

Phasic conservation equations are solved with an implicit finite difference method in fixed time steps. Characteristics of the lumped control volumes can be set and followed in special routines.

Applied to complex structures and circuits such as the coolant circuit of a nuclear reactor. Circuit is represented by a series of nodal volumes of concentrated specifications that are interconnected with junctions.

Used mainly by the safety codes of the nuclear energy industry [TRAC, RELAP etc.] that aim for fast and reasonably accurate checking up of the order of the critical quantities with up to one hundred cells of very different characteristics.

3.2. CHARACTERISTIC EQUATIONS.

Hyperbolic character of the governing differential equations of the bubbly - liquid mixture flows in separated - flow model, established in Chap 2.6 [Eqns.(2.26) to (2.28)] imposes the *Method of Characteristics* as by far the best method of numerical solution.

The *Characteristic Equations* that substitute the governing equations are valid on lines - theoretically curves - called *Characteristic Lines* and expressed with the corresponding material

derivative format given below ;

$$\frac{D^{\mp} \xi}{Dt} = \frac{\partial \xi}{\partial t} + (u_m \mp C_m) \frac{\partial \xi}{\partial x} = \frac{D\xi}{Dt} \mp C_m \frac{\partial \xi}{\partial x} \quad (3.1)$$

The *Characteristic Lines* and the *Particle Path Characteristics* are referenced in the short formats given below ;

$$\frac{dx}{dt} = u_m \mp C_m \quad : \quad C^{\mp}(u \mp C) \quad : \quad C^{\mp} \quad (3.2,A)$$

$$\frac{dx}{dt} = u_m \quad : \quad C(u) \quad : \quad C_u \quad (3.2,B)$$

The most practical way of arriving to the *Characteristic Equations* is adding and substituting the two governing equations [Eqns.(2.26) and (2.27)] in the form of " $\{V\} \mp C_m \{Y\}$ " (*) ; which, when properly arranged, can be reduced into the format given below ;

$$\frac{D^{\mp} C}{Dt} p_m \mp E \rho_m C_m \frac{D^{\mp} C}{Dt} u_m \mp F \frac{D}{Dt} u_m + G = \rho_m C_m^2 V_1 \mp C_m V_2 \quad (3.3)$$

$$E = 1 + (r - 1) \beta \quad (r = 1 : E = 1) \quad (3.3,A)$$

$$F = (r - 1) (1 - \beta) \left(1 + \frac{\rho_l}{\rho_m} \right) \quad (r = 1 : F = 1) \quad (3.3,B)$$

$$G = \frac{2 \sigma}{R^2} \left[\beta \left(\frac{D^{\mp} R}{Dt} - \frac{DR}{Dt} \right) - \left(1 - (1 - \beta) \frac{\rho_m C_m^2}{\rho_l C_l^2} \right) \dot{R} \right] \quad (3.3,C)$$

$$V_1 = V_1^* - [1 + (r - 1) \beta] \frac{u_m}{A} \frac{dA}{dx} \quad (3.3,D)$$

$$V_1^* = \left(\frac{1}{\rho_g} - \frac{1}{\rho_l} \right) \frac{m_{ig}}{A} - \left(V_g \frac{\beta}{\rho_g} \frac{\partial \rho_g}{\partial h_g} + V_l \frac{1-\beta}{\rho_l} \frac{\partial \rho_l}{\partial h_l} \right) \quad (3.3,E)$$

$$V_{k=g,l} = \frac{(q_{wk} + q_{ik}) + (\tau_{wk} + 2 \tau_{ik}) u_k}{\beta_k \rho_k A} \quad (3.3,F)$$

$$V_2 = -g \rho_m \frac{dz}{dx} - \frac{(\tau_{wg} + \tau_{wl}) + (\tau_{ig} + \tau_{il})}{A} \quad (3.3,G)$$

(*) C_m acts as a dimensional correction factor.

As the void fraction distribution equation [Eqn.(2.28)] written on the *characteristic lines* involve both of them at the same time, the particle path need to be used as the third characteristics. The void fraction distribution equation on the particle path may be given in the format below ;

$$\frac{1}{\beta (1 - \beta)} \frac{D\beta}{Dt} + \left(\frac{1}{\rho_g C_g^2} - \frac{1}{\rho_l C_l^2} \right) \frac{Dp_m}{Dt} - B = V_3 \quad (3.4)$$

$$B = \frac{r - 1}{u_m} \left(\frac{Du_m}{Dt} - \frac{du_m}{dt} \right) + \frac{1}{\rho_g C_g^2} \frac{2\sigma}{R^2} \dot{R} \quad (3.4,A)$$

$$V_3 = V_3^* - (r - 1) \frac{u_m}{A} \frac{dA}{dx} \quad (3.4,B)$$

$$V_3^* = \frac{1}{\beta (1 - \beta)} \frac{\rho_m}{\rho_g \rho_l} \frac{m_{ig}}{A} - \left(\frac{V_g}{\rho_g} \frac{\partial \rho_g}{\partial h_g} - \frac{V_l}{\rho_l} \frac{\partial \rho_l}{\partial h_l} \right) \quad (3.4,C)$$

In their full format, the *Characteristic Equations* involve particle path characteristics and special bubble oriented terms which mostly disappear for the simple cases like the one employed.

Full format application of the *Characteristic Equations* require the enthalpies of the phases and the mixture, which may be calculated by an equation that can not be put into a characteristic format.

$$\left[V_k = \frac{(q_{wk} + q_{ik}) + (\tau_{wk} + 2\tau_{ik}) u_k}{\beta_k \rho_k A} \right] \quad \frac{Dh_k}{Dt} - \frac{1}{\rho_k} \frac{Dp_k}{Dt} = V_k \quad (3.5)$$

$$\frac{\partial h_k}{\partial \rho_k} = \frac{\rho_k / C_k^2}{1 - \frac{\partial \rho_k / \rho_k}{\partial h_k / h_k}} \quad (3.6)$$

The enthalpy of the mixture is defined and established as below ;

$$\rho_m \frac{Dh_m}{Dt} = \beta \rho_g \frac{Dh_g}{Dt} + (1 - \beta) \rho_l \frac{Dh_l}{Dt} \quad (3.7)$$

$$\left[V_m = \frac{\beta_g \rho_g V_g + \beta_l \rho_l V_l}{\rho_m = \beta_g \rho_g + \beta_l \rho_l} \right] \quad \frac{Dh_m}{Dt} - \frac{1}{\rho_m} \frac{Dp_m}{Dt} = V_m - 2 \beta \frac{\sigma}{R^2} \dot{R}_x \quad (3.8)$$

3.3. CHARACTERISTIC EQUATIONS OF THE " EVET " MODEL.

As mentioned in Chap.2.1 , the " EVET(EP) : Equal Velocity - Equal Temperature (- Equal Pressure -) " model is assumed practically applicable to the cases under consideration as reasoned below ;

" EV " Equal Velocity $\equiv$ " No Slip " $\equiv$ " No Interfacial Stress "

$$u = u_m = u_l = u_g : r = \frac{u_g}{u_l} = 1 : \tau_{i_{k=g,l}} = 0 \quad (3.9)$$

Result : All terms ; with "(r-1)" drop ; "[1+(r-1)]" itself drop !

" ET " Equal Temperature $\equiv$ " No Heat Transfer " (Wall & Interface)

$$T = T_m = T_l = T_g : q_w = 0 ; q_{i_{k=g,l}} = 0 \equiv m_{i_{k=g,l}} = 0 \quad (3.10)$$

This assumption is made under the proven condition that the heat transfer between the phases due to varying gas temperatures as a result of pressure changes are very small ; which does not necessitate a constant temperature field system. (Energy equation exists !)

" EP " Equal Pressure : $p = p_m = p_l = p_g : R_o > 10^{-2}$ [mm]

" EP " assumption is an integral part of the " EVET " model, but like the other principal assumptions ; to be valid, bubbles must not be very small.

The resulting *Characteristic Equations* of the "EVET" model are ;

$$C^{\mp}(u^{\mp}C) : \frac{1}{\rho_m C_m} \frac{D^{\mp} p_m}{Dt} \mp \frac{D^{\mp} u_m}{Dt} = C_m V_1 \mp \frac{1}{\rho_m} V_2 \quad (3.11)$$

$$V_1 = - \frac{u_m}{A} \frac{dA}{dx} \quad (3.11,A)$$

$$V_2 = - \frac{\tau_{wg} + \tau_{wl}}{A} - g \rho_m \frac{dz}{dx} \quad (3.11,B)$$

The friction loss term may be expressed with the conditions of the continuous phase with a two - phase flow corrected friction factor.

$$\tau_{wg} \ll \tau_{wl} : \tau_{wg} + \tau_{wl} \cong \tau_{wl} = \tau_{wm} \quad (3.11,C)$$

$$\tau_{wm} \cong \beta_l \rho_l A F \quad F = \frac{1}{2} \left(\frac{4 f_m}{D_e} \right) |u| u \quad (3.11,D)$$

$$V_2 = - 2 (1 - \beta) \frac{\rho_l f_m}{D_e} |u_m| u_m \pm g \rho_m \sin \theta \quad (3.11,E)$$

f_m is the friction loss coefficient of the mixture and the D_e is the equivalent radius of the cross-section area. The format of the calculation of f_m is given in App. C.5.

The particle path characteristic also simplifies as given below ;

$$C(u) : \quad \frac{D\beta}{Dt} + \beta (1 - \beta) \left(\frac{1}{\rho_g C_g^2} - \frac{1}{\rho_l C_l^2} \right) \frac{Dp_m}{Dt} = 0 \quad (3.12)$$

The coefficient, with very small error, can be simplified as below ;

$$\beta (1 - \beta) \left(\frac{1}{\rho_g C_g^2} - \frac{1}{\rho_l C_l^2} \right) \cong \left(1 - n \frac{p_m}{K_l} \right) \frac{1 - \beta}{\rho_m C_m^2} \quad (3.13)$$

Further simplifications may be made on the relation above ;

$$\left. \begin{array}{l} n \cong 1 \\ K_l \cong 21500 \text{ [bar]} \\ p_m = 2 \sim 30 \text{ [bar]} \end{array} \right\} 1 - n \frac{p_m}{K_l} \cong 1 : \quad \frac{D\beta}{Dt} + \frac{1 - \beta}{\rho_m C_m^2} \frac{Dp_m}{Dt} = 0 \quad (3.14)$$

3.4. THE SPEED DIFFERENCES RATIO APPROACH.

The speed differences ratio, " $\Delta C/\Delta u$ " equation gives some insight on the *Characteristic Equations* and may be used instead of them without their restrictions as being valid for all directions.

The simple governing equations of one dimensional flow of a non-viscous fluid in a channel of variable cross-section may be reduced to the form below ;

$$\left[\frac{\partial u_m}{\partial C_m} \right]^2 + \frac{N}{F} \frac{\partial A / A}{\partial p_m / p} \frac{u_m}{C_m} \left[\frac{\partial u_m}{\partial C_m} \right] - \frac{1}{F^2} \left[1 + \psi \rho_m \frac{\partial x}{\partial \rho_m} \right] = 0 \quad (3.15)$$

$$C_m^2 = \frac{dp_m}{d\rho_m} = \frac{1}{\alpha \beta} \frac{n p_m}{\rho_m} = N \frac{p_m}{\rho_m} ; \quad N = 1 / \left(\frac{\beta}{n} - (1 - \beta) \frac{p_m}{K_l} \right) \quad (3.15,A)$$

$$\alpha = 1 - n \left(\frac{1}{\beta} - 1 \right) \frac{p_m}{K_l} \quad (3.15,B)$$

$$\left[\frac{d C_m}{C_m} = F \frac{d \rho_m}{\rho_m} \right] \quad F = \frac{d C_m / C_m}{d \rho_m / \rho_m} = \frac{1 + \frac{n}{\alpha^2}}{2 \beta} - 1 \quad (3.15,C)$$

$$\psi = g \frac{dz}{dx} + \xi \quad ; \quad \xi = \frac{1}{2} \left(\frac{4 f_m}{D_e} \right) |u_m| u_m \quad (3.15,D)$$

Eqn.(3.15) is a quite complex "de" that can not be solved analytically , but it may be simplified as a second degree polynomial as given below with a quite small error ;

$$\left(\frac{\Delta u_m}{\Delta C_m} \right)^2 + \frac{2 \theta_1}{F} \left(\frac{\Delta u_m}{\Delta C_m} \right) - \frac{1 + \theta_2}{F^2} = 0 \quad (3.16)$$

$$\left(\mp : C^\mp(u \mp C) \right) \quad \frac{\Delta C_m}{\Delta u_m} = \frac{F}{\mp \sqrt{1 + \theta_1^2 + \theta_2} - \theta_1} \quad (3.17)$$

$$\theta_1 = \frac{1}{2} \frac{\frac{u_m}{C_m} \frac{\Delta A / A}{\Delta p_m / p_m}}{\frac{\beta}{n} (1 - \beta) \frac{p_m}{K_l}} \quad ; \quad \theta_2 = \frac{\psi}{\frac{1}{p_m} \frac{\Delta p_m}{\Delta x}} \quad (3.18)$$

For the frequently encountered simple cases , Eqn.(3.17) may be simplified as below for both mixture and gas medias ;

- Constant cross - section channel : $A = \text{Cst.} \quad ; \quad \theta_1 = 0$
- Small channel length ; unimportant friction effect ; $\xi \approx 0$
- Horizontal channel or small $\frac{\text{Gravity Effect}}{\text{Dynamic Effects}}$ ratio ; $\theta_2 \approx 0$
- Further simplification for the Gas media ; $\beta = 1 \quad ; \quad \alpha = 1$

$$\left[\frac{\Delta C}{\Delta u} \right]_m = \mp F_m = \mp \frac{1 + \frac{n}{\alpha^2}}{2 \beta} - 1 \quad (3.19,A)$$

$$\left[\frac{\Delta C}{\Delta u} \right]_g = \mp F_g = \mp \frac{n - 1}{2} \quad (3.19,B)$$

Eqn.(3.17) is valid for all directions in the flow field but by proper manipulation of the *Characteristic Equations* (Eqn.(3.11)), equivalent equation for the *Characteristic Lines* only may be found ;

$$C^{\mp}(u \mp C) : \begin{matrix} i=m : \text{Mixture} \\ i=g : \text{Gas} \end{matrix} \quad \frac{dC_i}{du_i} = \mp \frac{F_i}{1 - \frac{\rho_i C_i^2 v_{1i} \pm C_i v_{2i}}{dp / dt}} \quad (3.20)$$

The speed differences ratio approach does not bring any savings and the standard method that is employed in the programme gives a clearer picture in most respects.

3.5. TRUE CHARACTERISTIC DIRECTIONS.

The most correct way of finding the characteristic directions is the matrix analysis procedure as described in Chap.6.7 for the determination of the speed of sound, with a simplified set of governing equations.

Matrix method produce a set of real and imaginary roots related with the complexity and the number of the set of governing equations employed, through the solution of the eigenvalue problem ;

$$\det (A \lambda + B) = 0 \quad (3.21)$$

" λ " : Characteristic Directions

Employment of the basic set of governing equations of Sec.6.7 would suffice to produce the basic set of characteristic equations of Eqn.(6.11) ; that is fuller and more complex sets produce more realistic but too complex to handle characteristic direction equations. Lyczkowski [32] has shown that, even the simple variable cross - section area concept complicates the characteristic line equations to a degree enough to produce complex characteristics under certain conditions as seen from its format given below ;

$$\lambda = u \mp \frac{C}{\sqrt{1 + \frac{dA / A}{d\rho / \rho} C^2}} \quad (3.22)$$

A nearly full set of governing equations produces such a complex characteristic determinant that the related polynomial may have up to eight roots (Arai [2]).

For the slip flow cases, after some simplifications on the set of equations, a better format was proposed for the characteristic directions equations by Prosperetti & Wijngaarden [42] ;

$$\lambda = \frac{1+r}{2} u_m \mp C_r ; \quad C_r = \phi C_0 ; \quad \phi = \sqrt{0.5 + 1.39 \beta} \quad (3.23)$$

It is obviously wrong to consider the subject in respect to being precise or otherwise alone; because even the relatively simple characteristic directions equations given above can bring so much problem that the standard numerical procedures can no longer be applied. That is, unfortunately, the only practical way of increasing precision is to employ finer meshes and smaller time steps with the standard characteristic directions.

3.6. THE STABILITY CRITERIA.

The well known "CFL : Courant-Friedrichs-Levy" (1928) condition states that a hyperbolic - first order d.e. with a single dependant variable that can be solved by the Lax & Wendroff [30]'s explicit method, can be regarded stable if the characteristic lines always stay in one mash that is the well known condition given below is satisfied at all cross sections and at all time steps ;

$$\left[\frac{\partial \xi}{\partial t} \mp (u \mp C) \frac{\partial \xi}{\partial x} = 0 \right] \quad \Delta t \leq \frac{\Delta x}{u + C} \quad (3.24)$$

This is the bottom line condition of stability; but even for the simple cases without any discontinuity front, the working time step may well be a tenth or even less of the theoretical limit. If a front, such as a shock front exists, it is quite possible to be forced to work with a time step less than a thousandth of the basic limit value and continuously for many time steps.

Not only no better but no other format exists as the stability criteria. As a result, Eqn.(3.24) is used as of the basic criteria

for numerical stability but the intrinsic condition of keeping the characteristic lines in the same mesh and other obvious limits on some quantities such as pressure and Mach number are rigorously checked at every part of the calculation steps with the aim of preventing the errors piling up and block the process and to detect problems as early as possible.

3.7. CHARACTERISTIC EQUATIONS OF THE GAS.

The *Characteristic Equations* of the flow of an ideal gas under polytropic conditions is a well established and documented subject so the aim is to set the nomenclature and the format only.

The EVET model equation of of Eqn.(3.11) can easily be reduced to the generally accepted format of the gas flow cases.

$$\frac{p}{\rho^n} = \text{Cst.} \quad \& \quad C^2 = n \frac{p}{\rho} \quad : \quad \frac{1}{\rho C} dp = \frac{2}{n-1} dC \quad (3.25)$$

$$\frac{1}{\rho C} \frac{D_c^{\mp} p}{Dt} = \frac{2}{n-1} \frac{D_c^{\mp} C}{Dt} \quad (3.26)$$

In the program, a reduced but similarity maintained format of Eqn.(3.11) given below is employed for ease of use ;

$$\frac{D_c^{\mp}}{Dt} \left(u + \frac{2}{n-1} C \right) = \mp C v_1 + \frac{1}{\rho} v_2 \quad (3.27)$$

$$v_1 = - \frac{u}{A} \frac{dA}{dx} - \frac{q_w + \tau_w u}{\rho^2 A} \frac{\partial \rho}{\partial h} \quad (3.27,A)$$

$$v_2 = - g \rho \frac{dz}{dx} - \frac{\tau_w}{A} \quad (3.27,B)$$

$$\tau_w = \rho A F \quad ; \quad F = \frac{1}{2} \left(\frac{4 f}{D_e} \right) |u| u \quad (3.27,C)$$

CHAPTER 4

FLOW OF BUBBLY LIQUIDS THROUGH EXPULSION ELEMENTS AND THE CRITICAL PRESSURE RATIO

The subject under consideration is the flow of bubbly - liquid two - phase mixtures through expulsion elements and the associated concepts of choked flow and critical pressure ratio.

For some of the cases under consideration, the flow of an ideal gas through expulsion elements too occur but the well known solutions related with this case will not be considered.

4.1. INTRODUCTION.

The aim is to find the rate of flow equations of the flow of bubbly liquids through an expulsion element, by a free jet and to an atmosphere of constant physical conditions equal to the Standard Atmospheric Conditions. Through these relations, the equations for the determination of the critical conditions related with the sonic to subsonic flow transformation will also be found out.

For the cases under consideration, depending on the initial pressure and the character of the mixture - especially the void fraction - , expulsion may start as sonic or as subsonic and end as subsonic except for some partial / emergency relief system cases.

4.2. PRINCIPAL WORKS OF THE SUBJECT.

In spite of its practical importance, there is not enough experimental work and especially the kind of systematical works that

may be used without checking up. Most of the related research on the subject is done on and through steam - water mixtures that can be of a very limited interest.

The program considers all known formulas, including the ones for the steam - water mixture expulsion (the works of Crisholm and his co-researchers [8-11]) and they are named and documented at their places of use as a record.

Two proper bubbly-liquid mixture method is considered ; the standard method (EVET with slip) (Thang & Davies [47]) and the bubble surface energy calculation method (Kabza et.al [26]).

4.3. MAIN CONCEPTS AND DEFINITIONS.

Main concepts and definitions of the subject of flow of bubbly liquids through expulsion elements are considered under seven subsections.

4.3.1. The Expulsion Element Concept.

The term "Expulsion Element" covers all types of openings which may be divided into two main groups.

- Standard Expulsion Elements; the standard diaphragms and nozzles.
- Non-Standard Expulsion elements; can be considered in two groups :
 - Geometric / symmetrical shapes that at least some single phase flow coefficients data is available.
 - Arbitrary shapes ; usually results of accidental ruptures.

Can be valued through informed guesses only.

Although only the standard expulsion elements are taken into account, the type of the expulsion element has no importance in respect to the basic aims of the study and the program.

4.3.2. The Flow Coefficients.

There is no comprehensive study on the flow coefficients for bubbly-liquid flows through standard openings. Mainly experimental studies are all aimed at or claim producing all-inclusive rate of flow (correction - on the single phase, clean water flow data) equations.

In the program, some parameters for extracting the bubbly liquid two-phase flow coefficients from the well known data on Newtonian fluids are provided but just for the sake of programming harmony, that is although they are the results of intelligent guesses, no claim is made in that respect. As their true value has no importance, in respect to the principal goals, some of the created parameters practically ignored in the data files (assigned zero or unity as it fits).

All related definitions and the information on the data that the coefficient functions are based upon, are given in the related part of the programme (Subroutine SFCDN).

4.3.3. Back - Flow Case Treatment.

As a result of the dynamic character of the expulsion system under consideration, in both mixture and gas expulsion cases, near the end of the expulsion process, back - flow may occur. Although no reference to the phenomena has been found in the literature and its effect can only be very limited ; the case was not put out of the cycle by simply ignoring it or assuming the process ended before the stage that back-flow may take place.

Principals of the treatment of the case are summarized below ;

- Back-flow , principally effects the fluid that was just expelled at the previous full step ; that is no bulk gas in-flow may occur.
- Rate of flow coefficient may be corrected with a constant parameter given as data.
- Back flow condition in full opening case is treated separately.

4.3.4. Undeveloped Flow Stage Treatment.

Due to the non-instant opening phenomena, the flow related with the initial steps up to the duration of opening may be regarded as undeveloped.

It is not possible to accept that a diaphragm plugged by some kind of membrane behaves like its final form at its newly burst stages. It is also very difficult to define the characteristics of an opening at these stages.

Due to the impracticality of any other form of treatment; at

the initial stages up to the duration of opening ; the calculations are done with the coefficients related with the fully developed opening and flow of the case ; but whenever possible the parameters were related to the area ratio to minimize the error. This treatment should hold quite well for ordinary sudden expulsion cases, but it may produce considerable error in long duration applications like controlled relief system operations.

4.3.5. Formats of the Time Dependant Variables.

The two time dependant phenomena that a function need to be fitted are to be considered separately.

* Area of the Opening Function.

No duration of opening value may be regarded too small and can be ignored, that is no opening may be regarded as instant. The area of opening change, except fully controlled relief operations is not physically controlled but still a function must be supplied for it which for some degree depends on the employed method of bursting.

Through high speed camera controlled experiments, it is known that these functions are of the exponential type, for almost all cases of electric or pressure bursting, as to be expected.

Area of the opening function is fixed as seen below (Subr."SPHIV").

$$\left. \begin{array}{l} \frac{t}{t_0} = .01 \ 05 \ 10 \ 25 \ 50 \ 80 \ 90 \ 99 \\ \frac{A}{A_0} = .03 \ 14 \ 26 \ 53 \ 78 \ 91 \ 93 \ 95 \end{array} \right\} \frac{A}{A_0} = 1 - \frac{1}{\exp \left(3 \left[\frac{t}{t_0} \right] \right)} \quad (4.1)$$

* Pressure Settlement Function for Full Opening.

For the full opening case, it is essential to employ a function for the gradual change and settlement of the pressure at the top of the vessel. The process is expected to be exponential and only slightly dependant on the initial pressure ratio as established in the format given below. (Subroutine "SPOEFO")

$$\frac{p}{p_e} = 1 + \frac{PR_0 - 1}{\exp \left(3 \left[\frac{t}{t_0} \right] \right)} \quad (4.2)$$

4.3.6. Principal Definitions of the Expulsion Element.

The shape of the top of the vessel determines the position of the last calculation point at the top of the vessel and it is not always possible to use the cross-section of the opening as the last calculation point.

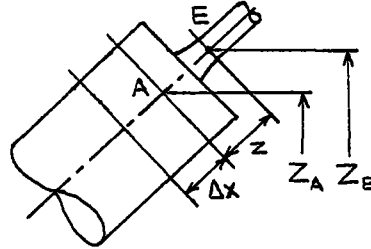


Fig. 4-1 The Opening Cross-Section and the Last MC Calculation Node.

Principal definitions of the subject are summarized below ;

- t_D : Duration of Opening ;
 $\varphi = \varphi(t) : t < t_D \quad \& \quad \varphi = \varphi_{o(max)} : t = t_D$
- ξ : Pressure Ratio ;
 $\xi = p_A / p_E$ (P. at the top / P. of the expulsion medium)
- φ : Area Ratio ;
 $\varphi = A_o / A_A$ (A. of opening / A. of the last cross-section)
- θ : Contraction Ratio ; $\theta = \theta(\varphi) ; \theta_o = \theta(\varphi_o) : \theta = \theta_o$ (Taken)
 $\theta = A_E / A_o$ (A. of contracted c.s. / A. of the opening)
- λ : Velocity Coefficient ; $u_E = \lambda u_{E,T}$
 $\lambda = u_E / u_{E,T} = q_E / q_{E,T}$ (Real V. / Theoretical V. Ratio)

4.3.7. Assumptions and Applicability.

The conditions assumed are generally the ones that are considered for the main body of the flow, so only a summary is given ;

- One dimensional and quasi-steady flow.
- Adiabatic process , equal phase temperatures , no mass transfer.
- Friction and surface tension effects can be omitted.

As an extension of the conditions listed, it is assumed that the speed of small perturbations can be accurately expressed with its simple format of Eqn.(6.5).

4.4. THEORETICAL SPEED OF EXPULSION.

The aim is not to find an as complete as possible equation for the theoretical value of the speed of expulsion. The numerical techniques employed can handle equations of all complexities, but less than even one percent saving in precision can not justify the usage of a full format equation. It is also essential to work with an handleable relation for the critical pressure ratio calculation which necessitates an analytical solution for the speed of expulsion and of a simple type too.

The generally made assumptions summarized above, allow to employ the simple Bernoulli -hydraulic load- equation ; [Eqn.(3.31)]

$$H = \frac{1 + \mu}{1 + \frac{\mu}{r}} z + \frac{1}{1 + \mu} \left(1 + \frac{n}{n-1} \frac{\beta}{1 - \beta} \right) \frac{p}{g \rho_l} + \frac{u_m^2}{2 g} \quad (4.3)$$

The equation above, allows to express the theoretical value of the speed of expulsion as below, with the pressure ratio as the sole variable quantity ;

$$(u_E)^2 = (u_A)^2 + \frac{2}{1 + \mu} \frac{p_A}{\rho_l} \left[1 - \frac{1}{\xi} + \frac{n}{n-1} \frac{\beta_A}{1 - \beta_A} \left(1 - \frac{r_A / r_E}{\xi^{1-1/n}} \right) \right] - Z \quad (4.4)$$

$$Z = 2 \frac{1 + \frac{\mu}{r}}{1 + \mu} g (z_E - z_A)$$

With the area and contraction ratio definitions, the theoretical speed of expulsion can be defined as a function of the pressure ratio only, as seen below ;

$$X_P = \frac{2}{1 + \mu} \quad ; \quad X_B = \frac{n}{n-1} \quad ; \quad X_R = \frac{1 + \frac{\mu}{r_E}}{1 + \frac{\mu}{r_A}}$$

(Coefficients "X_P, X_B, X_R" are the functions of "μ, r and n" only !)

$$(u_{ET}) = \left[\frac{X_P \left(1 - \frac{1}{\xi} + X_B \frac{\beta_A}{1 - \beta_A} \left(1 - \frac{r_A}{r_E} \frac{1}{\xi^{1-1/n}} \right) \right) \frac{p_A}{\rho_l} - Z}{1 - \left[\frac{X_R \theta \varphi}{1 + (\xi^{1/n} - 1) \beta_A} \right]^2} \right]^{1/2} \quad (4.5)$$

Due to its not so purposely arranged format - which is even more complex - , the equation above holds only for one limit single phase case of the pure liquid flow ($\beta=0$, $\mu=0$, $r=1$) as all coefficients either vanish or become equal to unity.

4.5. THEORETICAL MASS FLOW RATE.

With the appropriate definition of the specific mass expressed in terms of the pressure ratio (App.B.4) the mass flow rate can be expressed as below ;

$$q_T = A_E \rho_E (u_{ET}) = \theta A_0 \rho_l \frac{1 + \frac{\mu}{r_E}}{1 + \frac{\beta_A}{1 - \beta_A} \frac{r_A}{r_E} \xi^{1/n}} (u_{ET}) \quad (4.6)$$

Eqns. (4.6) and (4.5) produce the very complex full format ;

$$q_T = \theta A_0 \rho_l X \quad (4.7)$$

$$X = \left[2 X_1 \frac{\frac{p_E}{\rho_l} \left((1 + X_2) \xi - X_3 \xi^{1/n} - 1 \right) - X_4 g(z_E - z_A)}{\left(1 + (1 + X_5 \xi^{1/n}) X_5 \xi^{1/n} \right) - X_6 (\theta \varphi)^2} \right]^{1/2}$$

$$X_1 = \frac{1 + \frac{\mu}{r_E}}{1 + \mu} ; \quad X_2 = \frac{n}{n - 1} \frac{\beta_A}{1 - \beta_A} ; \quad X_3 = \frac{r_E}{r_A} X_2$$

$$X_4 = 1 + \frac{\mu}{r} ; \quad X_5 = \frac{r_A}{r_E} \frac{\beta_A}{1 - \beta_A} ; \quad X_6 = \frac{1 + \frac{\mu}{r_E}}{1 + \frac{\mu}{r_A}} \frac{1}{(1 - \beta_A)^2}$$

This equation too holds only for one limit single phase case of liquid flow ($\beta=0$, $\mu=0$, $r=1$), like the $(u_E)_T$ equation it is based on.

4.6. CRITICAL PRESSURE RATIO (CPR).

The well known descriptive relation of the "Critical Pressure Ratio" for single phase flows is valid for multi - phase cases too.

$$\xi = \xi_{cr} : q = q_{max} ; \left(\frac{dq}{d\xi} \right)_{\xi_{cr}} = 0 : (u_E)_{\xi_{cr}} = (u_E)_{max} = C_E \quad (4.8)$$

$$q = q \left(\xi = \frac{p_A}{p_E}, \beta_A, (\mu, r, \Delta z, \theta, \varphi) \right) \quad (4.9)$$

As the rate of flow is a function of many variables of widely different level of importance, other than the pressure ratio; only an approximate solution can be found. Here, the practical way of taking all of the coefficients of the Eqn.(4.7) as constants will be considered;

$$\xi = \xi_{cr} : \left(\frac{dq}{d\xi} \right)_{\xi_{cr}} \& (X_1, X_2, X_3, X_4, X_5, X_6) \quad (4.10)$$

The resulting equation is more complex than its originator;

$$Y_1 \xi^{\frac{2}{n}} + Y_2 \xi^{\frac{3}{n}-1} + Y_3 \xi^{\frac{1}{n}} + Y_4 \xi^{\frac{2}{n}-1} + Y_5 \xi^{\frac{1}{n}-1} + Y_6 = 0 \quad (4.11)$$

$$Y_1 = (1 - \frac{2}{n}) (1 + X_2) X_5 \quad ; \quad Y_2 = \frac{1}{n} X_3 X_5^2$$

$$Y_3 = (1 - \frac{1}{n}) (1 + X_2) X_5 \quad ; \quad Y_4 = \frac{2}{n} X_5^2 + X_4 Y_Z$$

$$Y_4 = \frac{2}{n} X_5^2 + X_4 Y_Z \quad ; \quad Y_6 = (1+X_2) (1- X_6 Y_D)$$

$$Y_5 = \frac{1}{n} \left[(X_5 - X_3) + X_3 X_6 Y_D + X_4 X_5 Y_Z \right]$$

$$Y_D = (\theta \varphi)^2 \quad ; \quad Y_Z = g \frac{\rho_l}{p_E} (z_E - z_A)$$

where $X_1 \dots X_6$ are of course has the formats fixed at Eqn.(4.7).

4.7. SIMPLIFIED AND PRACTICAL " CPR " EQUATIONS.

The theoretical speed and rate of flow equations of Eqns.(4.5) to (4.8) are based on somewhat simplified governing equations, but still they are too complex for practical use and would waste a lot of valuable run-time for almost nothing to gain. But other than the "Isothermal Equilibrium Flow" one, there is no realistic assumption to be made for the further simplification of these equations.

As already stated, the problem under consideration shows strong character of isothermal behaviour which allows to make considerable simplifications on Eqns.(4.5) to (4.7).

4.7.1. Isothermal Equilibrium Flow Speed of Expulsion.

For nearly isothermal behaviour, the theoretical speed of expulsion equation [Eqn.(4.4)] may be simplified as follows ;

$$(u_E)_T^2 \cong (u_A)^2 + \frac{2}{1 + \mu} \frac{p_E}{\rho_I} \left[(\xi - 1) + B \xi (\ln \xi) \right] - Z \quad (*) \quad (4.12)$$

$$B = \frac{r_A}{\bar{r}} \frac{\beta_A}{1 - \beta_A} \quad ; \quad Z = 2 \frac{1 + \frac{\mu}{\bar{r}}}{1 + \mu} g (z_E - z_A)$$

4.7.2. Sonic Speed of Expulsion.

Sonic speed of expulsion may easily be expressed through the simple speed of sound relation.

$$\xi = \xi_{cr} \quad : \quad u_E = (u_E)_{cr} = (u_E)_{max} = C_E \cong \sqrt{\frac{n}{\beta_E} \frac{p_E}{\rho_E}} \quad (4.13)$$

$$u_E^2 \longrightarrow C_E^2 = \left[\left(1 + \frac{1}{B \xi^{1/n}} \right) \left(\frac{s}{r_A} + \frac{1}{B \xi^{1/n}} \right) \right] \frac{n p_E}{\rho_I} \quad (4.14)$$

$$B = \frac{r_A}{\bar{r}} \frac{\beta_A}{1 - \beta_A}$$

As it is more practical to work with the void fraction value

(*) $\xi^{1-\frac{1}{n}} \approx 1 + \left(1 - \frac{1}{n} \right) \ln \xi$ approximation is employed !
 $n \gg 1$

before the opening element, β_E is expressed in terms of β_A and the pressure ratio ξ .

4.7.3. Isothermal Equilibrium Critical Pressure Ratio.

The simplified critical pressure ratio equation of the isothermal equilibrium flow case that is under consideration may be produced through the corresponding speed of expulsion equation of the Eqn.(4.14) may be given as below ;

$$\left(D_1 + D_2 \ln (\xi_{cr}) \right) \xi_{cr}^{1+\frac{1}{n}} - D_3 \xi_{cr}^{2/n} - D_4 \xi_{cr}^{1/n} - 1 = 0 \quad (4.15)$$

$$\begin{aligned} D_1 &= D_n B \quad ; \quad D_2 = D_n B^2 \quad ; \quad D_3 = \frac{s}{r_A} B \\ D_4 &= \left(\left(1 + \frac{s}{r_A} \right) + (D_n - D_z) \right) B \quad ; \quad B = \frac{r_A}{r} \frac{\beta_A}{1 - \beta_A} \\ D_z &= \frac{\rho_l}{n p_E} \left(u_A^2 - 2 \frac{1 + \frac{\mu}{r}}{1 + \mu} g \Delta z \right) \quad ; \quad D_n = \frac{2}{(1 + \mu) n} \end{aligned}$$

In the program ; not only for saving run-time, but also due to the lack of data on slip and acceleration ratios ; the isothermal equilibrium flow assumption is accepted and it is found that the results are precise enough for all of the cases under consideration. Isothermal - equilibrium flow : $n \approx 1$, $r \approx 1$, $s \approx 1$;

$$\begin{aligned} \left(E_1 + \ln (\xi_{cr}) \right) \xi_{cr}^2 - E_2 \xi_{cr} - E_3 &= 0 \quad (4.16) \\ E_1 &= \frac{Z_1 - Z_2}{Z_1 Z_2} \quad ; \quad E_2 = \frac{2 + (Z_1 - Z_3)}{Z_1 Z_2} \quad ; \quad E_3 = \frac{1}{Z_1 Z_2^2} \\ Z_1 &= \frac{2}{1 + \mu} \quad ; \quad Z_2 = \frac{\beta_A}{1 - \beta_A} \quad ; \quad Z_3 = \frac{\rho_l}{p_E} \left(u_A^2 - 2 g \Delta z \right) \end{aligned}$$

4.7.4. Practical Considerations on the CPR Calculations.

Even in its simplest format, the CPR equation [Eqn.(4.16)] is quite complex that is a full check would waste a lot of run-time, and also a precise result would rarely be required.

As the main variable of the CPR calculation is the void fraction , an extensive list of approximate $CPR = CPR(\beta)$ functions are given in the program [Routine "SCPR"] for quick calculations.

Full CPR calculation is done only when the actual pressure ratio is close enough to the approximate CPR value as defined by a data file parameter.

For the speedy calculation of the precise (enough) value of the CPR through Eqn. (4.16), in the programme an in-built procedure is supplied (Routine "SCPR"). A fitting routine of the NAG library [App. I.5] too was incorporated for the checking up purposes and it is seen that the supplied procedure can be as precise as the library routine.

4.8. USABILITY OF THE RATE OF FLOW EQUATIONS.

Due to strong acceleration and associated phase slip phenomena and in most cases quite high void fractions at the throat that put homogeneous flow assumption in jeopardy and some other related effects and reasons ; flow of bubbly-liquid mixtures through an opening is a quite more complex problem than the above given analysis may suggest. But still, if it were possible to find realistic values for the slip and acceleration coefficients, the theoretical equations may well be regarded accurate enough.

In the program , a couple of experimentally arrived equations are listed, but it is seen that especially the ones that are based on the steam-water mixture experiments are very much out of phase with the conditions under consideration. In all development runs the standard EVET model and without any slip or acceleration correction was employed.

As all principal application information on the subject is given in the related programme parts [Routines "SMED" & "SMEDS"] , and most of the related methods and formulas, due to their total unsuitability, appear in the programme as a matter of record only ; the experimentally arrived equations are not listed here.

CHAPTER 5
SHOCK WAVES
IN
BUBBLY-LIQUID MIXTURES

The formation and propagation of shock waves is one of the principal fields of interest in the studies on the flow of bubbly-liquid mixtures. Because, unlike other forms of two-phase flows, a bubbly-liquid mixture phenomena that is free of shock waves, in one form or another, is hard to imagine.

The subject, in the main, quite extensively studied, but as there are a couple of additional parameters to be considered with regard to the single phase cases and almost all experimental verification were done by means of shock - tube technique of still mixture columns with no mean mass flow, still the subject may not be regarded well covered.

The more representative name of Shock Front with the initials "SF" will be used instead of Shock Waves.

5.1. THE ORIGINS OF THE SHOCK FRONTS IN THE PROBLEM.

There are two sources of SF associated with the cases under consideration, namely ;

- Rapid initial expulsion ; of gas or mixture.
- Instant and very strong reduction of the speed of flow at the cross section of the expulsion element, due to instant change of the type of the expelled fluid after all the gas at the top region is discharged, in the case of partially full vessel.

Due to the abilities of smoothing even quite strong transient effects of the Method of Characteristics, it is seen that an Initial

Wave Front (IWF) concept produces sufficiently accurate results in the case of rapid initial expulsion. It is also observed that, even without an IWF assumption, the overall error does not increase more than 3 % in a representative case.

Initial expulsion problems may not, theoretically, be solved with a single front concept, that is an Expansion Fan concept need to be employed. Expansion Fan concept brings the interaction problems of successive SF's with varying strengths. Dealing with two interacting SF requires an immense programming effort and the facilities of a real super computer when MC is employed ; an expanding fan of SF's would create a task even more difficult, almost insolvable even without the complications that a Contact Surface and change of the fluid medium would bring.

The IWF concept employed is actually not just a substitute but a quite effective way of dealing with a practically insolvable problem. A physical phenomena, the reality of Duration of Opening plays an important role in IWF concept. However small is the actual duration, it allows to restrict gradients of all parameters by simply reducing the time step without any lower limit at all.

5.2. SHOCK FRONT CREATION DUE TO

INSTANT CHANGE OF THE TYPE OF THE EXPELLED FLUID.

Regardless of the value of the void fraction or the pressure , for corresponding conditions, speed of expulsion of a gas would be considerably higher than that of a bubbly liquid. As a result, in the case of non-full vessel, after all gas is removed, the mixture gets speeded up to the velocities may normally be associated with the expulsion of the gas ; is forced to reduce its speed -and increase the pressure- to a level that corresponds to the expulsion of that mixture under the eventually established conditions.

This phenomena must be assumed to be happening instantly ; that is, it is not physically possible to smoothen the effect of instant change by the introduction of an artificial duration of transformation. That is, the only correct way of tackling the problem is to employ the Shock Front (SF) concept.

The problem allows to apply the SF concept in a relatively simple and basic way as there will be just one front and no problems of interacting fronts.

Due attention is paid to the cases that need special care ; namely, the reflections from the closed and open ends , the decision on the removal or expulsion of the SF from the system and also the left or right running character of the front.

5.3. DEFINITIONS OF CHARACTER AND THE NOTATION CONVENTION.

The SF under consideration is of a non-stationary type as it is created through the transient process of instant choking due to phase change at the open end.

The SF is created as of the compression type as a result of its origin and, conforming basic rules ; it reflects as the rarefaction type at the closed end and as the compression type at the open end.

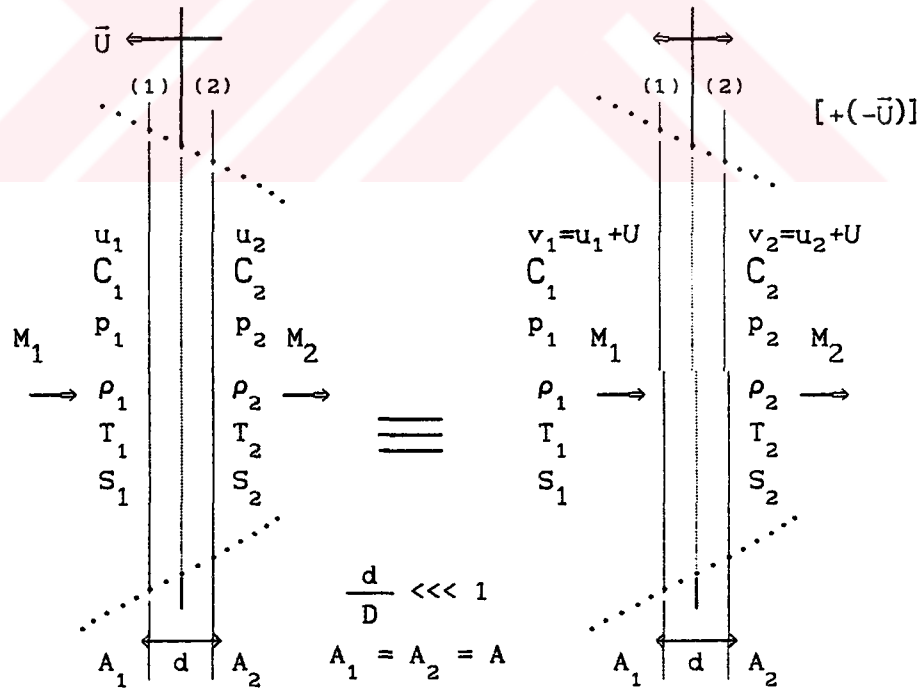


Fig. 5-1 Transformation from Moving to Stationary SF

The universally accepted notation convention given below with all of the formats it presents itself -in the text and the program-

is valid for all cases , that is for compression / rarefaction type, and left (downward, to the bottom) / right (upward, to the top) running fronts ;

("1" / "LP" / "U") "F" : FRONT (Low Pressure / Undisturbed) Side.
 ("2" / "HP" / "D") "B" : BACK (High " " / Disturbed) Side.

The velocities ; " U " , " u " and " v " are direction dependant quantities and have signed equations which need to be evaluated according to the sign convention given below ;

Minus (-) sign : Left / Top to Bottom Running SF

Plus (+) sign : Right / Bottom to Top Running SF

As it is much more practical to work with the stationary fronts , the easy to apply transformation from non-stationary to stationary fronts were employed [Fig.(5.1)]

5.4. LITERATURE REVIEW.

Literature usually down plays the difficulties of SF calculations in bubbly-liquid mixtures and attaches too much importance to the initial prediction of the speed of the front or some other starting parameter. But it is proved that, SF front calculations in bubbly-liquid (or other types of) two-phase flows is quite more complex than the well established ideal gas case.

Lack of knowledge and facilities for the numerical solution of the system of governing equations, in a way, forced early researchers to make not quite plausible assumptions for being able to arrive to a kind of analytical solution. Chambell & Pitcher [7] is the best example for the "analytical solution for all cost" approach which gave an equation for the temperature rise across an SF, which shows that isothermal behaviour assumption need not be changed for the existence of an SF.

Mix.:Water-Air	$\frac{\Delta T}{T_{LP}} \approx \frac{1}{2} \frac{\xi - \frac{1}{\xi} \frac{\rho_g}{\rho_l} \frac{R_b}{C_l}}{\beta - 1} \quad (5.1)$
$\xi = 10$	
$\beta_{LP} = 0.15$	
$\Delta T = 0.03 [^{\circ}C]$	

Crespo [12] mixed the macro -conservation- and micro -single bubble dynamic balance- state equations to be able to arrive to some kind of analytical solution but still is a much referenced work.

Wijngaarden [49] after a lot of assumptions but taking into account of virtual mass and Kelvin impulse effects, produced a complex equation for the void fraction distribution along the thickness of a front as seen below (without the inertia effect) ;

$$\frac{d\beta}{dx} = - \frac{3 U}{4 v_l} (\beta_U - \beta) (\beta - \beta_D) \quad (5.2)$$

Wijngaarden [50] produced an equation for the thickness of an SF which was experimentally checked by him and Noordzij [38]. Equation shows that the thickness of an SF may well be ignored.

Example : $M_{LP} = 3.0$ $\beta_{LP} = 0.05$ $d \approx 15 R_{b,LP}$	$\frac{d}{R_{b,LP}} = \frac{K^{Cst}}{\sqrt{\beta_{LP} \left[1 - \frac{1}{M_{LP}} \right]}}$	$K = 3.1$ (Wijngaarden) $K = 3.9$ (Noordzij)	(5.3)
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The application of Method of Characteristics to the problems of two-phase flows with SF, for the numerical solution, is a subject may only be found in works of restricted access [See Ref.]. Others such as Hoskin [21] and Fischer [15] dwell on the wave tracing aspect of the problem. Lascaux [29] is a very informative study and used as the principal source and the foundation setter.

5.5. THE ASSUMPTIONS AND RESTRICTIONS.

Relevant assumptions and restrictions given at Chap.1.3 are valid but some additions specific to the SF phenomena may be needed.

- No compaction or disintegration of bubbles occur, bubbles do not burst under shock pressure. It is found that when the Weber number is in limits, no significant bubble disintegration may occur (Gelfand et.al. [17])

$$We = \frac{\rho_l u_l^2 d_b}{\sigma_l} < 5 \quad (5.4)$$

Equation. practically states that under normal conditions bubbles of

$d_b \leq 1$ [mm] do not disintegrate and for " $\Delta p / p_b = 3 \sim 4$ " , only bubbles of $d_b > 4$ [mm] may burst and the ones of $d_b < 2$ [mm] usually only slightly deformed. The conditions under consideration would therefore allow to make the under mentioned assumption that experimentally verified by Akagava [1] : Dynamic slip has little effect on the pressure transients caused by an SF, That is the homogeneous flow theory holds quite well under the normal conditions of the problem in consideration.

5.6. THE WAYS OF APPROACH.

The four ways of approaching an SF problem , especially in multi - phase fluids are summarized below.

5.6.1. The Principle Method : Rankine - Hugoniot Equations.

Adaptation of Rankine - Hugoniot equations of the shock waves in ideal gases is the most preferred and tested method and also is the only one that may be used for getting a pictorial view of the SF phenomena.

This is the method employed and will be presented in detail in the following sections.

5.6.2. The Secondary Methods.

Tree methods listed below may be put in this category.

* Separated Flow Equations.

Separated flow equations that mix macro and micro structure balances are employed as fitted to the purpose. Single bubble's dynamic balance, radial pulsations etc. equations are used to determine phase pressures and other characteristic quantities.

Application of the method is limited to the works with simple aims such as studying the influence of a parameter on the SF (Crespo [12], Nigmatulin & Shagapov [37], Akagava et al [1]).

* Burgers - Kortweg - de Vries (BKV) Equation.

The BKV equation for the analysis of propagation processes of

finite amplitude in mediums of weak dispersion may also be used for the investigation of the low frequency , long wave length and finite amplitude disturbances in bubbly liquid mixtures and especially for the formation of shocks. The restrictions mentioned in Sec.5.5.3 are also valid for the application of the BKV equation.

Research on the application of BKV equation to bubbly liquids is an almost exclusive field of limited number of researchers approaching the subject from pure physics points of view. (Kutateladze et. al. [27], Burdukov et al [4], Kuznetsov et al [28])

* Pseudo Viscosity and Liquid Compressibility Method.

Experimental data on the pressure rise after a transient in bubbly - liquids fit the theoretical estimations better when the compressibility of the liquid is taken into account. It is also possible to get a better agreement on the prediction of the length or the thickness of a transient by the introduction of only a second order non-linear pseudo viscosity. (Enever [13])

5.7. THE RANKINE - HUGONIOT SHOCK EQUATIONS.

It is well known that an SF process can not be considered adiabatic, that is in addition to the equations of continuity and momentum, the energy balance equation too needs to be taken into account.

Well known formats of the balance equations over a discontinuity surface that is created by a Shock Front ; considering the notations employed in Fig. 5.1 may be summarized as below ;

Equation of continuity ;

$$\dot{M} = \dot{m} A = \text{Cst.} ; \quad \dot{m} = \rho v ; \quad v = u + U ; \quad A = \text{Cst.}$$

$$\rho v = \rho (u + U) = \text{Cst.} \quad (5.5,A)$$

$$\rho_1 v_1 = \rho_2 v_2 \quad (5.5,B)$$

$$\rho_1 (u_1 + U) = \rho_2 (u_2 + U) \quad (5.5,C)$$

$$\text{Simplification : } [\rho \approx (1-\beta)\rho_l] \quad (1 - \beta) v = \text{Cst.} \quad (5.5,D)$$

Equation of Momentum Balance ;

$$F = f A ; f = m u + p ; m = \rho v ; A = \text{Cst.}$$

$$p + \rho v u = \text{Cst.} \quad \equiv \quad p + \rho v^2 = \text{Cst.} \quad (5.6,A)$$

$$p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2 ; p_2 - p_1 = \rho_1 v_1^2 - \rho_2 v_2^2 \quad (5.6,B)$$

Equation of Energy Balance ;

$$E = h \mathcal{M} ; h = i + w_p ; \mathcal{M} = m A = \rho v A = \text{Cst.}$$

$$w_p = \frac{w_p}{m} ; w_p = p v ; m = \rho v ; w_p = \frac{p}{\rho}$$

$$i = e + \frac{1}{2} v^2 ; e = e(T, \beta) = \sum \beta_i \frac{\rho_i}{\rho_m} e_i(T)$$

$$e = [(1 - \beta) C_{v_l} + \beta C_{v_g}] T$$

$$\frac{p}{\rho} + \frac{1}{2} v^2 + e = \text{Cst.} \quad (5.7,A)$$

$$\text{Simplifications : } \Delta T \approx 0 : T_l = \text{Cst.} : e \approx (1 - \beta) C_{v_l} T = \text{Cst}$$

$$\frac{p}{\rho} + \frac{1}{2} v^2 = \text{Cst.} \quad (5.7,B)$$

The equation above, can not be considered suitable for the bubbly-liquid two-phase flows under consideration ; instead a simplified to the case version of the Bernoulli - motion - equation of the bubbly-liquid flows [Eqn.(2.30)] were employed.

With the simplifications of ; no slip ($r = 0$) , constant and very small mass ratio ($\mu = \text{Cst} \lll 1$) , uniform pressure field assumption (No surface tension effect $\sigma \approx 0$) and ignorable potential energy assumption ($z \approx 0$) ; the Bernoulli (energy) equation of the case may be reduced to the form below ;

$$\left(1 + \frac{n}{n-1} \frac{\beta}{1-\beta} \right) \frac{p}{\rho_l} + \frac{v^2}{2} = \text{Cst.} \quad (5.7,C)$$

Temperature change across the SFs under consideration would be very limited and the process may be assumed isothermal. When the well accepted assumption of Tangren [47] applied to Eqn.(4.4) , the equation of energy may be put into the form given below which was employed in the program ; (Approximation of Eqn. 4.12 is employed !)

$$\left(1 + \frac{\beta}{1 - \beta} \ln \frac{p}{p_0} \right) \frac{p}{\rho_l} + \frac{u_m^2}{2} = \text{Cst.} \quad (5.7, D)$$

To complete the set of SF equations ; the equation of state of the bubbles [App.B.1], together with the basic mixture and gas density description equations need to be taken into account ;

$$\frac{\beta}{1 - \beta} p^{1/n} = \text{Cst.} \quad (5.8)$$

$$\rho = \beta \rho_g + (1 - \beta) \rho_l \quad \& \quad \frac{p}{\rho_g^n} = \text{Cst.} \quad (5.9)$$

Eqns. (5.5) to (5.9) form a highly nonlinear set and is called " Rankine - Hugoniot Normal Shock Equations of the flow of low void fraction bubbly-liquid two-phase mixtures ". There are five equations and the same number of unknowns, namely ;

" U , v , p , ρ and β on the front side of the SF ".

The system of Rankine - Hugoniot normal shock equations can only be solved numerically and by step by step method only.

5.8. BASIC SHOCK RELATIONS.

The basic shock relations, derived from the set of SF equations except the energy conservation equation are listed in App.B.7.

It can easily be shown that, for not too strong SF's for which isothermal behaviour assumption can be made, the Mach number of the undisturbed side may be taken equal to the pressure ratio.

$$(n \approx 1) \quad M_1^2 = \frac{1}{n} \frac{p_2}{p_1} \quad (5.10)$$

The strength of a of an SF (P) (defined as the ratio of the pressure increase across the front to the initial pressure) can also be expressed in Mach number ;

$$P = \frac{p_2 - p_1}{p_1} = M_1^2 - 1 \quad (5.11)$$

For the cases under consideration , practical limits of the M_1 and the P may be given as ; $M_1 = 1.1 \sim 2.5$ (3.0) & $P = 1.5 \sim 5.0$ (8.0).

5.9. SUMMARY OF THE BASIC SF CASES.

The tree basic SF cases will be summarized with the notation employed in the program. In all cases, the principal relations of ;

$$p_2 > p_1 \quad \& \quad M_1 > M_2 \quad : \quad M_1^2 \approx \frac{p_2}{p_1} > 1 \quad \& \quad M_2 < 1 \quad (5.12)$$

and the SF equations are valid.

The cases are considered in both left and right running or approaching / departing front formats for easy following.

5.9.1. Ordinary Fronts.

* Left Running fronts:

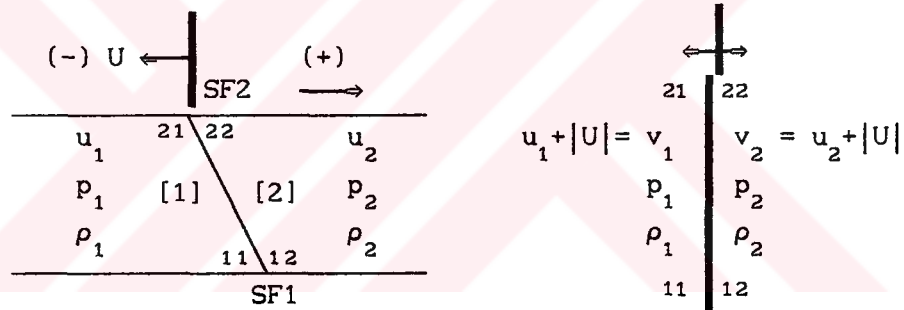


Fig. 5-2 Transformation of Left Running Ordinary Fronts.

* Right Running fronts:

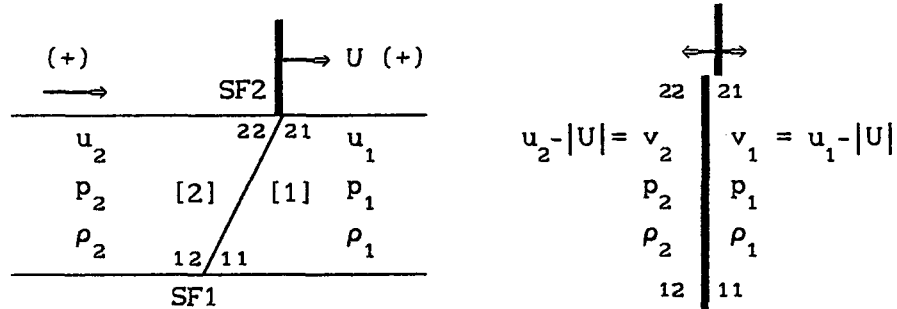


Fig. 5-3 Transformation of Right Running Ordinary Fronts.

$$v_2^2 - v_1^2 = \left(\frac{1}{\rho_1} + \frac{1}{\rho_2} \right) (p_2 - p_1) \quad (5.13)$$

5.9.2. Reflection at the Closed End.

$$\left(\frac{1}{\rho_M} - \frac{1}{\rho_{CE_A}} \right) (p_{CE_A} - p_M) = (p_M - p_{CE_B}) \left(\frac{1}{\rho_{CE_B}} - \frac{1}{\rho_M} \right) \quad (5.14, A)$$

* Approaching front:

$$-U : \left((u_1=0) - u_{2B} \right)^2 = \left(\frac{1}{\rho_{CE_B}} - \frac{1}{\rho_{2B}} \right) (p_{2B} - p_{CE_B})$$

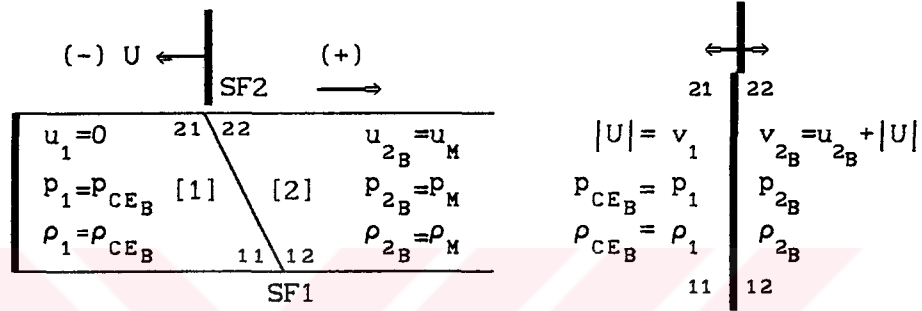


Fig. 5-4 Transformation of Approaching Closed-End Front.

* Departing front:

$$+U : \left(u_{1A} - (u_2=0) \right)^2 = \left(\frac{1}{\rho_{1A}} - \frac{1}{\rho_{CE_A}} \right) (p_{CE_A} - p_{1A})$$

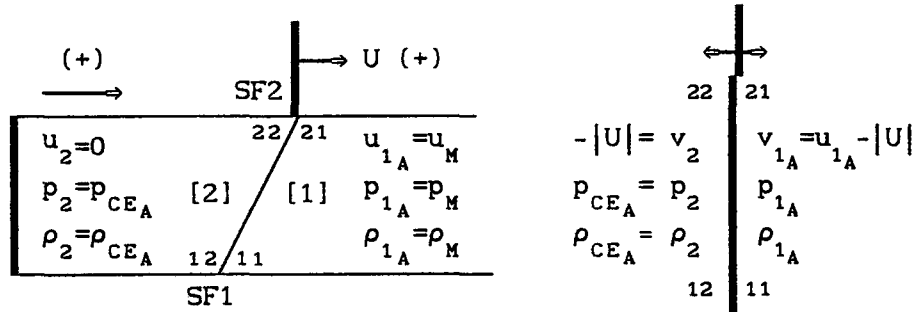


Fig. 5-5 Transformation of Departing Closed-End Front.

$$p_{CE_A} = p_M - \frac{\frac{\rho_M}{\rho_{CE_B}} - 1}{\frac{\rho_M}{\rho_{CE_A}} - 1} (p_M - p_{CE_B}) \quad (5.14, B)$$

5.9.3. Reflection at the Open End.

* Approaching front:

$$+ U : v_{2B}^2 - v_1^2 = \left(\frac{1}{\rho_{OE_B}} + \frac{1}{\rho_{2B}} \right) (p_{2B} - p_{OE_B})$$

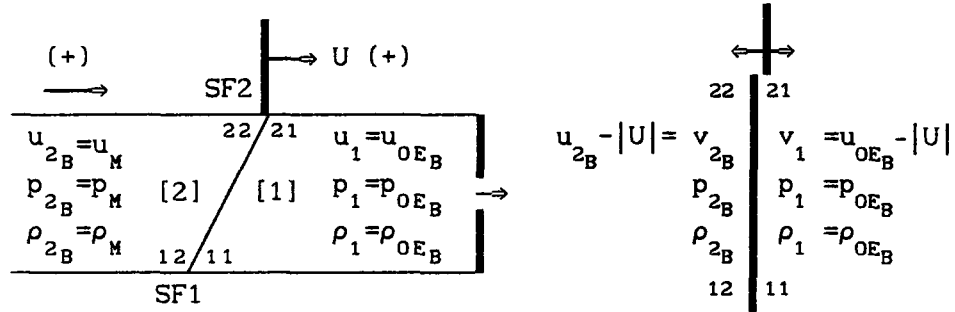


Fig. 5-6 Transformation of Approaching Open-End Front.

* Departing front:

$$- U : v_2^2 - v_{1A}^2 = \left(\frac{1}{\rho_{1A}} + \frac{1}{\rho_{OE_A}} \right) (p_{OE_A} - p_{1A})$$

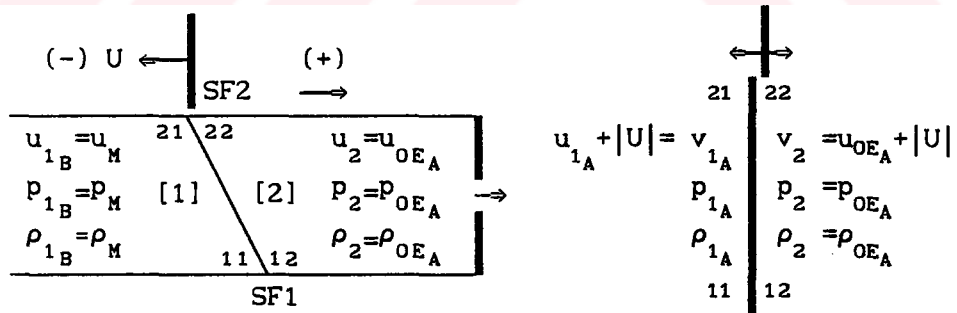


Fig. 5-7 Transformation of Departing Open-End Front.

$$p_{OE_A} = p_M - X (p_M - p_{OE_B}) + Y \rho_M (v_2^2 - v_1^2) \quad (5.15)$$

$$X = \frac{1 + \frac{\rho_M}{\rho_{OE_B}}}{1 + \frac{\rho_M}{\rho_{OE_A}}} ; \quad Y = \frac{1}{1 + \frac{\rho_M}{\rho_{OE_A}}}$$

5.10. NON - FULL TO FULL VESSEL TRANSFORMATION.

As already stated, the origin of the SF under consideration is the instant kinetic to potential energy transformation at the non-full to full vessel case change. This phenomena , although seems to be a practical way of creating an SF , due to the the almost total concentration on the shock tube experiments, has not been a subject of research at least for academic purposes (Excluding some special, restricted access type of research [See Ref.]..)

Principal point of the subject is the determination of the way that the instant energy transformation takes place. It may be possible to consider, a couple of more or less relatively less complex governing equations but; without difficult to menage experiments, it is not possible to choose the one best fitting. The program allows to use all relevant interpretations of the energy conservation equations including the ones for separated and quasi-single phase flows. In the routine SNFFT (Sub. Non-Full to Full vessel Transformation) some more or less different expressions were considered and through numerical experimentation, it is found that, not taking any special action and allowing the in built checks and balances of the numerical scheme to take charge may well be the best way. That approach is accepted and the methods mentioned were kept in the program as matter of record only.

5.11. PROGRAMMING FOR THE SF CALCULATIONS.

Programming for the SF calculations are the most complex and difficult to develop and introduce part of the whole programme. Although, as a result of countless trial runs with widely varying data from all ends of the spectrum under consideration, many checks and balances and parameters are provided for smooth running of the SF calculations part of the program, it is still the only program part that can not be considered fail-free. But, after proper and intelligent adjustments are made on one or more of the extensive list of SF calculations parameters, provided in the data file, most if not all errors would normally be cleared.

Due to the difficulties associated with their determination and interpretation, some of the parameters on the much thought concepts of start of the calculations pressure ratio decision and alike that normally -if ever- there would not be any need to consider; have not been incorporated into the program as data.

Due to its far too complex nature, even a flow chart would not be intelligible enough for acquiring an overall view on the SF calculations. In this respect, trying to give even a rough idea on its processes in words were considered not only too difficult to even to comprehend but also a useless effort. It is considered that overall, the best way of introducing the the SF programming ideas is to supply a routines call chart [App. H] , a job information table of the routines [App. G] and a list of related data file parameters in job oriented groups [App. F].

The strongly nonlinear system of equations of the SF, at first tried to be solved through, probably the best and richest mathematical routines library called NAG (Natural Algorithm Group), which offers at least tree seemingly suitable routines for the solution of the system of equations on hand. Although much attention is paid for the proper use of them (Routines SNLSF and SFNFN) none could even made a start. They were tried for the established SF stages for checks and comparisons but, as expected none could tackle that simpler case either.

Nonlinear character of the SF equations is so strong that through many experimental runs, many special coefficients were seemed to be needed and created at different stages, literally one by one when the jobs failed or got stuck. But, although due attention is paid, a couple of the nearly eighty -half integer, half real number- SF related data file parameters may still be regarded obsolete. (It is more difficult -and risky- to remove a redundant parameter than to introduce a new one for large programs !)

C H A P T E R 6

S P E E D O F W A V E P R O P A G A T I O N

I N

B U B B L Y L I Q U I D T W O - P H A S E M I X T U R E S

Since a bubbly-liquid possesses the large compressibility of the gas phase and the big density of the liquid phase, a pressure wave propagating in such a medium can show extremely different behaviour from that of its components in single phase. This behaviour can not be expressed with any mean value characteristics. In fact, the difference can be so big that, it can be as low 1% of the corresponding value in the liquid phase and only 1% by volume of air in water lowers the speed of small perturbations to about 5% of the single phase value.

The subject may be considered as a physical one, and it is quite well investigated in all its aspects that is in the scope of the study, as characterized below.

6.1. THE RESTRICTIONS AND ASSUMPTIONS.

The restrictions and the assumptions given in Chap.1.3 are valid and practically comprise the ones mentioned below too ;

- Perturbations are produced through the normal dynamic behaviour of the bubbly - liquid only.
- Amplitudes are very small; no external excitation is allowed.
- Perturbations has no character of periodicity.
- Perturbation frequencies are such that the wave lengths are much larger than that of the inter-bubble distance.

6.2. PRINCIPAL WORKS OF THE SUBJECT.

The reasons of interest on the subject follow the changing pattern of the dominant subject of interest to the bubbly-liquid

mixtures, static and in motion.

Fist known work (Mallock [33]) was on a simple observation of sound propagation in a glass full of a frothy drink, which suggested a very crude formula of " $C_m = C_l / (1 - \beta)$ ". First aimed interests were due to military research on underwater tracking (Carstensen & Foldy [6]) and jet propulsion (Tangren et.al. [46]).

Increasing interest on the safety aspects of the nuclear power technology that very much depend on the safe use of pressurized hot water; brought a lot of works on the subject after 1960s.

Hsieh & Plesset [23] were found the "Frozen" case equation through some average quantity concepts. McWilliam & Duggins [51] found the basic equations [Eqn.(6.3) & (6.4)] and gave the fist full graphics on the speed of sound change for void fraction, pressure and bubble radius.

Baum & Horn [3] have investigated the non - equilibrium flow case [Chap.(6.5)]. Mecredy & Hamilton [34] were the first investigators of transfer effects; and produced the largest set of equations -characteristic determinant- which can only be solved with iterative techniques. Nguyen et.al. [35] were considered all of the principal bubbly flow types by the same basic relation.

The subject in its basic concepts may be considered as saturated since late 1980's , with at least a couple of dozen major work that only a few firsts has been mentioned above.

6.3. THE PRINCIPAL FORMATS.

The well known Laplace equation for the speed of propagation of small perturbations is valid for the multi - phase media too ;

$$C_m^2 = \left(\frac{\partial p}{\partial \rho_m} \right)_S \quad : \quad C_m^2 = \frac{1}{\left(\frac{\partial p}{\partial \rho_m} \right)_\mu} \quad (6.1)$$

Inclusion of the surface tension effect, and accepting adiabatic bubble behaviour represent the general case. Application of the descriptive equation above, to the most general form of the ;

$\rho_m = \rho_m [p, (\mu, Z, K, n, r)]$ relation [Eqn.B.14] produce;

$$C_m^2 = \frac{A + B}{\left[(1 + \mu) \left(C \frac{A}{n p} + \frac{B}{K} \right) \right]^{1/2}} \quad (6.2)$$

$$A = \mu \left(\frac{Z}{p + \frac{2 \sigma}{R}} \right)^{1/n} ; \quad Z = \frac{p_0}{\rho_{g_0}^n}$$

$$B = \frac{r}{\rho_{l_0}} \exp \frac{p_0 - p}{K} ; \quad C = \frac{1 + \frac{1}{3 n} \frac{2 \sigma}{R}}{1 + \frac{2 \sigma}{R p}}$$

Two principal cases of interest may be distinguished ;

* Not - Too - Small Bubbles Case : $R_0 > 10^{-2}$ [mm].

Surface tension effect may be neglected ; $\sigma \approx 0$

$$C_m^2 = \frac{A_1 + B_1}{\left[(1 + \mu) \left(\frac{A_1}{n p} + \frac{B_1}{K} \right) \right]^{1/2}} \quad (6.3)$$

$$A_1 = \mu \left(\frac{Z}{p} \right)^{1/n} ; \quad B_1 = \frac{1}{\rho_{l_0}} \exp \frac{p_0 - p}{K}$$

* Very Small Bubbles Case : $R_0 < 10^{-8}$ [mm].

Surface Tension effect is important ; $\sigma \neq 0$.

Thermodynamic behaviour is isothermal ; $n = 1$.

$$C_m^2 = \frac{A_2 + B_2}{\left[(1 + \mu) \left(C_2 \frac{A_2}{n p} + \frac{B_2}{K} \right) \right]^{1/2}} \quad (6.4)$$

$$A_2 = \frac{\mu Z}{p + \frac{2 \sigma}{R}} ; \quad B_2 = \frac{1}{\rho_{l_0}} \exp \frac{p_0 - p}{K} ; \quad C_2 = \frac{\frac{1}{3} + \frac{p}{2 \sigma / R}}{1 + \frac{p}{2 \sigma / R}}$$

The equations above become much more complex when the mass conservation equation [App.B.5], is used instead of the simple isentropic law (as done in most of the literature).

6.4. THE PRACTICAL FORMATS.

Simplifications may be made on Eqn.(6.2) for the reasons that only relatively large bubbles and moderate pressures cases are of any interest, that is the surface tension and compressibility of the liquid may well be ignored. A simple error analysis can prove that the related errors do not normally exceed 0.1 % which is quite low. Simplifications on Eqn.(6.2) ;

$$\left. \begin{array}{l} K \Rightarrow \infty \\ \sigma \Rightarrow 0 \\ r \Rightarrow 1 \end{array} \right\} \quad A = \mu \left(\frac{Z}{p} \right)^{1/n} = \frac{\mu}{\rho_g} \quad ; \quad B = \frac{1}{\rho_{l_0}} \quad ; \quad C = 1$$

$$C_m = \sqrt{\frac{n p}{\beta \rho_m}} \quad (6.5)$$

This quite simple result involves only two very agreeable assumption and nothing else. The effect of compressibility of the liquid can be added to the equation above in a simpler way by applying the description equation to the basic mixture density eqn.;

$$C_m^2 = \frac{1}{\alpha} \frac{n p}{\beta \rho_m} \quad ; \quad \alpha = 1 + n \left(\frac{1}{\beta} - 1 \right) \frac{p}{K} \quad (6.6)$$

The effect of " α " is usually no more than 0.5 % .

The well known Lövy-Raabe equation for the calculation of the effect of the elasticity of the pipe material is valid for the multi phase systems too, that is ; (Woods [52])

$$C_{m,E}^2 = (1 + \alpha_E) C_m^2 \quad ; \quad \alpha_E = \frac{K_m D}{E e} \quad (6.7)$$

where K_m is the two-phase corrected bulk modulus of the liquid ;

$$K_m = \alpha_K K_l \quad ; \quad \alpha_K = 1 / \left(1 + \beta \frac{K}{p} \right) \quad (6.8)$$

Void fraction corresponding to the minimum speed of sound, the critical void fraction (β^*) can be easily calculated ; Eqn.(6.5) produces the simple but quite accurate result below ;

$$\left(\frac{d C_m}{d \beta} \right)_p = 0 : \quad \beta^* = \frac{1}{2 \left[1 - \frac{\rho_g}{\rho_l} \right]} \quad \& \quad C_m^* = 2 \frac{C_g}{\frac{\rho_l}{\rho_g} - 1} \quad (6.9)$$

At atmospheric conditions, the experimental value is $C_m^* \approx 18.3$ [m/s] which is about 20% lower than the theoretical value ; that is the simple format is quite incorrect for high void fractions. Approximate values of the critical void fraction and the speed of sound may be given as below.

$$\beta^* \approx 0.50 \quad \& \quad C_m^* \approx 0.07 C_g \quad (6.10)$$

6.5. NON - UNIFORM FLOW CASE.

Phase slip concept is an integral part of the accelerated multi phase flow phenomena. Appropriate parameters are provided for the non-equilibrium expulsion flow which necessitates appropriate equations for the speed of sound calculations. Simplifications that are mentioned above ; namely not too small bubbles [$p_g = p_l$, $\sigma \approx 0$] and moderate pressures [$\rho_l = C^{st}$, $K \approx \infty$] are accepted. The flow is also assumed steady and frictionless and free of any heat or mass exchange.

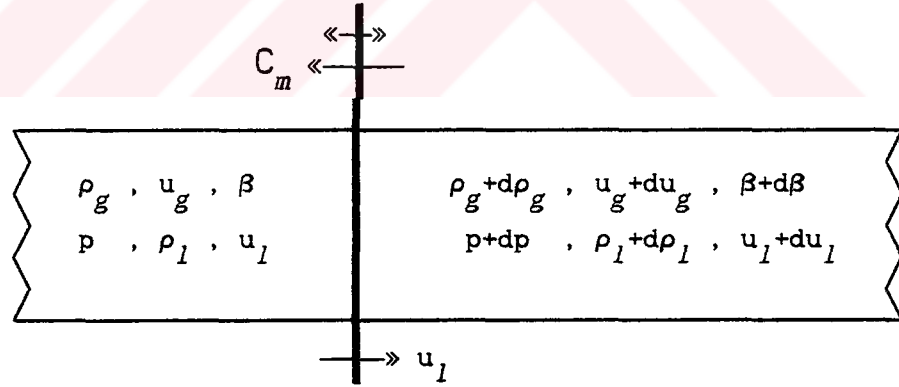


Fig. 6-1 Stagnating Wave Front.

Fig.(6.1) depicts the conditions under consideration ; a discontinuity , propagating upstream is stagnated by the fluid flowing downstream with the same speed. The continuity and the conservation equations are ; ($k = l$: Liquid p. & $k = g$: Gas p.)

$$\beta_k \rho_k u_k = (\beta_k + d\beta_k) (\rho_k + d\rho_k) (u_k + du_k) \quad (6.11)$$

$$p + \sum \beta_k \rho_k u_k^2 = (p + dp) + \sum (\beta_k + d\beta_k) (\rho_k + d\rho_k) (u_k + du_k)^2 \quad (6.12)$$

Equation of state for the gas ; $\frac{p}{\rho_g^n} = Z^{Cst}$ (6.13)

From the tree state equations above, without any assumption at all, the non-equilibrium flow speed of sound relation given below can be found ;

$$(u_I \rightarrow) \quad C_{m_{neq}} = \alpha_{neq} \frac{1 - (1 - \frac{s}{r}) \beta}{1 + \frac{1 - \beta \frac{n p}{K}}{\beta}} C_m^2 \quad (6.14)$$

$$\alpha_{neq} = \frac{1 + \mu}{1 + \mu r s} ; \quad C_m^2 = \frac{n p}{\beta \rho_m}$$

Simplifications may be made for non-slip and low mass ratio flows ;

$$r, s \approx 1 \quad \& \quad \mu \ll 1 : \alpha \approx 1 \quad \left(\frac{1 - \beta}{\beta} \frac{n p}{K} \right)_{ov} \approx 1 \cdot 10^{-2} \ll 1$$

$$C_{m_{neq}}^2 \approx \left(1 - (1 - \frac{s}{r}) \beta \right) C_m^2 \quad (6.15)$$

As seen, the " neq " conditions equation given above is valid for the homogenous non-slip flows too.

Crespo [12] gives the coefficient of Eqn.(2.14) as below; which reduces to the form of his own slip formulation [Eqn. (C.22)] ;

$$\alpha_{neq} = 1 + \frac{(1 + \mu) \beta - \mu}{1 + \mu r} (r - 1) \quad (6.16,A)$$

$$\alpha_{neq} \approx \frac{1 + 2 (1 - \beta) \beta}{1 + 2 \frac{\mu}{1 + \mu} (1 - \beta)} \quad (6.16,B)$$

Further simplifications may be made on the equation above ;

$$\mu \approx 0 \quad \& \quad \beta \ll 1 : \quad \alpha_{neq} \approx 1 + 2 \beta \quad (6.17)$$

Result : For high frequencies , ignoring the slip effect may produce considerable error even for low void fractions [App. (C.2)].

6.6. SOME NAMED DEFINITIONS.

In addition to the equilibrium and non-equilibrium speed of sound concepts ; there are some other definitions of special cases some of which are summarized below ;

- * Frozen Speed of Sound (C_{mf}). (Rudinger & Chang [43])

Stationary dispersed phase ; No Slip ($r = 0$)

$$\frac{1}{C_{mf}^2} = \rho_m \left(\frac{\beta}{\rho_g C_g^2} + \frac{1 - \beta}{\rho_l C_l^2} \right) \quad (6.18)$$

- * Stratified Speed of Sound (C_{ms}^2). (Grolmes & Fauske [18])

Dispersed phase is concentrated in layers, that is the distribution in cross sections are non - uniform.

$$C_{ms}^2 = \frac{\beta \rho_l + (1 - \beta) \rho_g}{\frac{\beta \rho_l}{C_l^2} + \frac{(1 - \beta) \rho_g}{C_g^2}} \quad (6.19)$$

- * Pseudo Two - Phase Speed of Sound (C_{mp}).

Calculated through simple partial volumes of the phases ;

$$\frac{1}{C_{mp}^2} = \frac{\beta}{C_g^2} + \frac{1 - \beta}{C_l^2} \quad (6.20)$$

- * High Frequency Limit Speed of Sound (C_{mhf}).

Equilibrium or otherwise equations given above are all correspond to the low frequency limit. Many, One of the simplest of the usually very complex high frequency limit equations which ignores all transfer phenomena is given below ; (Mecredy & Hamilton [34])

$$C_{mhf} = \left(1 + 2 \beta \frac{1 - \beta}{1 + 2 \beta} \right) C_{meq} \quad (6.21)$$

6.7. EIGENVALUE PROBLEM APPROACH.

Application of the Characteristic Determinant and Eigenvalue Problem concepts to the system of governing equations may produce the speed of sound equation of the case, but it can not be the one most practical to use.

The phasic continuity and momentum equations of a two-phase (bubbly-liquid) flow with the properties averaged over the flow cross-section area can be given as below ; $k = g$ [Gas] / l [Liquid]

$$(k=g/l) \quad \frac{\partial}{\partial t} A \rho_k^* + \frac{\partial}{\partial x} A \rho_k^* u_k = \frac{\partial}{\partial t} m_{i_k} \quad (6.22-23)$$

$$\rho_k^* = \beta_k \rho_k \quad , \quad \rho_k = \rho_k (C_k) \quad , \quad A = A(p)$$

$$(k=g/l) \quad \frac{\partial}{\partial t} A \rho_k^* u_k + \frac{\partial}{\partial x} A \rho_k^* u_k^2 + A \beta_k \frac{\partial}{\partial x} p_k = f_k \quad (6.24-25)$$

$$p_{k=g,l} = p \quad ; \quad f_k (\text{Gravity, Drag, Friction, } \dots) \equiv f_k (x, t)$$

The equation of conservation of energy is reduced to the equation of state for the basic no transfer phenomena case under consideration.

The governing equations may be put into the matrix format as;

$$\{ A \} \frac{\partial W}{\partial t} + \{ B \} \frac{\partial W}{\partial x} = f \quad (6.26)$$

$$W = \{ u_g, u_l, p, \beta \} \quad , \quad f = \{ f_g, f_l, 0, 0 \}$$

$$\{ A \} = \begin{vmatrix} \rho_g & 0 & 0 & 0 \\ 0 & \rho_l & 0 & 0 \\ 0 & 0 & x_g & 1/\beta_g \\ 0 & 0 & x_l & -1/\beta_l \end{vmatrix} \quad ; \quad \{ B \} = \begin{vmatrix} \rho_g u_g & 0 & 1 & 0 \\ 0 & \rho_l u_l & 1 & 0 \\ 1 & 0 & x_g u_g & u_g/\beta_g \\ 0 & 1 & x_l u_l & -u_l/\beta_l \end{vmatrix}$$

where " x_g " and " x_l " represent the quantities given below ;

$$x_g = \frac{1}{A} \frac{dA}{dp} + \frac{1}{C_g} \quad ; \quad x_l = \frac{1}{A} \frac{dA}{dp} + \frac{1}{C_l}$$

Eigenvalues associated with the matrix representation are the propagation velocities under consideration , and may be determined through the characteristic determinant (Mecredy & Hamilton [35]);

$$F(C) = \det(\{ A \} - C \{ B \}) = 0 \quad (6.27)$$

The characteristic determinant may be reduced to the form below ;

$$F(C) = W_g^2 \frac{\rho_g}{\beta_g} + W_l^2 \frac{\rho_l}{\beta_l} - X W_g^2 W_l^2 \rho_g \rho_l = 0 \quad (6.28)$$

$$W_g = u_g - C \quad ; \quad W_l = u_l - C \quad ; \quad X = \frac{x_g}{\beta_l} + \frac{x_l}{\beta_g}$$

Non-slip conditions ($r = 1$, $u_g, u_l = u$) and low Mach number ($M \ll 1$: $u \ll C$, $C \bar{u} \approx C$) assumptions allow some simplifications ;

$$F(C) = X \rho_g \rho_l C^4 - \left(\frac{\rho_g}{\beta_g} + \frac{\rho_l}{\beta_l} \right) C^2 = 0 \quad (6.29)$$

The two non-zero conjugate roots represent the speed of sound which is the Stratified case value given before with an addition ;

$$C_m = C_{ms} = \frac{\frac{\rho_g}{\beta} + \frac{\rho_l}{1-\beta}}{\frac{\rho_l}{(1-\beta)C_g^2} + \frac{\rho_g}{\beta C_l^2} + \frac{\rho_g \rho_l}{\beta(1-\beta)} \frac{1}{A} \frac{dA}{dp}} \quad (6.30)$$

It is not possible to produce more representative equations by the way of more comprehensive system of governing equations , because the high order and too complex characteristic equations can not have analytical solutions.

6.8. The ROUTINE "FSWP" (FUNCTION ; SPEED OF WAVE PROPAGATION).

Speed of Wave Propagation (SWP) is calculated through the routine "FSWP" with the parameters listed below.

$$\text{FSWP} \left(\begin{array}{ccccc} \text{Pressure} , & \text{Void} & \text{Specific} & \text{Bubble} & \text{Vessel} \\ & \text{Fraction} , & \text{Mass} , & \text{Radius} , & \text{Diameter} \end{array} \right)$$

All of the main formats of calculation are supplied in the routine with all alternative ways of calculation , such as ; taking into account of the effect of the surface tension , bulk modulus of the liquid phase, elasticity of the vessel material, phase slip and the corrected adiabatic expansion coefficient use.

The equations referenced and named in the routine FSWP may be summarized as given below ;

- Simple format : Eqn.(6.5) with " $\rho_m \approx (1-\beta)\rho_l$ " simplification.

The simplest possible speed of sound equation.

- Basic format : Eqn.(6.5) ; the basic equation.
- Full format : Eqn.(6.14) ; the standard equation.

Eqns.(6.2) to (6.4) are also considered with all special terms taken into account as additions, for easy comparison. Enough information is given in the data file for its easy and full use.

CHAPTER 7

NUMERICAL APPROACH

TO THE

METHOD OF CHARACTERISTICS

The aim of the chapter is to establish the basic principals of the application of the Method of Characteristics (MC) in a compact format only. As the basics of the MC are quite well known, most efficient way of presenting knowledge on the specialties of its application to problem under consideration, must be to list all the characteristic grid forms that may be encountered.

Only the points that are strictly related with the MC application of the problem will be considered. The measures of good programming are considered in the next chapter.

7.1. GENERAL CONSIDERATIONS.

The problem on hand, not only for dealing with two phases but also for the principal points of complications listed below, is quite a special example of the fields of application of the MC. Specialties of the case may be summarized as below ;

- Two - phase fluid ; one more that is three instead of two characteristic lines. The third characteristic line denotes the trajectory of the dispersed phase -the bubbles- and allows to calculate the changes in void fraction.

- Strong shock front creation, due to instant throttling.

- Moving jump condition ; a moving contact surface separating the two distinct fluid regions of the bubbly-liquid and the gas.

- Rapidly accelerating initial flow, instead of the common format of initially arrested flow structure encountered at most of

the classic hydraulic transient problems.

The secondary but still important sources of complications may be listed as below ;

- Moving discontinuity surfaces very much complicates the calculations at points next to them.

- Very high difference between the velocities of sound in the mixture and the gas regions separated by the CS necessitates complicating special treatment in the gas region.

7.2. PRINCIPAL POINTS OF THE MC APPLICATION.

Due to its complex character, the solution of the problem requires special attention at a lot of points of the calculation process, not for precision enhancement but just to make it work.

The principals and ideas that were taken under consideration in MC applications will be examined in Chap.8 . Only the basic concepts and in short remarks are to be considered here ;

- Full format MC application ; due to low sound speeds and the existence of moving discontinuity surfaces.

- A third characteristic for the bubble movement and void fraction calculation ; no averaging calculation would suffice.

- Full treatment for the moving Contact Surface ; no concept of simplification can be accommodated.

- Shock Front creation at the throttling instant ; no energy transformation calculation correction can be acceptable.

7.3. CHARACTERISTIC GRID FORMS.

Two-phase fluid , two distinct regions system and the existence of three types of moving discontinuity surfaces - however similar they are - , increases the total number of more or less different MC grid forms to nearly a hundred when all variations are considered. All these alternative formats were checked and catered for, and basically in separate special to the case routines.

About a dozen characteristic grid form examples that will be given are chosen as a complete representative of all the possible

formats. The notation used do not wholly correspond to the ones in the program but the bridging should not be difficult and the the examples are given without comment as the drawings are quite self explanatory. (Examples for the principal grid forms and with the notations employed are given in appropriate parts of the program as comments.)

7.3.1. Ordinary Points.

Ordinary points in the mixture region represent the simplest case and are taken into account in its subsonic [Fig. 7-1] and sonic [Fig. 7-2] flow condition formats.

* Subsonic Flow case ;

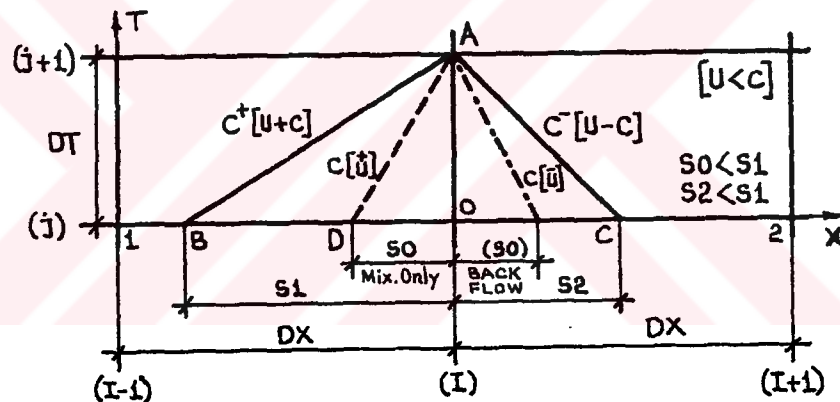


Fig. 7-1 MC Grid for Ordinary Points ; Subsonic Flow Case.

* Sonic Flow case ;

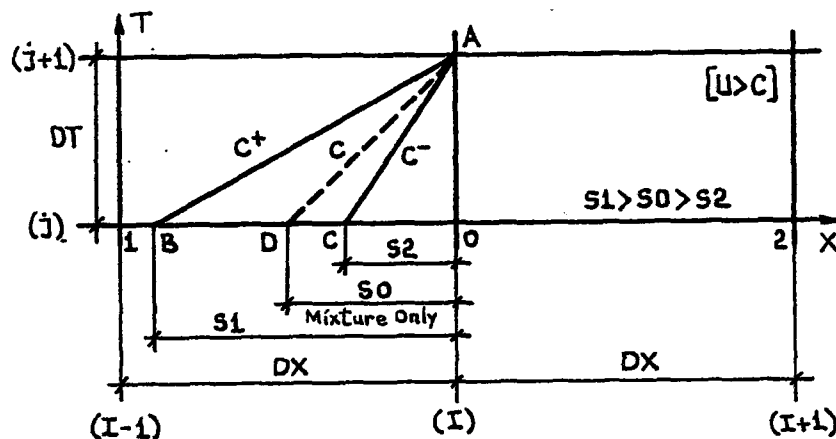
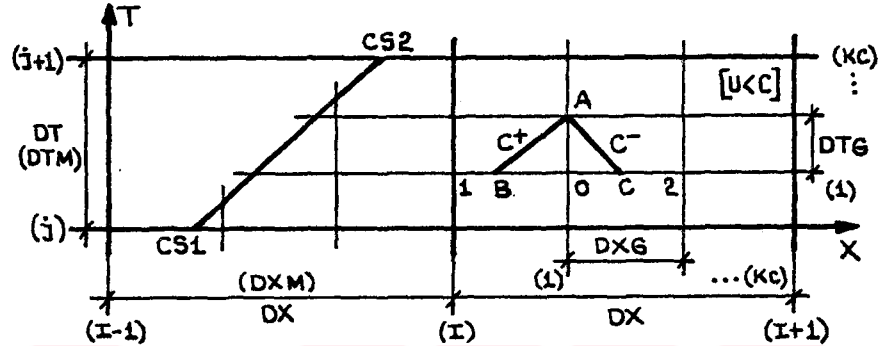


Fig. 7-2 MC Grid for Ordinary Points ; Sonic Flow Case.

* Ordinary Points in the Gas Region ;

Due to the finer mesh that it requires, in terms of both step length and the time increment ; the case has some special features as depicted in Fig. 7-3.



$$DXG = DX / KC \quad \& \quad DTG = DT / KC$$

$$KC = \left| \left[(C_M + |U_M|)_{\max} / (C_G + |U_G|)_{\min} \right] + 0.1 \right| + 1$$

Fig. 7-3 MC Grid for Ordinary Points ; The Gas Region.

7.3.2. The End Points.

MC mesh of the end points, namely the Open End (OE) point and the Closed End (CE) point do not represent any special format in comparison with the basic single phase cases for the mixture medium.

* The Open End (OE) point ;

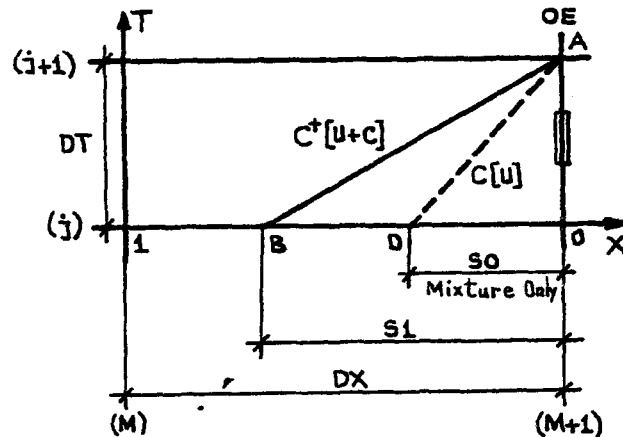


Fig. 7-4 MC Grid for the Open End Point.

* The Closed End (CE) point ;

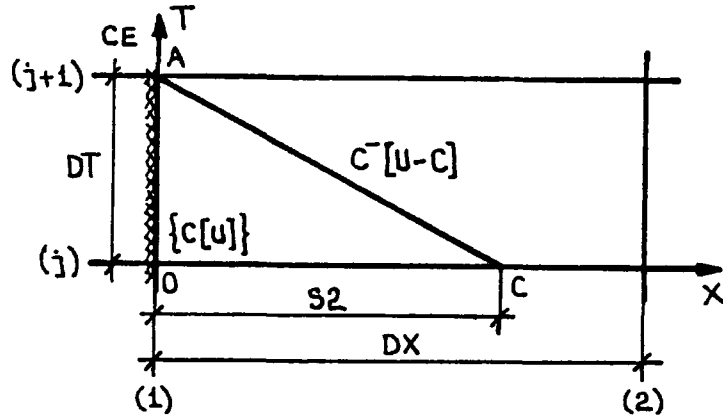


Fig. 7-5 MC Grid for the Closed End Point.

7.3.3. The Contact Surface (CS) point.

The CS is quite a special point ; it is the particle path and the sound speed difference between the mediums of its sides is huge.

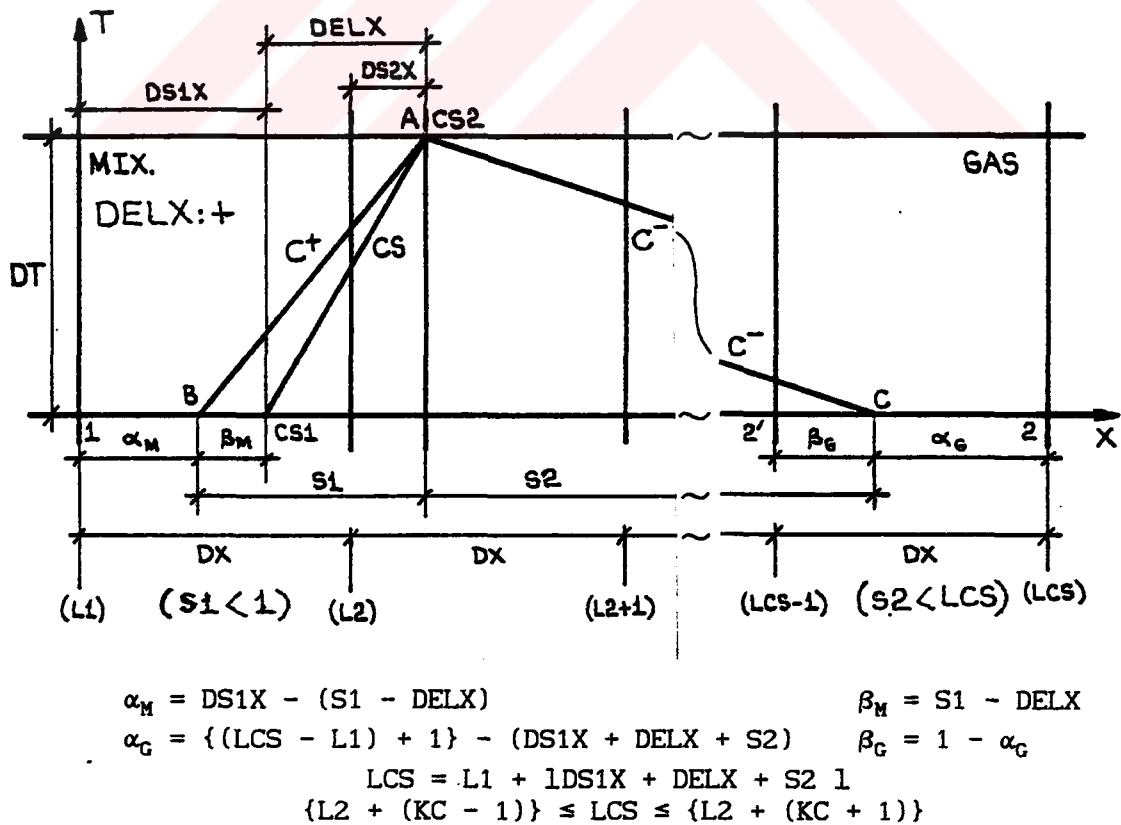


Fig. 7-6 MC Grid for the Contact Surface Point.

7.3.4. Points Near the Contact Surface.

CHAPTER 8

THE PROGRAMME

CONCEPTS AND CHARACTERISTICS

In this chapter, the computer programme will be explained through the main concepts taken into account and put into it, its main characteristics and the extent of its facilities.

Before elaborating on the concepts of resources saving measures, it would be helpful to establish the point that ; the non MC loop calculations part of the programme - reading data, initialization, printing etc. - do not normally consume more than 10% of the job time ; that is the savings on the MC calculations can have a major effect on the total run-time requirement of a job.

8.1. GENERAL CALCULATION STRATEGY.

MC calculations on established and not-too-strong transient flows are very straightforward processes even for the multi-phase flow cases. But the addition of discontinuities and especially the Shock Front and the very rapid character of the transients makes the problem quite complicated and very much prone to errors which would call a strategy in programming.

The two extreme approaches mentioned below were rejected and a balanced and optimized solution strategy were followed. The principles that this approach calls, in their relative order of importance may be summarized as below ;

- Fail - free run,
- High precision,
- Minimized run-time,
- Not too complicated program structure.

The principals listed above and the measures they call will be examined in detail.

The rejected extreme approaches may be summarized as below ;

- "No error-restart" runs.: Would be impossible to implement for the SF cases, and also would be very much job-time consuming without any benefit for the FV cases, due to its requirement of far too many nodes and resulting continuous use of far too small time steps.

- "No error preventative measure" runs. : Can not be regarded as a sound strategy to follow for simplified programming ; because reduced time steps can not clear all error conditions especially the ones related with the discontinuity surfaces such as an SF.

8.2. CORRECT MC CALCULATION MEASURES.

Correctly followed and also rejected ways of MC calculations may be summarized as below.

- No mixing with the calculation concepts of wave tracing algorithms like the head and tail wave fronts were allowed.

- The proper full characteristics application for multi-phase fluid media is employed that is an additional characteristic line is employed for the void fraction instead of a quite wrong QSS solution equations that also imposes uniform initial void fraction distribution.

- Ability of the MC of smoothing the effects of jump conditions were not exploited. For example , the initial wave front concept was installed for all cases.

8.3. FAIL - FREE RUN MEASURES.

Fail free run measures are basically related with maintaining smooth transitions that is preventing abrupt changes. There are two sources of extreme transient behaviour ; the initial expulsion and the SF calculation stages.

8.3.1. Initial Expulsion Stage.

The initial expulsion stage measures may be listed as below ;

- No instant opening allowed ; no duration of opening, however small, is considered too small for dividing it into many - at least half a dozen - calculation steps.

- Time steps are reduced considerably and for a considerable time compared with the duration of expulsion (TCO) ;

$$DT \leq TCO / [CTD = 10 \sim 20] \quad \text{until} \quad T \geq [CTM = 5 \sim 10] TCO$$

- Initial wave front concept is created ; the undisturbed section is put out of the calculation region.

8.3.2. The SF Calculation Stage.

In addition to the reduced time step application of the kind mentioned above, the measures summarized below are taken.

- Determination of the starting value of the SF pressure ratio calculation were tried to be made as properly as possible for the initial and all ordinary steps, through ; starting conditions, the value and the rate of change associated with the previous step and some other relevant parameters.

- Continuous reduction of time step can create quantities that are out of limit in either extreme and cause error stops. For its prevention , the relevant programme parts are equipped with limiters related with the ;

- Job time spent for a particular program part.

- Number of loop returns made for the calculation of the part.

The program contains safe min. and max. real number definitions and critical parameters are checked against them at critical points for unnecessary error stoppage preventions.

SF programming contains many measures solely for reaching the goal of fail - free run, no other part of the program contain any similar special measure for that purpose.

8.3.3. General Failure Prevention Measures.

The failure prevention measures that apply all parts of the programme may be summarized as below ;

- Utmost attention is paid to the principle that, only the values of the last full step is used for the new time step calculation after an error re-start. Observation of this vital rule

requires great care, especially for the error stops in complex, a couple of levels inner loops of the SF calculations and in the gas region of the non-full vessel case.

- A special all inclusive routine (SIFMC) is prepared for full, no-miss ordinary variable initialization before the execution of every MC calculation routine.

- All related data and parameters are made compatible with the others just after they are read or created.

- All arrays are initialized before any data put into them ; including the multi data file run cases.

- To prevent error creeping into due to too complex programming, all special frames of MC calculations that involve end points and discontinuity surfaces (CE,OE & IWF,CS,SF) were treated in separate routines.

8.4. RESOURCES SAVING MEASURES.

The programme can be considered as quite a large one not only for its size but also the resources in terms of space and time that it consumes. That is; resources saving measures needed to be considered very seriously and they were. The measures taken are summarized below in three characteristic groups.

8.4.1. Decreased Run - Time Measures.

The program has many parts that with a careful investigation can offer a lot of savings in terms of required job-time for a targeted precision.

- Calculation step time intervals at initial opening stages are kept at a minimum by the use of smallest suitable time step division and the extension of its application duration parameters.

- When the CS gets very near to the OE, even for reasonable overall efficiencies, number of calculation nodes must be very much increased in order to decrease the size of the uncalculated gas region when much less would be enough for the bulk of the mixture region. As a resources saving measure, at ordinary MC calculation regions, a couple of nodes away from the special points, only one in

2 to 10 nodes are fully calculated and averaging techniques are applied to the inner nodes. It is observed that this measure alone can save up to 40 % of the job time required up to the FV stage.

- For the NFV case, due to the considerable difference between the wave speeds in the two mediums ; in spite of the quite important complications it was brought in the gas region ; not a time wasting single minimum time increment but separate time steps were employed for the phases with only minor restrictions.

- At all parts of the program, the number of calculation nodes are increased only when it was absolutely necessary and to twice as much only and decreased back immediately when not required.

- Many parameters were provided in the data for short cutting the ways of calculations that are geared to maximum precision but has no importance in development runs. Examples are ; the critical pressure ratio calculation, corrections for temperature etc. dependant physical quantities , the Reynolds number and the friction coefficient calculations.

8.4.2. Decreased Size and Modularization.

The programme has a quite modular structure, but not as much as it may be made of, due to the required job time increase that excessive modularization brings and the complications in programming as a result of too frequent calls to too many routines. For these reasons, all averaging calculations related with the MC programming were done in routine. Due to the requirement of the CALL statements with parameters lists as long as the lists of the averaging calculation procedures, no size - physical and binary - saving can be made with the modularization in that extend. The five principal points of modularization are listed in Table 8-1.

Table 8-1. Principal Points of Modularization of the Programme.

- | | |
|---|-----------------|
| 1. MC - velocity and pressure calculations. | (R. SMCUAP) |
| 2. MC - void fraction and density | " . (R. SMCBOR) |
| 3. Initialization of the MC loops | " . (R. SIFMC) |
| 4. Movement of discontinuity surfaces | " . (R. SMDS) |
| 5. Job time , date and real time | " . (R. SMDS) |

8.4.3. Easy Error Tracing (Debugging).

As it is not covered by the language standards, error tracing facilities are very much compiler dependant and usually very difficult to use and master.

Compiler supplied debugging and extended error dump facilities also slow down jobs and increase machine code sizes considerably which is a major drawback for large programs.

Being aware of the fact that ; good quality in-built error tracing facilities save a lot of user and machine resources, the program was incorporated with so comprehensive error tracing facilities that, for its development, the compiler provided error tracing facilities were hardly ever required.

The debugging facilities are particularly extensive in the SF calculations sections. Extensive list of parameters are provided in the data file for narrowly targeted, compact and easy to use error tracing listings.

Due to the complete COMMON block structure of the programme, even ordinary error stops provide detailed information for debugging as most compilers list COMMON parameters after every error stop.

An absolute, "first occurrence stop" routines list is provided for the compilers that use error counters by default. For the compilers that provide error dump at under and over flow conditions, dummy error conditions are created at critical error stop points.

8.5. QUALITY IMPROVEMENT MEASURES.

The quality improvement measures are summarized under six headings in which the points are presented in concise format.

8.5.1. Accuracy Improvement Measures.

- The programme does not contain any false procedure for increasing accuracy and provides accurate precision information calculated with the total amount of the content expelled and left in the vessel for every calculation step.

- Temporary node number increase and then decrease - when become unnecessary - procedures are provided at places where it is

needed for increased accuracy.

- The effect of phase slip is taken into account for the highly accelerated flow through expulsion elements.

- Precise ways of calculating CPR values are provided for the exact choked flow condition determination.

- Back flows - however rare and unimportant - are taken into account for both mixture and gas phases.

- Shock fronts are allowed to reflect at the open end and not just expelled through the expulsion element.

- Counters and limiters are provided in the data files as repeated calculation and discontinuity surface movement limiters.

- Sonic flow condition checks are made at all relevant points and the sonic case MC calculation procedure is fully incorporated into the program.

Only the principal accuracy improvement measures that were taken are listed here, the programme and the data files contain many more parameters specifically created for some other improvement measures [App. F].

8.5.2. Comparative Study Facilities.

Almost all known formats and ways of calculation were included into the program with easy to use parameters in the data files. The main examples are ;

- Speed of - sound - wave propagation.

- Rate of flow of the the expulsion of bubbly mixtures through expulsion elements.

- The wall friction calculation for bubbly mixtures.

All meaningful ways of averaging for the MC frame calculations were also included.

Limits of all MC calculation loops are assigned to data file parameters for easy checks on the effects of individual programme parts for the overall and step-specific accuracy.

8.5.3. Structure of the Mixture Functions Use.

Main components of the initial structure of the mixture, like the void fraction and bubbles size distribution can be altered

through data file parameters [App. F.3 : 3.3 & 3.4] in linear and basic nonlinear formats.

All physical quantities that establish the the phases of the mixture are provided as parameters in the data files. For most common fluids; the equations like the viscosity versus temperature relation, were provided in the program.

8.5.4. Shape of the Vessel Functions Use.

The shape of the vessel functions allow to implement a quite wide range of axially symmetrical shapes from cylindrical pipes to stylish vase like shapes through simple data file parameter changes.

8.5.5. Area of the Opening Function Use.

Time dependant and instantaneous openings are allowed and a rate of change of the area of opening function in exponential format is provided [Chap. 4.3.2]. The special case of full - unrestricted opening is fully considered including for the instant opening case.

8.5.6. Expandability and Adoptability.

When the needs arise, the program can be expanded quite easily. The principal characteristic of the programme that make it easily expandable is that all parameters were put in COMMON blocks and were grouped according to their functions. As a result, with very minor exceptions, the subroutine calls have no parameters list.

Very comprehensive COMMON and PARAMETER blocks editing software were prepared and provided with the programme that allow fully automatic changes in the blocks in all 100+ routines.

The tidy and easily expandable data file structure of the program may also be considered as a major positive point in respect to its expandability and adoptability.

8.6. INTELLIGIBILITY IMPROVEMENT MEASURES.

The intelligibility improvement measures are summarized under three headings in which the points are presented in concise format.

8.6.1. Intelligible Programme Measures.

- Acronyms were used as variable names as much as possible for easy remembering and recognition.

- For automatic type recognition no TYPE statement is used.

- With the aim of less complex program structure , fashionable facilities of the FORTRAN-77 language were not employed ; for this respect the only criteria was being easy to follow.

8.6.2. Intelligible Output Measures.

All types of output files ; the ordinary results file, the output arrays listing file, and the graphics output can be annotated with all or some of the information listed in Table 8-2

Table 8-2. Principal Intelligibility Information on the OF's.

1. A short remark line supplied with the data file.
2. The computing center recognition information.
3. Run-time and job in/out times information.
4. Automatic and full date and time marking.
5. Full data file list with separate main data list.
6. Full initial conditions information.

8.6.3. Dimensional Versus Non-Dimensional Format.

The programme is prepared in dimensional format, fully and without any exception. Because of the nature of the problem and the size and complexity of the programme, non dimensional format would provide little help if any on easy evaluation of the results but would certainly make the program very difficult to follow and as a result make error tracing far more difficult.

Dimensional format increases the intelligibility of the output files too but some very obvious dimensionless quantity additions would of course be preferable. Fully nondimensionalized output were not considered even for the multi data run cases. None of the output file formats that can be considered, allowed to keep dimensional and otherwise quantities side by side in a great extend, and for that reason, although it is quite an easy job to do, nondimensionalization was kept at a minimum.

There has not been any work on the subject that consider the nondimensional calculation format. The problem has more than one characteristic quantities for length (vessel diameter and length, diameter of the opening and average bubble diameter) and time (duration of opening, duration of expulsion and quasi-steady flow case duration of expulsion) and finding meaningful non-dimensional quantities is a very difficult task as proved by the two well thought but quite useless example for the FV-MD cases [Chap. 10.1.1].

8.7. PORTABILITY MEASURES.

Portability criterions were taken into account very seriously and it may well be said that the programme is as portable as it can be, considering its size and other requirements.

Full portability can not be claimed; because, unfortunately, the FORTRAN compiler standard do not cover many important aspects of programming ; that is some machine dependant limits may well be exceeded for some small or medium capacity main frames.

Main sources of trouble would probably be the COMMON blocks ; their total number and for example the number of names in them. If error condition arises from more than one factor, the adaptation job may well be impossible to carry out.

Most probably, there is not a commercially available FORTRAN compiler for the Personal Computers (PC's) that can handle the programme, but some work-station software may well menage.

8.7.1. Fully Standard Language.

The rules of the Standard ANSI & ISO FORTRAN-77 Language are fully observed , no extension to the language by any compiler is used. For the points not set by the standard , the limits of the most widely available mainframe compiler were taken as the standard.

8.7.2. Independence of Library Availability.

Except the obvious dependence of the graphics part to the GHOST graphics library, the program is totally independent of the availability of any library routine.

The time - run-time and actual time - and date information routines are all located in one routine only. Similar routines with minor parameter format differences are available in all installations and the transformation would be an easy task.

The NAG Numerical Algorithm Library routines are referenced in SF and CPR calculations ; but in the SF part the routines do not work and kept for informative purposes only and in the CPR part it does not provide any more precision than the supplied algorithm.

8.8. THE INPUT FILE.

There is only one input file to note for all cases which is the data file of the case. The program does not require any data input through terminal in any stage of a run.

8.8.1. General Description of the Data Files.

All cases has their own, customized data files which were named and given a descriptive number as stated below. [Chap.1.4]

Table 8-3. Data Files of the Cases.

<u>The Name of the Case.</u>	<u>File Name</u>	<u>Descriptive Number.</u>
Non - Full Vessel.	DNF	KDF = 1
Full Vessel.	DFV	" = 2
" " " - Multi Data.	DFM	" = 3
" " " - Special.	DFS	" = 4
Pressurized Gas Bottle.	DGB	" = 5
Full Vessel - Multi Data - Special	DMS	" = 6

The data files were organized in a very user friendly way but they are larger in size than they may be, because every parameter, short of being absurd were put into them to allow to test and investigate all considered aspects of the problem , the numerical method and the programme itself.

8.8.2. Content of the Data Files.

- Variable names are assigned as the most suitable short names

or abbreviations fitting their function.

- Dimension and symbolic, but quite useful function information are provided for all data.

- When applicable, limiting and the normal values information are provided for guidance.

- All integer numbers are read as easy to handle real numbers and a special format were employed for very small or large numbers that are employed in exponential format, for easy handling.

8.8.3. Format of the Data Files.

- Related data are kept in the same line and grouped together in the same screen-page of data.

- Most frequently changed data are kept in the first or the last screen page for easy access.

- Corresponding parts of the data files have the same format for all data files of the cases.

8.9. THE OUTPUT FILES.

The program uses up to six input / output channel for the purposes summarized in Table 8-4. (The channel numbers can be easily adjusted to the site requirements as they are defined implicitly.)

Table 8-4. Input / Output Channels Information.

<u>Channel Number Name</u>	<u>Default Channel Number</u>	<u>Input Output I/O</u>	<u>Function</u>
KIF	1	I	Data Read.
KOF	2	O	Main Output File.
KIS	3	I	ICD Run Data Read.
KOL	4	O	Output Arrays List File.
KGR	5	O	Graphics Related Messages.
KOT	6	O	Terminal Output.

Only three of these channels - 1., 2. and 6. - are used by all cases ; but all of them were included into the in program file hand-

ling statements list which allow full facilities for the use of site independent job handling.

The two principal output files are the Output File and the Output Arrays List file ; the former is for the evaluation of a run and the later is for the production of graphics like full pictorial information.

The program and its data file, contain all of the foundation for the full use of the batch job facilities of the computing sites.

8.9.1. General Description.

Output files of the cases are organized in tidy, orderly and in fully self sufficient format.

It is obvious that not all calculation steps and the nodes information can be put into the output files, for saving resources and practical reasons. But utmost attention is given to the principle that the information on all special steps and nodes listed in Table 8-3 and Table 8-4 are to be present in the output file ;

Table 8-5. The Characteristic Steps of the Output Files.

- The first couple of steps.
- The end of initial wave front step.
- The end of duration of opening step.
- The full vessel declaration step.
- The shock front creation step.
- The first couple of newly created SF steps.
- The reflected SF steps, before and after.
- The end of the expulsion declaration step.

Table 8-6. The Characteristic Nodes of the Output Files.

- The open and closed ends and the middle points.
- A couple of points near the open and closed ends.
- The CS point, both sides, clearly indicated.
- At least one point near CS, on both sides.
- The SF point, both sides, clearly indicated.
- At least one point near SF, on both sides.

8.9.2. The Format and the content.

The principal points on the format and the content of the output files may be listed as in Table 8-7.

Table 8-7. Principal Points on the
Format and the Content of the Output Files.

- * Heading with annotation, - special remarks line and date.
- * Full list of all - corrected to the case - data of the run.
- * List of principal derived quantities.
- * Full dimension information for non-cylindrical vessels.
- * Initial conditions list. Also provided for NFV to FV shift.
- * Full information for the evaluation of the calculation of a step ; some arrayed or otherwise quantities are listed both in dimensional and non-dimensional formats.
- * End of the run page contains all data for the evaluation of the run including the principal arrayed values on the state of the mixture left in the vessel.
- * Job time information for each time step , for the whole run and for the graphics part, if exist.

8.9.3. The Output Arrays Listing Files.

- Output arrays listings of the cases were developed principally for being able to run complete graphics jobs independent of the run which also help the evaluation of the results of a run as a complementary to the output file.

- OAL is a clearly annotated file with special marks for the characteristic positions of the discontinuity fronts for easy evaluation and contains almost all information required to draw the graphics considered in Chap.9.

- OAL is a much less practical but still useful and better than nothing type alternative to the graphics output when it can not be made available.

- OAL is produced at the end of a job, that is it can not be used for error tracing purposes.

END OF CHAPTER 8

CHAPTER 9

THE GRAPHICS

Due to the rightful importance given to the graphical evaluation and presentation and its special importance for large and complex programs like the one prepared for the subject under consideration ; a lot of attention was paid for the production of high quality, clearly annotated and complete set of graphics for all of the cases under consideration.

9.1. INTRODUCTION.

Unfortunately there is no universally known and recognized graphics library and there is no standard for them. The graphics programs are very much site dependent and conversion from one package to an another requires effort almost equal to writing anew.

The GOST graphics library that were employed in this study, is probably, one of the most internationally known one of its kind but still no claim at all is made for the portability of the graphics part of the program.

9.2. THE GHOST GRAPHICS LIBRARY.

The GHOST^(*) graphics library package used in this work , is the principal 2D graphics package of the computer laboratories of many higher education and research establishments.

Main characteristics of the GHOST library is summarized below ;

- It is basically a 2D graphics package with limited 3D facilities (not required). It is not a simple and packaged, all inclusive,

(*) GHOST : Graphics HOST ; A computer graphics drawing library.
Developed jointly by Culham Lab. of the Atomic Energy
Agency of U.K. and the National Engineering Lab. U.K.

fixed format routines program ; it has no fixed format and a graph has to be put together in bit by bit by a dozen or more special calls chosen from more than a hundred available. Its extensive facilities does not impose restraints to the ideas of the users.

- It is somewhat difficult to master and due to its multi CALL structure, it must be especially difficult to convert the graphics part of the program from this package to an another.

9.3. GENERAL CHARACTER OF THE GRAPHICS OUTPUT.

Graphics output of all cases are prepared as complete files with information on main data file parameters and results. The graphics output consist of three main parts.

- Heading and the main input and output parameters page(s).
- All arrayed input of the multi data cases are printed on a separate information page.
- Extensive detailed information plots of most of the characteristic quantities ; almost all of them non-dimensionalized and presented in tidy, multi-graph a page format.
- Full page detailed plot(s) of the principal characteristic quantities which are the pressure at the top, middle and bottom versus nondimensional time plot for single data cases.

Main characteristics of the plots of the programme may be summarized as below ;

- Almost all plots are produced with the non-dimensionalized parameters and the method of non-dimensionalization is clearly indicated when appropriate.
- Plots are produced in the most user friendly format with clear axis annotation and in most fitting drawing method; curve fitted, point plotted or points connected. With the aim of preventing wrong conclusions to be drawn up, most multi data case plots were produced not as curve fitted but in line draw format.
- Plots are produced in color, when appropriate ; but care taken for preventing confusion in the case of single color draws, in the forms of solid, dashed, dotted etc. lines and clear annotations.
- Great care was taken for the production of quality plots; for example overprinted and unsuitably placed annotations are prevented through in some cases quite complex routines.

9.4. GRAPHICS INFORMATION PARAMETERS.

All characteristic quantities that were made a subject to a plot are listed at the initiation part in function based groups.

The parameters of the plots of the principal cases of non-full and full vessel are summarized on Table. 9.1 as a description of the extent of the related plot files ;

Table 9.1. Parameters and the Plots of the Graphics Output.

The abscissa parameters.

- * Time in percentage of the duration of expulsion.
- * Time in percentage of the duration of gas expulsion.
- * Time in SF phenomena as a percentage of SF duration.
- * Calculation step number, in absolute value.

Non-Full and Full Vessel cases common plot parameters.

- (1) * Pressure at the top - middle - bottom of the vessel,
In percentage of the initial value.
Versus time in percentage of the duration of expulsion.
Also an enlarged version for the SF calculation region.
 - (2) * Overall calculation precision up to a time or step.
 - (3) * Precision of the expulsion calculations.
Calculated through expelled and depleted amounts.
 - * Time increment in percentage of the mean value.
 - (4) * Time increment in percentage of the theoretical value.
 - (5) * Percentage of the contents expelled, p. of the final value.
 - * Volumetric void fraction, p. of the -mean- initial value.
 - * Mass of the contents expelled, p. of the initial value.
 - * Pressure at the top of the vessel, in absolute value.
- Multi parameter plot of (1) with (2) to (5) (not scaled).
Drawn for the easy evaluation of the results only.

Special Plots of the NFV Case.

- * Height of the mixture level, in p. of the vessel height.
- * Movement of the contact surface, in p. of the mean value.

CHAPTER 10

CONCLUSION

10.1. THE RESULTS.

The results of the study may be considered under two headings corresponding the principal cases of the programme.

10.1.1. The Full Vessel Case.

The Full Vessel Case is considered with all its aspects through the three FV case data [Chap. 1.4.2]. Helped by the small run time requirement of the case, through many multi data runs under widely varying conditions, all interactions between the principal parameters of the case were evaluated on graphical output.

Principal results of the examination of the FV cases output [App.K.1] may be listed as below.

- * The case is fully supported ; the program does not fail for reasonable extremes even without any special measure, but by the use of suitably increased number of calculation nodes and initial time step adjustment parameters, all extremes can be covered ; such as full and near instant opening at high pressures and high void fractions.

- * For the ordinary cases of ; low pressure , low void fraction , low opening area ratio and not too fast opening (durations of opening in milli rather than micro seconds) ; reasonable precision can be achieved with no more number of calculation nodes than the most basic MC applications -simple water hammer problems- require, which is about ten or even less. This result in some respect proves the strength of the code of the programme.

- * If the initial steps adjustment parameters are chosen properly, the program work without error restart and use the standard

time increment value until the near end of expulsion that the pressure at the top drops very near to the environmental value. This fact too may be regarded as a sign of the strength of the code for the critical initial time steps calculations.

* For moderate conditions - low pressure and void fraction ; the time history of the pressure change at the top , midpoint and the bottom ; do not appear much different than the corresponding - same vessel and pressure - pressurized gas bottle case result when the speed of wave propagation difference is taken into account. That is , below given conclusion may be drawn quite reasonably ;

" For moderate conditions, sudden discharge of bubbly liquids from full pressurized vessels is no more a disorderly process than the ideal gas expulsion under equivalent conditions. "

* For moderate conditions , percentage of the content expelled , calculated through the program is very near but less than the simple Quasi-Steady State (QSS) value [App.C.3]. Only for the cases that correspond fastest expulsion ; the high initial void fraction and opening area ratio , that the QSS value may be exceeded slightly due to some extra discharge, as a result of the negative pressure field created at the end of the expulsion (Low initial pressures may artificially enlarge this effect.)

* Whatever the initial conditions are , the pressure history can never have a peak anywhere near the initial pressure at the top, that is no excess pressure built up - hammering effect - can occur that may worsen the emergency conditions , especially in the case of long / pipe like vessels.

* Further results of the experimental runs [App.K.1] may be summarized as below ;

- Amount of the liquid expelled depends almost only to the initial pressure ratio , its dependence to the area of opening ratio is minimal and positive as to be expected.

- Void fraction of the mixture left in the vessel too depends on the initial pressure ratio only and as expected its dependence to the area of the opening ratio is minimal.

- The two dimensionless number that were created , not by the evaluation of the results but as ordinary dimensionless numbers are;

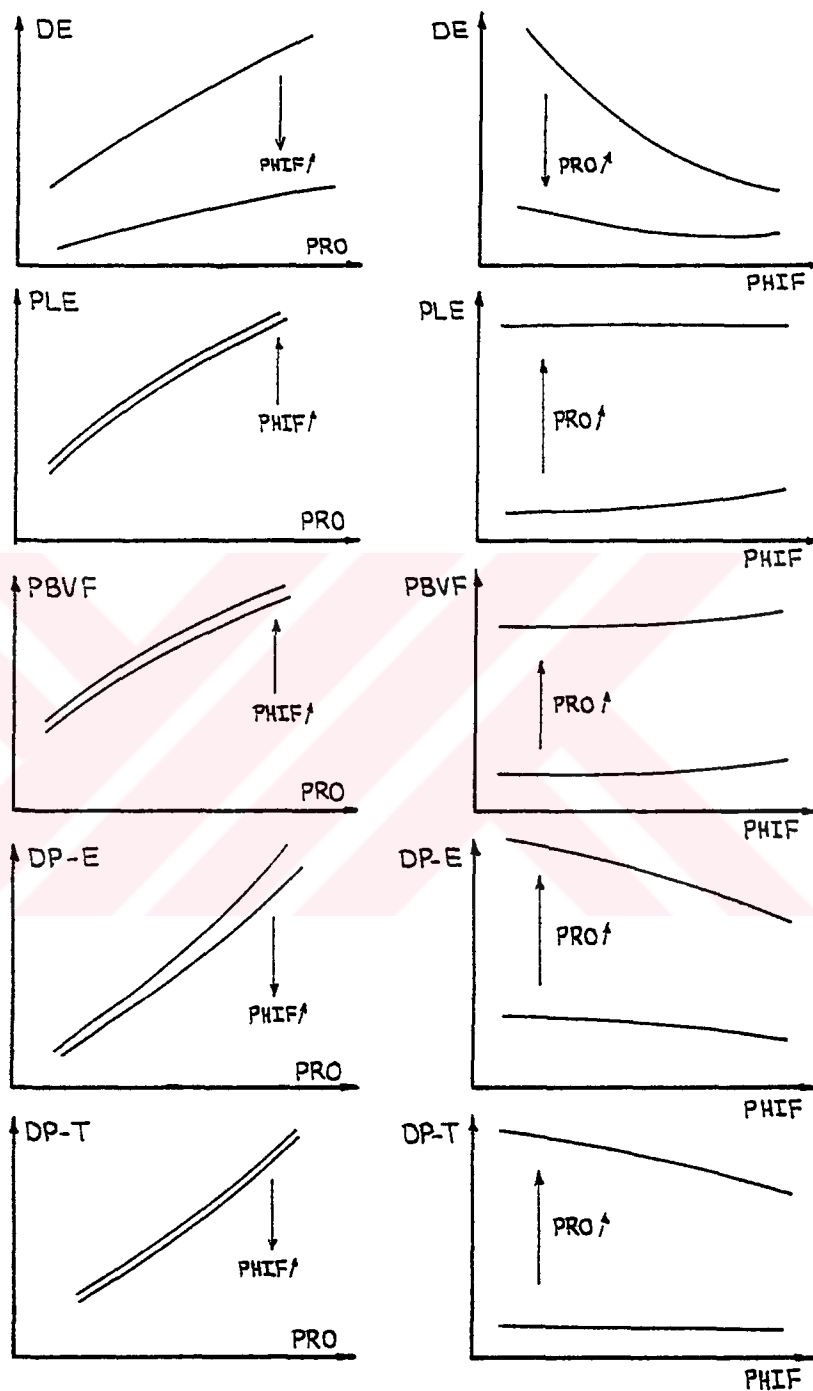


Fig. 10-1 Interaction Between the Main Full Vessel Case Parameters.

DE : Duration of expulsion. PLE : Percentage of liquid expelled.
 PBVF : Final, average void fraction ; percentage of initial value.
 PRO : Initial pressure ratio at the top of the vessel.
 PHIF : Final value of the area of the opening ratio.

$$DP-E = \frac{PHI}{PLE} \frac{DE}{HV} CVO \quad (10.1)$$

$$DP-T = \frac{AO}{VV} DE CVO \quad (10.2)$$

DE : Duration of expulsion. HV : Height of the vessel.
CVO : Initial mean speed of sound. VV : Volume of the vessel.
PHI : Area of the opening ratio. AO : Area of the opening.
PLE : Final value of the percentage of the liquid expelled.

These dimensionless numbers were considered against the principal parameters of the phenomena and it is observed that [App. K.1] the DP-T is a slightly better dimensionless number than the DP-E but none may be regarded good enough to elaborate on as.

Fig.10-1 summarizes the interaction between the five principal output quantities and the two principal input quantities of the FV case.

One full and three compact graphical examples of the FV case and eight pages of examples from the multi data run drawings of the type seen in Fig.10-1 are given in App.K.1.

10.1.2. The Non-Full Vessel Case.

Due to its quite different character than its simple sub case, the Full Vessel case ; first of all, in respect to the minimum job time requirement that can be up to a hundred times more for a comparable (in respect to initial pressure , void fraction, opening area ratio and the dimensions of the vessel) case ; no multi data run format was incorporated into the program for the non-full vessel case. As a result, the NFV case was not investigated as thoroughly as its sub case as a subject of comparative study , but still , quite a lot of - no less than 30 - successful run were realized, many with full graphical output and from all corners of the data field - in ; pressure, void fraction and its distribution, the fullness ratio, opening area, and vessel dimensions - that would certainly enable to draw really informed conclusions.

Principal results of the examination of the NFV case output [App.K.2] may be listed as below ;

* The result of a NFV case run can be considerably distorted if the related data is not generous enough in respect to the required run time ; the minimum starting value for the number of calculation steps is about 50 and the SF calculations also require at least 20 calculation nodes for reasonable functioning.

* The initial stage of the expulsion of gas usually takes only about one tenth or less of the duration of expulsion - but higher in job time due to high number of calculation nodes employed - .

* At the expulsion of mixture (Full Vessel - SF) calculations part of the duration of expulsion, time step value shows twice as many drops and peaks as there are pressure peaks at a node , for example at the open end. At the instants corresponding to the creation and reflection - at both ends - of the SF, time step drops to a fraction of the normal value , for small number of steps but still it is the main reason for its requirement of unproportionally long job time compared with its FV sub case.

* The effect of the strong throttling at the NFV to FV transformation stage asserts itself on the time history of pressure change very much , but still ; under normal conditions , the highest pressure peak , the first peak of the instant of transformation, can only reach about half of the initial pressure or may be just slightly higher. That is , not the value of the peak pressure itself but the speed of its creation may need to be taken into account as the principal design parameter.

* Under normal conditions , and most probably never ; nowhere in the vessel and at no stage of the duration of expulsion , the pressure can drop high enough to start cavitation in water and the liquids of similar character ; which would create considerable errors for long duration, controlled relief calculations. Especially for low initial pressure and high area ratio cases , pressure at the closed end can drop considerably ; that is cavitation problem may arise in the case of some volatile liquids but can hardly effect the overall behaviour due to its small share in already very small time scale of the phenomena.

* The runs with the data corresponding to the QSS solution for the critical mixture height for no expulsion [App.C.3] , was proved

that , with only a couple of percentage points error on the negative side , the QSS equation holds and that the difference can not create an expulsion equivalent of more than one percent of the initial volume of the mixture.

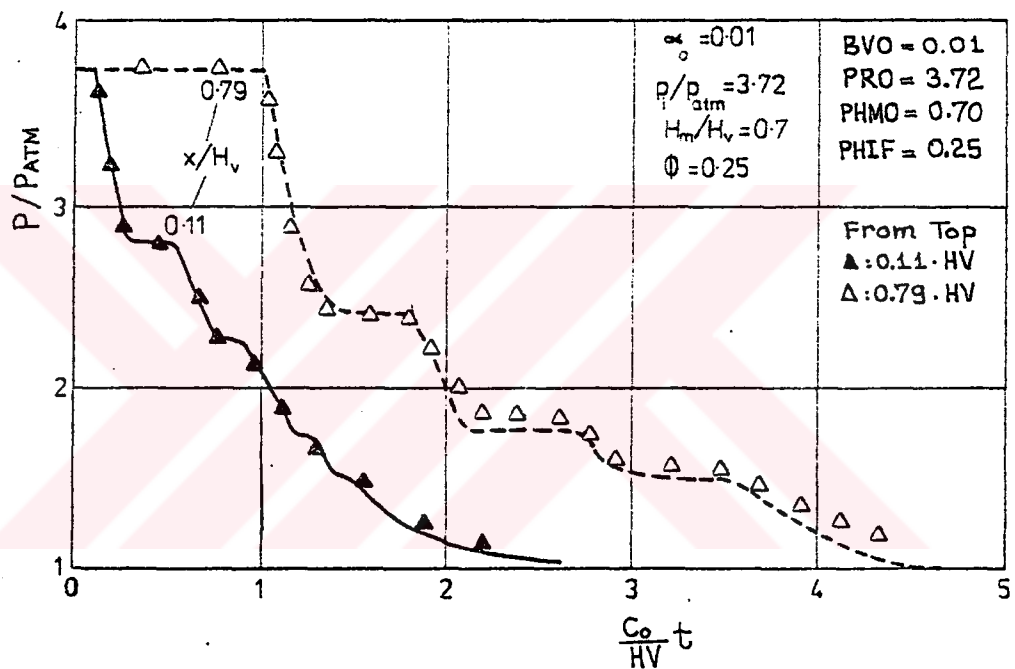
Two full graphical examples of the NFV case are given in App.K.2 with lists of their principal input and output parameters.

10.2. CHECKING THE RESULTS.

Although absolutely no question mark was raised for the integrity of the MC calculation routines , the Pressurized Gas Bottle Case was incorporated into the programme specifically for the purpose of being able to check the general format of the MC calculations. But, although most of the probable sources - the books on computational fluid / gas dynamics - were checked and a literature survey was carried out but no comprehensive source of time history of gas expulsion from a pressurized vessel - experimental or computational - was found for anywhere near a full comparison. More than tree decades old book of Rudinger [53] from the pre-computational science times , and a couple of again very limited source [54] that can be no real help at all were the only sources. However limited, the available data were checked against the full time history output of the programme and good agreement was observed.

Though a couple of papers that according to their names are about bubbly liquid blowdown but actually quite unrelated were found [55,56], no experimental or computational work have been accessed to other than the one of Fahmy [57] that would enable to check Full Vessel or Non-Full Vessel case results. This source too does not contain a time history of expulsion study for the FV case and there is just one and rather basic example for the NFV case. (The vessel of the experiments was pipe like : $D=50$ [mm] , $L/D=36$) Due to the extremely poor quality of the both theoretical and computational side of the work, not much importance were given to the source but its experimental findings were fully checked against the programme.

Due probably to the enormous difficulties that can be encountered when experimenting with bubbly liquid mixtures under so fast transient conditions, the experimental data of [57] for the FV case form rather scattered bunch, that is only a general mean value fit could be sought. Checking up with this data showed good agreement with the results of the programme, for the amount of the contents expelled, the only quantity considered in [57].



(— : Computed & Δ : Experimental)

Fig. 10-2 NFV Case Time History Output of [57].

The sole experimental and computational output of [57] for the time history of a NFV case, is for very low initial void fraction and pressure ratio case that may not require to be computed with SF calculations (Fig. 10-2). Experimental data for the point near the top - taken as the top point - shows a good fit but not the one near the bottom (Most probably due to buoyancy effect, the void fraction near the bottom dropped much below the already low value and distorted the results considerably. The computational results were not found dependable enough and were not considered.

Somewhat related literature on the safety aspects of the nuclear energy industry cite some test cases concerning expulsion of boiling water (as bubbly liquid) from burst, hot and pressurized water transport lines [14] that obviously are totally unsuitable for testing the programme under consideration.

10.3. RECOMMENDATIONS.

The recommendations will be considered under three parts according to their character.

10.3.1. Recommendations for Improved Accuracy.

Recommendations for the improvement of the programme as it stands, are all on the parts of the programme that use experimental or otherwise research data. As a result of the good programming principles that were followed, all of the related improvements require changes or additions to only one routine of the programme.

- * When - and if - a comprehensive and consistent slip - and rate of acceleration - ratio equation is available , it can be incorporated into the programme through corrections and additions to the routine SMCUAP which handles the characteristic directions calculations - and for best results also in SMCBOR - . Obviously it is not a strait forward job and the general format of the MC equations needed to be studied carefully.

- * New and improved equations for the rate of flow of expulsion of bubbly liquids through standard expulsion elements can be added to the programme through simple additions to the routine SMED only.

- * When available , rate of flow coefficients data specific to the flow of bubbly liquid mixtures through standard expulsion elements can be installed over the ones for single phase fluid by simple replacement work in the routine SFCDN only.

- * Improved wall friction coefficient data for the flow of bubbly liquid mixtures can be easily added to the programme through the routine SCFM only.

- * Improved speed of sound relations can be incorporated into

the programme by simple additions to the routine FSWP only.

Some of the improvements mentioned above may require an additional data file parameter at least for choice between the old and new format for which a suitable space can be found in the data files or a new line of the standard format can be added.

10.3.2. Recommendations for Further Investigation.

Checking the program against all available data of the case , experimental or computational, that especially contain time history information is certainly the first recommendation as it has not been done properly due to lack of data.

Further investigation on the subject and with the programme as it is, may on whole have just one simple aim ; production of better equations for the amount of mixture / liquid expelled , the critical height for no expulsion and the duration of expulsion than that of the QSS solution offer. The QSS solution must be considered as the base and only through it that a correlation between the results of at least 100 (300 recommended) and high quality runs of the program should be sought. Seeking a correlation for the non QSS characteristics of the phenomena , such as on the level of the pressure jump at NFV to FV transformation throttling, must be a much more difficult job.

The FV case does not require any computational work for the study mentioned above as the multi data format has already been incorporated into the programme for the case. But for the NFV case , first of all , a proper multi data run format , as a new case with its own data file must be incorporated into the program which is not an easy task and should never been attempted without studying the FV Multi Data case thoroughly and carefully.

At least for the NFV case , proper accomplishment of the study mentioned above require a lot of run time that may only be available at computing centers with super computers. And as the program was checked quite comprehensively , the multi data runs may be done with the highest level of code optimization for run time savings.

Full analysis of the sources of errors through the

discrepancies of the results of the multi data runs with sets of data of poor and rich job parameters will certainly improve the knowledge on the subject.

10.3.3. Recommendations for Enlargements.

Two ways of enlargement or rather conversion of the programme may be considered.

- * The enlargements that aim to cover the cases as they are but more comprehensively in respect to the physical conditions.

- * The enlargements or rather transformations into a format that cover the fluids -liquids- that initially not bubbly but when de-pressurized acquire considerable bubbly character.

The program can be enlarged to cover , for example , the case that the vessel contain one or more screens in it for slowing down the transient effects and the passages in these screens can be established in such a way that the flow field would be axisymmetrical and that the polar coordinates needed to be used. This case may not be solved through standard application of the MC and certainly require a lot of creative effort in both theoretical and computational fields.

Transformation of the program to the format that allow to work with subcooled / cryogenic and / or superheated fluids require considerable enlargements but the process may be considered rather straightforward as the additional parameters of heat (and mass) transfer will fit into the established MC calculations formats and the principles of the theoretical background are given in the text and are well established in most respects.

END OF CHAPTER 10

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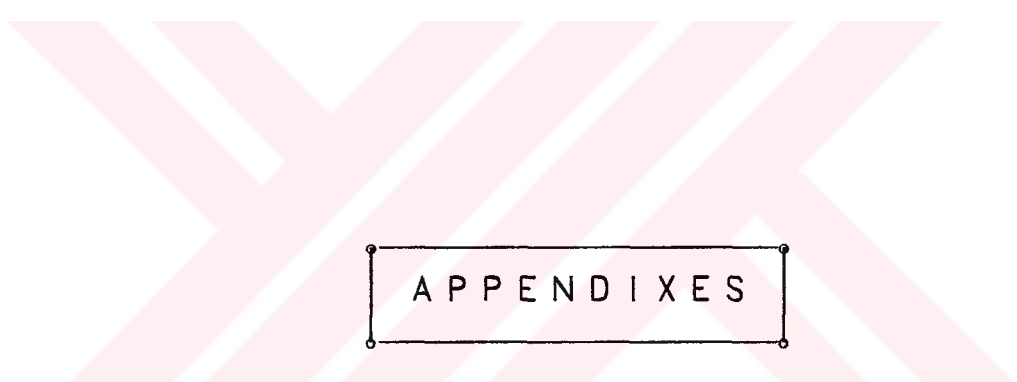
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APPENDIXES

A P P E N D I X - A

M U L T I - P H A S E F L O W Q U A N T I T I E S

A.1. DEFINITION OF THE NON - DIMENSIONAL QUANTITIES.

- β : Void Fraction / Volumetric Concentration.
Volume percentege of the disphersed phase -bubbles-.
- β_B : Phasic void fraction of the Bubbles ; the gas phase.
- β_L : Phasic void fraction of the Liquid.
- α : Volume Ratio / Volume Fraction.
Ratio of the volume of the dispersed phase -bubbles- to the volume of the continuous phase -liquid-.
- μ : Mass Ratio / Mass Fraction.
Ratio of the rate of flow of the dispersed phase -bubbles- to that of the continuous phase -liquid-.
- χ : Quality / Mass Quality. Ratio of the mass flow rate of the dispersed phase -bubbles- to that of the whole mixture.
- r : Slip / Slip Ratio ; Holdup / Holdup Ratio.
Ratio of the phase velocity of the dispersed phase -bubbles- to that of the continuous phase -liquid-.
- s : Acceleration Ratio. Ratio of the acceleration of the distri-
buted phase to that of the continuous phase.

A.2. DEFINITION EQUATIONS OF THE NON-DIMENSIONAL QUANTITIES.

$$\beta = \frac{V_B}{V_M} = \frac{V_B}{V_B + V_L} = \frac{1}{1 + V_L / V_B} \quad ; \quad \beta_B = \frac{V_B}{V_M} \quad ; \quad \beta_L = \frac{V_L}{V_M} \quad (A.1)$$

$$\beta_B + \beta_L = 1 \quad ; \quad \beta_B = \beta \quad ; \quad \beta_L = 1 - \beta \quad (A.2)$$

$$\alpha = \frac{V_B}{V_L} = \frac{V_B}{V_M - V_B} = \frac{1}{V_M / V_B - 1} = \frac{1}{1 / \beta - 1} = \frac{\beta}{1 - \beta} \quad (A.3)$$

$$\mu = \frac{M_B}{M_L} = \frac{\rho_G [Q_B = (A_B = \beta_B A) u_B]}{\rho_L [Q_L = (A_L = \beta_L A) u_L]} = \frac{\beta}{1 - \beta} \frac{\rho_G}{\rho_L} r \quad (A.4)$$

$$\chi = \frac{M_B}{M_M} = \frac{M_B}{M_B + M_L} = \frac{M_B / M_L}{1 + M_B / M_L} = \frac{\mu}{1 + \mu} = \frac{1}{1 + 1 / \mu} \quad (A.5)$$

$$r = \frac{u_B}{u_L} = \frac{[Q_B = M_B / \rho_G] / [A_B = \beta_B A]}{[Q_L = M_L / \rho_L] / [A_L = \beta_L A]} = \mu \frac{1 - \beta}{\beta} \frac{\rho_L}{\rho_G} \quad (A.6)$$

A.3. RELATIONS BETWEEN THE NON-DIMENSIONAL QUANTITIES.

$$\beta = \frac{\alpha}{1 + \alpha} = \frac{1}{1 + \frac{r}{\mu} \frac{\rho_G}{\rho_L}} = 1 - \frac{r}{1 + \mu} \frac{\rho_M}{\rho_L} = \frac{r}{r + \mu} \frac{\rho_M}{\rho_G} \quad (\text{A.7})$$

$$\beta_B + \beta_L = 1 \quad ; \quad \beta_B = \beta \quad ; \quad \beta_L = 1 - \beta \quad (\text{A.8})$$

$$\beta_L = 1 - \beta = \frac{1}{1 + \alpha} = \frac{1}{1 + \frac{\mu}{r} \frac{\rho_L}{\rho_G}} = \frac{r}{1 + \mu} \frac{\rho_M}{\rho_L} = 1 - \frac{\mu}{r + \mu} \frac{\rho_M}{\rho_G} \quad (\text{A.9})$$

$$\alpha = \frac{\beta}{1 - \beta} = \frac{\mu}{r} \frac{\rho_L}{\rho_G} = \frac{1}{\frac{1}{1 - \frac{r}{\mu} \frac{\rho_M}{\rho_L}} - 1} = \frac{\mu / r}{\frac{r + \mu}{\rho_M / \rho_G} - \mu} \quad (\text{A.10})$$

$$\mu = \frac{\beta}{1 - \beta} \frac{\rho_G}{\rho_L} r = \left(\frac{\rho_M / \rho_L}{1 - \beta} - 1 \right) r = \frac{r}{\frac{1}{\beta} \frac{\rho_M}{\rho_G} - 1} = \frac{\chi}{1 - \chi} \quad (\text{A.11})$$

$$\chi = \frac{\mu}{1 + \mu} = \frac{1}{1 + \frac{1 - \beta}{\beta} \frac{\rho_L}{\rho_G} \frac{1}{r}} = \frac{1}{1 + \frac{1 / r}{\frac{\rho_M / \rho_L}{1 - \beta} - 1}} = \frac{1}{1 + \frac{1}{r} \left(\frac{1}{\beta} \frac{\rho_M}{\rho_G} - 1 \right)} \quad (\text{A.12})$$

$$r = \mu \frac{1 - \beta}{\beta} \frac{\rho_L}{\rho_G} = \frac{\mu}{\frac{1}{1 - \beta} \frac{\rho_M}{\rho_L} - 1} = \frac{\mu}{\frac{1}{\beta} \frac{\rho_M}{\rho_G} - 1} = \frac{\frac{1}{\beta} - 1}{\frac{1}{\chi} - 1} \frac{\rho_L}{\rho_G} \quad (\text{A.13})$$

A.4. SLIP RATIO TERMS EQUATIONS.

$$\frac{\mu}{r} = \frac{\beta}{1 - \beta} \frac{\rho_G}{\rho_L} \quad \Bigg| \quad \frac{r}{\mu} = \frac{1 - \beta}{\beta} \frac{\rho_L}{\rho_G} \quad (\text{A.14})$$

$$\frac{r + \mu}{r} = \frac{1}{1 - \beta} \frac{\rho_M}{\rho_L} = 1 + \frac{\beta}{1 - \beta} \frac{\rho_G}{\rho_L} \quad \Bigg| \quad \frac{r + \mu}{\mu} = \frac{1}{\beta} \frac{\rho_M}{\rho_G} = 1 + \frac{1 - \beta}{\beta} \frac{\rho_L}{\rho_G} \quad (\text{A.15})$$

$$\frac{r}{r + \mu} = (1 - \beta) \frac{\rho_L}{\rho_M} = \frac{1}{1 + \frac{\beta}{1 - \beta} \frac{\rho_G}{\rho_L}} \quad \Bigg| \quad \frac{\mu}{r + \mu} = \beta \frac{\rho_G}{\rho_M} = \frac{1}{1 + \frac{1 - \beta}{\beta} \frac{\rho_L}{\rho_G}} \quad (\text{A.16})$$

A.5. RELATIONS BETWEEN THE SPECIFIC MASS QUANTITIES.

$$\rho_M = \beta_G \rho_G + \beta_L \rho_L \quad ; \quad \beta_G = \beta \quad \& \quad \beta_L = 1 - \beta \quad (A.17)$$

$$\rho_M = \beta \rho_G + (1 - \beta) \rho_L = \rho_L - (\rho_L - \rho_G) \beta \quad (A.18)$$

$$\rho_M = \frac{r + \mu}{r} (1 - \beta) \rho_L = \frac{r + \mu}{\mu} \beta \rho_G = \frac{r + \mu}{\frac{r}{\rho_L} + \frac{\mu}{\rho_G}} \quad (A.19)$$

$$\rho_M = \frac{r + \mu}{1 + \mu \frac{\rho_G}{\rho_L}} \rho_L = \frac{1 + \frac{\mu}{r}}{1 + \frac{\mu}{r} \frac{\rho_L}{\rho_G}} \rho_L = \frac{1 + \frac{\beta}{1 - \beta} \frac{\rho_G}{\rho_L}}{\frac{1}{r} + \frac{\beta}{1 - \beta}} \rho_L \quad (A.20)$$

$$\rho_M = \frac{r + \mu}{\mu} \beta = \beta + (1 - \beta) \frac{\rho_L}{\rho_G} = \frac{r + \mu}{\frac{r}{\rho_L / \rho_G} + \mu} \rho_G \quad (A.21)$$

$$\rho_L = \frac{r}{r + \mu} \frac{1}{1 - \beta} \rho_M = \frac{\beta}{1 - \beta} \frac{r}{\mu} \rho_G = \frac{1}{\frac{r + \mu}{\rho_M} - \frac{\mu}{\rho_G}} \quad (A.22)$$

$$\rho_G = \frac{\mu}{r + \mu} \frac{1}{\beta} \rho_M = \frac{1 - \beta}{\beta} \frac{\mu}{r} \rho_L = \frac{1}{\frac{r + \mu}{\mu} \frac{1}{\rho_M} - \frac{r}{\mu} \frac{1}{\rho_L}} \quad (A.23)$$

$$\frac{\rho_L}{\rho_G} = \frac{\beta}{1 - \beta} \frac{r}{\mu} = \frac{1}{\frac{r + \mu}{\rho_M} - \mu} = \frac{r + \mu}{\mu} \frac{\rho_L}{\rho_M} - \frac{r}{\mu} \quad (A.24)$$

$$\frac{\rho_G}{\rho_L} = \frac{1 - \beta}{\beta} \frac{\mu}{r} = \frac{r + \mu}{\rho_M / \rho_G} - \mu = \frac{1}{\frac{r + \mu}{\mu} \frac{\rho_L}{\rho_M} - \frac{r}{\mu}} \quad (A.25)$$

$$\frac{\rho_M}{\rho_L} = \frac{r + \mu}{r} (1 - \beta) = 1 - \left(1 - \frac{\rho_G}{\rho_L}\right) \beta = \frac{1 + \frac{r}{\mu}}{\frac{\rho_L}{\rho_G} + \frac{r}{\mu}} \quad (A.26)$$

$$\frac{\rho_M}{\rho_G} = \frac{r + \mu}{\mu} \beta = \beta + (1 - \beta) \frac{\rho_L}{\rho_G} = \frac{r + \mu}{\frac{\rho_G}{\rho_L} r + \mu} \quad (A.27)$$

A P P E N D I X - B

P R I N C I P A L R E L A T I O N S

B.1. PRESSURE FIELD EQUATIONS.

Equation of the pressure field in bubbly liquids ;

Polytropic law for the gas in the bubble ;

The equation of state for the gas ;

$$\frac{p_g}{\rho_g^n} = \text{Cst.} \quad (\text{B.1})$$

The surface tension effect equation ;

$$p_g - p_l = \frac{2 \sigma}{R} \quad (\text{B.2})$$

Equation of state for bubbly-liquid mixtures of not very small bubbles of ideal gases [with Eqn.(A.23)] ;

$$\frac{\beta}{1 - \beta} \frac{r}{\mu} \left(p + \frac{2 \sigma}{R} \right)^{1/n} = \text{Cst.} \quad (\text{B.3})$$

- * For not too small bubbles , the surface tension effect can be omitted and uniform pressure field may be assumed.
 $D = 2 R \geq 1 \text{ [mm]} : 2 (\sigma / R) \approx 300 \text{ [Pa]} = 3 \cdot 10^{-3} \text{ [Atm]}$
 Result : $p_{\min} \approx 2 \text{ [Atm]} / [2 (\sigma / R)]_{\max} \approx 3 \cdot 10^{-3} \geq 500$
- * For not too heavily accelerated flows (all accept a small region near the open end for the case under consideration), the slip effect may be omitted ; $r \approx 1$
- * For steady or quasi-steady flows , mass ratio may be taken as a constant ; $\mu \approx \text{Cst.}$
- * The simplified state equation may be written as below ;

$$\frac{\beta}{1 - \beta} p^{1/n} = \text{Cst.} \quad (\text{B.4})$$

B.2. VOID FRACTION - PRESSURE RELATIONS.

Void fraction - pressure relation in bubbly liquids of not very small bubbles is of interest for many related equations. When the surface tension effect is omitted , the Equation of State [Eqn.(B.3)] may be put into the form given below ;

$$\beta = \frac{1}{1 + \frac{1 - \beta_o}{\beta_o} \frac{r / \mu}{r_o / \mu_o} \left(\frac{p}{p_o} \right)^{1/n}} \quad (\text{B.5})$$

For fairly steady - constant mass ratio - flows ; $\mu \approx \text{Cst.}$

$$B = \frac{1 - \beta_o}{\beta_o} \frac{1}{r_o p_o^{1/n}} \quad ; \quad \beta = \frac{1}{1 + B r p^{1/n}} \quad (\text{B.6})$$

B.3. MIXTURE DENSITY AND PRESSURE HEAD RELATIONS.

From Eqn. (A.26) and Eqn. (B.6), $\rho_m = \rho_m(p_m)$ & $p_m = p_m(\rho_m)$;

$$\left(B = \frac{1 - \beta_o}{\beta_o} \frac{1}{r_o p_o^{1/n}} \right) \quad \rho_m = \frac{1 + \frac{\mu}{r}}{1 + \frac{1}{B r p_m^{1/n}}} \rho_l \quad (\text{B.7})$$

$$p_m = \left[\frac{1}{B r} \frac{1}{\left(1 + \frac{\mu}{r} \right) \frac{\rho_l}{\rho_m} - 1} \right]^n = \left[\frac{1}{B r} \left(\frac{1}{\beta} - 1 \right) \right]^n \quad (\text{B.8})$$

Pressure head - void fraction relationship ;

$$\frac{p_m}{\rho_m} = \frac{1}{\left(1 + \frac{\mu}{r} \right) r^n} \frac{\left(\frac{1}{\beta} - 1 \right)^n}{1 - \beta} \frac{1}{B^n \rho_l} \quad (\text{B.9})$$

Differential of the pressure head has a simple format ;

$$d \left(\frac{p_m}{\rho_m} \right) = \left(1 - \frac{1}{n} \right) \frac{d p_m}{d \rho_m} \quad (\text{B.10})$$

B.4. SPECIFIC MASS QUANTITIES AND PRESSURE RELATIONS.

Specific mass of a compressible liquid and an ideal gas ;

$$\frac{dp}{K} = - \frac{d\rho_l}{\rho_l} \quad ; \quad \rho_l = \rho_{l_o} \exp \left(\frac{p - p_o}{K} \right) \quad (\text{B.11})$$

$$\frac{p_g}{\rho_g^n} = \frac{p_{g_o}}{\rho_{g_o}^n} = Z \quad ; \quad \rho_g = \left(\frac{p_g}{Z} \right)^{1/n} \quad (\text{B.12})$$

The descriptive equation of the specific mass of a mixture ;

$$\rho_m = \beta \rho_g + (1 - \beta) \rho_l \quad (\text{B.13})$$

From Eqns.(B.11) to (B.13); for not too small and isothermally behaving bubbles ;

$$\rho_m = \frac{r + \mu}{\frac{\mu Z}{p + \frac{2\sigma}{R}} + \frac{r}{\rho_{l_0}} \exp \left(\frac{p_0 - p}{K} \right)} \quad (\text{B.14})$$

B.5. IMPLICIT BALANCE EQUATION FOR A SMALL BUBBLE.

Mass of the gas in the bubble is constant ;

$$m_b = \rho_g v_b = \rho_{g_0} v_{b_0} \quad ; \quad m_b = \frac{4}{3} \pi R^3 \rho_g \quad (\text{B.15})$$

$$\frac{p_g}{\rho_g^n} = \frac{p_{g_0}}{\rho_{g_0}^n} = Z \quad ; \quad \rho_g = \left(\frac{p_g}{Z} \right)^{1/n} \quad ; \quad p_g = p_l + \frac{2\sigma}{R} \quad (\text{B.16})$$

The equation of bubble radius, [Eqn.(B.14)] ;

$$R = \frac{2\sigma}{\frac{\mu Z}{\frac{r + \mu}{\rho_m} - \frac{r}{\rho_{l_0}} \exp \frac{p_0 - p}{K}} - p} \quad (\text{B.17})$$

The implicit balance equation of a small bubble ($n \approx 1$) ;

$$\frac{\theta}{\psi} - \left(\frac{\xi}{\psi} - p \right)^3 = 0 \quad ; \quad p = \frac{\xi}{\psi} - \left(\frac{\theta}{\psi} \right)^{1/3} \quad (\text{B.18})$$

$$\theta = \frac{32 \pi \mu \sigma^3}{3 m_b} \quad ; \quad \psi = \frac{r + \mu}{\rho_m} - \frac{r}{\rho_{l_0}} \exp \left(\frac{p_0 - p}{K} \right) \quad ; \quad \xi = \mu Z \quad (\text{B.19})$$

B.6. PRESSURE AND SPECIFIC MASS RATIOS.

Pressure and specific mass ratio terms expressed with the temperature change are of interest for SF calculations ;

$$\frac{\rho_{m_1}}{\rho_{m_2}} = \left[1 + (1 - \beta_1) X_P + \beta_1 X_T \right] \left(\frac{p_1}{p_2} \right)^{1/n} \quad (\text{B.20})$$

$$\frac{p_1}{p_2} = \left[\frac{\frac{\rho_{m1}}{\rho_{m2}} - (1 - \beta_1)}{\beta_1 X_T} \right]^n \quad (\text{B.21})$$

$$X_P = \left(\frac{p_1}{p_2} \right)^{1/n} - 1 \quad ; \quad X_T = \frac{T_2}{T_1} - 1 \quad (\text{B.22})$$

$$\frac{1 - \beta_1}{1 - \beta_2} = \frac{1 + \mu_2}{1 + \mu_1} \frac{\rho_{m1}}{\rho_{m2}} \approx \frac{\rho_{m1}}{\rho_{m2}} \quad (\text{B.23})$$

Isothermal behavior ; $n \approx 1$, $T_2 = T_1$

$$\frac{\rho_{m1}}{\rho_{m2}} \approx 1 + \beta_1 \left[\left(\frac{p_1}{p_2} \right)^{1/n} - 1 \right] \approx \frac{1 - \beta_1}{1 - \beta_2} \quad (\text{B.24})$$

$$\frac{p_1}{p_2} \approx \left[\frac{\frac{\rho_{m1}}{\rho_{m2}} - (1 - \beta_1)}{\beta_1} \right]^n \approx \left[\frac{1 + \beta_1 \beta_2}{(2 - \beta_1)(1 - \beta_2)} \right]^n \quad (\text{B.25})$$

Void fraction at the front of an SF ;

$$\beta_1 = \frac{\frac{\rho_{m1}}{\rho_{m2}} - 1}{\frac{p_1}{p_2} - 1} \quad (\text{B.26})$$

B.7. BASIC SHOCK FRONT EQUATIONS.

The basic SF equations listed below can easily be extracted from the SF conservation equations. [Eqns. (6.5) & (6.6)]

$$v = u + |U| \quad (\text{B.27})$$

$$v_1 = u_1 + |U| \quad ; \quad v_2 = u_2 + |U| \quad (\text{B.28})$$

$$U = \mp \frac{\rho_1 u_1 - \rho_2 u_2}{\rho_2 - \rho_1} \quad (\text{B.29})$$

$$(u_1 - u_2)^2 = \left(\frac{1}{\rho_1} - \frac{1}{\rho_2} \right) (p_2 - p_1) \quad (\text{B.30})$$

$$v_2^2 - v_1^2 = \left(\frac{1}{\rho_1} + \frac{1}{\rho_2} \right) (p_2 - p_1) \quad (\text{B.31})$$

$$v_1 = \mp \frac{V}{\rho_1} \quad ; \quad v_2 = \mp \frac{V}{\rho_2} \quad (\text{B.32})$$

$$V = \left[\frac{p_2 - p_1}{\frac{1}{\rho_1} - \frac{1}{\rho_2}} \right]^{1/2}$$

$$C_1^2 = \frac{n}{\beta_1} \frac{p_1}{\rho_1} = \frac{1 - \frac{\rho_1}{\rho_2}}{\frac{p_2}{p_1} - 1} \frac{n}{\beta_1} v_1^2 \quad (\text{B.33})$$

$$M_1^2 = \left(\frac{v_1}{C_1} \right)^2 = \frac{1 - \frac{\rho_1}{\rho_2}}{1 - \frac{\rho_1}{\rho_2}} \frac{\beta_1}{n} \frac{p_2}{p_1} \quad (\text{B.34})$$

END OF APPENDIX B

APPENDIX - C

RELATED KNOWLEDGE

C.1. THERMODYNAMIC BEHAVIOUR OF GAS BUBBLES IN A LIQUID.

Bubbles in a liquid pulsate under body forces due to changes in the pressure field which very much effects the thermodynamic behaviour of the gas in them.

Criteria on the thermodynamic behaviour of the gas has to be based on observations as the theoretical efforts have not produced firm results. A simple criteria has been put forward (Plesset[39]) ; ratio of heat that can be transferred from the liquid to the gas in the bubble and the heat required to increase the temperature of the gas by an amount during a compression half-cycle ;

$$\frac{q_l}{q_g} = \frac{(S_B = 4 \pi R^2) \rho_l C_l \sqrt{\frac{h_{Tl}}{\omega}} \Delta T}{(V_B = \frac{4}{3} \pi R^3) \rho_g C_g \Delta T} = \frac{K}{\sqrt{f} R} \quad (R[\text{mm}]) \quad (\text{C.1})$$

$$K_{\text{Water Air}} = 3.75 h_{Tl} \frac{\rho_l / \rho_{g_o}}{p / p_{At}} \approx 10 p \quad (p[\text{Atm}])$$

$$\left(\begin{array}{c} \text{Adiabatic} \\ \text{Behaviour} \end{array} \right) 1 \gg \frac{q_l}{q_g} \approx \frac{10 p}{\sqrt{f} R} \frac{[\text{Atm}]}{[\text{mm}]} \gg 1 \left(\begin{array}{c} \text{Isothermal} \\ \text{Behaviour} \end{array} \right) \quad (\text{C.2})$$

The simplest condition for the isothermal behaviour may be set as ;

$$R [\text{mm}] \ll \frac{100}{\sqrt{f}} \quad \& \quad f \ll \frac{10^4}{\sqrt{R}} \left(\begin{array}{c} \text{Isothermal} \\ \text{Behaviour} \end{array} \right) \quad (\text{C.3})$$

With non-uniform bubble interior assumption it is shown that, for very high frequencies too, isothermal behaviour is possible (Plesset & Hsieh [40]). The wavelength is also an important parameter ; if it is small in comparison with the average bubble size , isothermal behaviour and homogeneous mixture assumptions can be made.

Table (C.1) is the summary of the best regarded criteria of bubble behaviour and uses the characteristic lengths defined below. These criteria are found valid for the forced radial oscillation cases too (Prosperetti [41]). ($\omega = 2 \pi f$)

$$\left(\begin{array}{c} \text{Wave} \\ \text{Length} \end{array} \right) l_w = \frac{C_g}{\omega} \quad (\text{C.4})$$

$$\left(\begin{array}{c} \text{Thermal} \\ \text{Diffusion} \\ \text{Length} \end{array} \right) \quad \Lambda_g = \sqrt{\frac{h_{Tl}}{\omega}} \quad (C.5)$$

Some criterions use characteristic numbers with the dimension of time for the purpose (Nigmatulin & Khabaev [36]) ; Table (C.2) uses the characteristic times given below ;

$$\left(\begin{array}{c} \text{Pulsation} \\ \text{Time} \end{array} \right) \quad t_v = \frac{R_o}{dR_o/dt} \quad (C.6)$$

$$\left(\begin{array}{c} \text{Pressure} \\ \text{Equilization} \\ \text{Time} \end{array} \right) \quad t_p = \frac{R_o}{C_g} \quad (C.7)$$

$$\left(\begin{array}{c} \text{Temperature} \\ \text{Equilization} \\ \text{Time} \end{array} \right) \quad t_T = \frac{R_o^2}{h_g} \quad (C.8)$$

Table C-1. Behaviour of Gas Bubbles in Liquids in Terms of Characteristic Lengths.

Frequency Range	Length Comparison	The Criteria	Thermodynamic Behaviour	
Low	$R_o < \Lambda_g < l_w$	$\frac{\Lambda_l}{R_o} \gg 1$	Isothermal	(C.9)
Moderate	$\Lambda_g < R_o < l_w$	$\frac{\Lambda_g}{R_o} < 1$	Adiabatic	(C.10)
High	$\Lambda_g < l_w < R_o$	$\frac{\Lambda_g}{l_w} < 1$	Adiabatic	(C.11)
Very High	$l_w \ll \Lambda_g \ll R_o$	$\frac{\Lambda_g}{l_w} \gg 1$	Isothermal	(C.12)

Table C-2. Behaviour of Gas Bubbles in Liquids in Terms of Characteristic Times.

$$t_p \ll t_v : \frac{dR_o}{dt} \ll C_g : \left(\begin{array}{c} \text{Uniform Pressure} \\ \text{Field in Buuble.} \end{array} \right) \quad (C.13)$$

$$t_T \gg t_v : R_o \frac{dR_o}{dt} \gg h_g \approx R_o \gg \frac{h_g}{C_g} \left(\begin{array}{c} \text{Adiabatic} \\ \text{Behaviour} \end{array} \right) \quad (C.13)$$

$$t_T \ll t_v : R_o \frac{dR_o}{dt} \ll h_g \approx R_o \ll \frac{h_g}{C_g} \left(\begin{array}{c} \text{Isothermal} \\ \text{Behaviour} \end{array} \right) \quad (C.14)$$

With the data of water and air at atmospheric conditions ;

$$\left(\begin{array}{c} \text{Isothermal} \\ \text{Behaviour} \end{array} \right) R_o \gg \gg R_{Cr} = .06 [\mu m] \gg \gg R_o \left(\begin{array}{c} \text{Adiabatic} \\ \text{Behaviour} \end{array} \right) \quad (C.15)$$

The equation above dictates that, in all cases under consideration, behaviour of the bubbles may be taken as isothermal.

C.2. SLIP AND RELATIVE ACCELERATION RATIOS.

$$\text{Slip Ratio : } r = \frac{u_g}{u_l} \quad (C.16)$$

$$\text{Relative Acceleration Ratio : } s = \frac{du_g}{du_l} \quad (C.17)$$

Slip and acceleration ratios are not widely investigated due to the inherent problems of both theoretical and experimental studies.

It is found that the slip ratio may be related to a nondimensional number called the *Valensi* number " V " (Crespo [12]).

$$[\omega = \omega_{\nu_l=0} !] \quad V = \frac{\omega R_o^2}{\nu_l} \quad (C.18)$$

The table below summarizes the argument related with " V " ;

Table C-3. The Slip Effect Criteria with Valensi Number.

$$\sqrt{V} \ll 1 : r \approx 1 \quad \left\{ \begin{array}{l} \text{Low Frequencies , Isothermal Behaviour} \\ \text{Viscous Forces } \gg \text{ Inertia Forces} \\ \text{Viscous Forces Drag Bubbles With Liquid} \end{array} \right. \quad (C.19)$$

$$\sqrt{V} \gg 1 : r \approx 1 \quad \left\{ \begin{array}{l} \text{High Frequencies , Small Perturbations} \\ \text{Viscous Forces } \ll \text{ Inertia Forces} \\ \text{Inertia Forces Create Relative Acceleration} \end{array} \right. \quad (C.20)$$

For very small void fractions , the simplified theory produces the equation below for the slip ratio where Γ is a shape function ;

$$r = \frac{\Gamma + 2 (1 - \beta)}{\Gamma + 2 (1 - \beta) \frac{\rho_g}{\rho_l}} \quad (C.21)$$

For spherical bubbles; the shape function is equal to unity ;

$$(\Gamma = 1) \quad r = \frac{3 - 2\beta}{1 + 2(1 - \beta) \frac{\rho_g}{\rho_l}} \cong 3 - 2\beta \quad (C.22)$$

Much less can be said for the relative acceleration ratio ; experiments show that "s" principally is a consequence of void fraction variation within the pressure wave ; that is, it is most important for the transient flows (Baum & Horn [3]).

It is strongly argued that the value of s can not be more than the maximum slip ratio which is about three. The well accepted practice is to ignore the relative acceleration for ordinary flow cases as the ratio will be very near to unity.

C.3. QUASI - STEADY STATE (QSS) EXPANSION AND EXPULSION.

Imaginary, very slow, steady state like expansion - very slow depressurization , the whole volume behaves like a single body. No wave motion , no transient process , no acceleration , no slip.

Differential relation between the pressure and the void fraction ;

$$\frac{dp}{p} = \left[\frac{1 - \frac{\beta}{1 - \beta} \frac{d\beta}{\beta}}{1 + \frac{d\beta}{\beta}} \right]^n - 1 \quad ; \quad \frac{d\beta}{\beta} = \frac{1 - \left(1 + \frac{dp}{p}\right)^{1/n}}{\frac{\beta}{1 - \beta} + \left(1 + \frac{dp}{p}\right)^{1/n}} \quad (C.23)$$

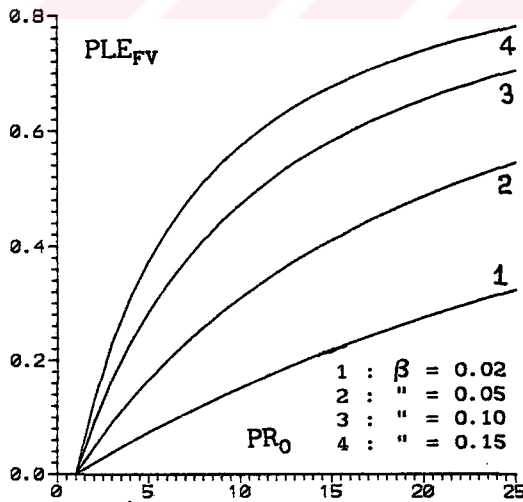


Fig. C-1. FV Case ; QSS ,
PLE - PR_0 Plot.

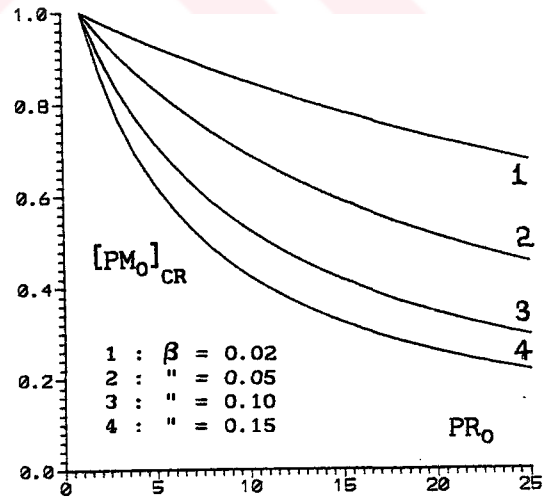


Fig. C-2. NFV Case ; QSS ,
[PM_0]_{CR} - PR_0 Plot.

QSS calculations are evaluated through the two principal quantity listed below and separately for the NFV and FV cases.

QSS Expansion : Volume of the mixture at the end of the expulsion.

QSS Expulsion : Total percentage of the mixture expelled.

Definitions ; $PR = p / p_{Atm}$ & $PLE = V_{Le} / V_{Lo}$

QSS Expansion :

$$\left[\beta = \frac{1}{1 + \frac{1}{\frac{\beta_o}{1 - \beta_o} PR_o^{1/n}}} \right] \quad V_m = \left[1 + (PR_o^{1/n} - 1) \beta_o \right] V_{m_o} \quad (C.24)$$

QSS Expulsion :

Percentage of Liquid Expelled ;

$$\text{Full Vessel Case ; } PLE = 1 - \frac{1}{1 + (PR_o^{1/n} - 1) \beta_o} \quad (C.25,A)$$

$$\text{Non-Full Vessel Case ; } PLE = 1 - \frac{1}{[1 + (PR_o^{1/n} - 1) \beta_o] PM_o} \quad (C.25,B)$$

NFV Case : The critical Percentage of Mixture (PM).

The critical initial content for no expulsion ;

$$(PM_o)_{PLE=0} \quad (PM_o)_{cr} = \frac{1}{1 + (PR_o^{1/n} - 1) \beta_o} \quad (C.26)$$

NFV Case : The Ratio of Expulsion (REX) is defined as below ;

$$REX = \frac{PM_o}{(PM_o)_{cr}} = \left[1 + (PR_o^{1/n} - 1) \beta_o \right] PM_o \quad \begin{cases} < 1 : \text{NO} \\ \text{Expulsion} \\ > 1 : \text{YES} \end{cases} \quad (C.27)$$

C.4. EQUATION OF RADIAL MOTION OF A BUBBLE IN A LIQUID.

Dynamic equation of the radial pulsations of a spherical bubble in a liquid and under a pressure field is considered. The well known Rayleigh equation of radial motion of a bubble in a liquid of ignorable viscosity and surface tension is (Knapp et.al. [25]) ;

$$\frac{p_l - p_\infty}{\rho_l} = R_o \frac{d^2 R_o}{dt^2} + \frac{3}{2} \left(\frac{dR_o}{dt} \right)^2 \quad (C.28)$$

The pressure on the bubble interface can be related to the pressure in the bubble with the equation below when the -in the order they appear- surface tension, viscosity and compressibility effects are considered (Flynn [16]) ;

$$p_i = p_l + \frac{2\sigma}{R_o} + 4 \frac{\mu}{R_o} \frac{dR_o}{dt} + \frac{4}{3} \frac{\mu_l}{C_{li}^2} \frac{dR_o}{dt} \frac{dH_{li}}{dt} \quad (C.29)$$

where H_{li} and C_{li} are the enthalpy and speed of sound at interface. C_{li} may be calculated through the experimental pressure - density relation of a liquid for isentropic compression ;

$$\left[\begin{array}{l} B \approx 3 \cdot 10^{-8} \text{ [Pa]} \\ m \approx 7 \text{ (Water)} \end{array} \right] \frac{p_l + B}{p_{l\infty} + B} = \left(\frac{\rho_l}{\rho_{l\infty}} \right)^m \quad \& \quad \frac{C_{li}}{C_{l\infty}} = \left(\frac{p_l + B}{p_{l\infty} + B} \right)^{\frac{m-1}{2m}} \quad (C.30)$$

The compressibility effect would be very small for even the extreme end of the cases under consideration. The complete equation of radial motion of a bubble may be given as below (Hsieh [22]) ;

$$R_o \frac{d^2 R_o}{dt^2} + \frac{3}{2} \left(\frac{dR_o}{dt} \right)^2 = \frac{p_g - p_{l\infty}}{\rho_l} - 2 \frac{\sigma_l}{\rho_l R_o} - 4 \frac{\nu_l}{R_o} \frac{dR_o}{dt} \quad (C.31)$$

The simple - no surface tension, viscosity or thermal effect - equation of the natural period of isothermal radial oscillations of a spherical gas bubble in a plain sound wave field is well known ;

$$t_o = \frac{2\pi}{\omega_o} = 2\pi R_{oEq1} \sqrt{\frac{\rho_l}{3 n p_{gEq1}}} \quad (C.32)$$

Isothermal frequency of oscillations of spherical gas bubbles, for the equilibrium values equal to the initial values is ;

$$f_{Iso} = \frac{\omega_{Iso}}{2\pi} = \frac{\sqrt{3}}{2\pi} \frac{1}{R_{o,o}} \sqrt{\frac{p_{g,o}}{\rho_l}} \quad (C.33)$$

Characteristic case example ;

$$\left. \begin{array}{l} (p_{g,o})_{min} \approx 1.5 \cdot 10^5 \text{ [Pa]} \\ (R_{o,o})_{max} \approx 3 \cdot 10^{-3} \text{ [m]} \\ \rho_l = 10^3 \text{ [Kg / m}^3\text{]} \end{array} \right\} : (f_o)_{min} \geq 1100$$

The example above, in a way, proves that under the conditions taken into account , there can not be any danger of resonance.

C.5. THE BUBBLY - LIQUID TWO - PHASE FLOW WALL FRICTION COEFFICIENT.

Except for the extreme cases that involve pipes rather than vessels, friction does not play an important role, in the flow of

bubbly - liquid two - phase mixtures.

Related literature contain only a couple of set of equations on the wall friction coefficient calculation for bubbly - liquid flows and the one most preferred by the researchers and the computer code developers was given by Hancox & Nicoll [19 & 20] and was employed in the programme. The formula ; like the others , gives a coefficient to be used with pure liquid -water- data which is calculated from the well known Colebrook & White equation with the starting value taken from the equation of Knudsen & Katz.

The pure liquid data calculation may be summarized as below ;

$$R_e = \frac{D u}{\nu_l / \rho_l} \begin{cases} < 1462.3 \\ \geq 1462.3 \end{cases} \begin{cases} f_l = 16 / R_e & : \text{Laminar Flow} \\ f_l = 0.46 / R_e^{0.2} & : \text{Turbulent} \end{cases} \quad (C.34)$$

$$f_l = [0.5 / \text{Log} (\chi)]^2 \quad (C.34,A)$$

$$\chi = [(\epsilon / D) / 3.71] + [2.513 / (R_e \sqrt{f_l})] \quad (C.34,B)$$

Hancox & Nicoll's quite complex correction coefficient calculation procedure is given below in an exact but simpler format rather than its original format used in the routine "SCFM".

$$f_m = K_m f_l \quad (C.35)$$

$$K_m = 1 + K_1 K_2 K_3 \quad (C.35,A)$$

$$K_1 = \left[\left(\frac{\nu_g}{\nu_l} \right)^{0.2} - (1 + Z) \right] \frac{Z}{Z + \beta} \quad (C.35,B)$$

$$K_2 = 1 + 3.57 / \exp (x) \quad (C.35,C)$$

$$K_3 = 1 - 1 / \exp (y) \quad (C.35,D)$$

$$Z = \frac{1}{\beta} \left(\frac{\rho_m}{\rho_l} - 1 \right) \quad (C.35,E)$$

$$x = 8.84 \cdot 10^{-3} \frac{\rho_m u}{(g \nu_l \rho_l^2 Z)^{1/3}} \leq 30 \quad (C.35,F)$$

$$y = 4.96 Z \left(\frac{1 - \beta}{Z + \beta} \right) \leq 30 \quad (C.35,G)$$

The limiting conditions on the "x" and "y" were strictly observed.

END OF APPENDIX C

APPENDIX - D

GEOMETRY OF THE VESSEL

The conditions imposed on the geometry of the vessel are basically the requirements of maintaining the one-dimensional flow assumption which in practice imposes the shapes resembling a tall rather than a barrel like cylinder [Chap. 1.3.1].

D.1. GENERAL CONDITIONS OF SHAPE.

The conditions need to be imposed on the shape of the vessel ;

- * Vessel should look " tube like " ; the aspect (Height to Mean Diameter) ratio must be considerably bigger than unity.
- * Vessel must have a straight axis of radial symmetry.
- * Vessel must have self similar cross sections along its axis.
- * Cross-sections must have at least two axis of symmetry, and the aspect ratio for all - non cylindrical - cross sections must be considerably close to unity.
- * Changes in the cross-section area must be smooth and limited. The ratio between the extreme values of the equivalent diameters of the cross-sections must be considerably close to unity.

D.2. THE CONDITIONS IMPOSED.

The shape of the vessel has necessarily been restricted to the circular cross-section area volumes that may be described as below ;

- * The general appearance of the vessel may be described as a two bellied vase with proportional measures.
- * The length of the vessel is divided into four regions, all with their own shape functions. It is possible to remove one or two of the regions for the creation of simpler shapes.

D.3. DEFINITION OF THE SHAPE OF THE VESSEL.

Enough information, with a very representative drawing, is provided in the routine " FSHV : Function SHape of the Vessel " for the easy use of the data file parameters related with the shape of the vessel. As non cylindrical shapes are of no real interest, only the basic shape functions information will be considered.

The shape functions of the regions are simple (linear) equations, and they perfectly satisfy the conditions at the boundaries at both ends.

From shape functions, the other necessary functions, namely ;

- Cross-section area change function.
- Rate of change of area function.
- Volume - from the bottom to a node - function.

are defined without any simplification.

END OF APPENDIX D

APPENDIX - E

"MC" APPLICATIONS

SAMPLE SET OF EQUATIONS

AND A

CALCULATION FORMAT EXAMPLE

The aim is to give a couple of examples from the main MC calculation cases only ; an elaborate guide, however good and orderly it is, would probably have no practical use at all. The program was prepared in as much intelligible format as it may be, but still it is not possible to distinguish for example the set of equations that govern a case or to follow the steps used to solve the set as easily as it can be done on a text.

The chapter has simple aims ; through the most basic cases , to show the level of completeness of the MC application and allow easy comparison with the basic format of the MC generally employed for the standard transient processes of applied fluid mechanics.

Two examples for the set of MC equations and one example for the solution of the set of MC equations are given. As all of the cases were made familiar enough in the main text, explanatory words are forsaken as much as possible. The notation employed in the programme were used as much as possible , that is the the MC grid formats given in Chap.7.3 are not followed exactly but the differences are very slight ; like employing capital letters and Latin alphabet equivalents for the Greek characters. The list of the characteristic quantities of a point given below should clear any question that may arise. For the point " X " ;

Velocity	: Ux	Void Fraction	: Bx
Speed of Sound	: Cx	Bubble Radius	: BRx
Pressure	: Px	Vessel Diameter	: Dx
Specific Mass - Mixture	: Rx	Cross-Section Area	: Ax
" " " - Bubble Gas	: Rbcx	Rate of Change of "A"	: DAX
Wall Friction Coef.-Mix.	: FM	Slope ; C[U+C] Char.	: S1
" " " " -Gas	: FG	" ; C[U-C] "	: S2
		" ; C[U] "	: S0
Pressure in the Bubble	: PBG	Index for Bubble Gas	: BN
" " " " Gas Region	: PG	" " Gas Region	: GN

The wall friction calculation routines ; Mix./Gas : SCFM / SCFG
The speed of wave propagation routine for the Mixture : FSWP

E.1. MC EQUATIONS ; ORDINARY POINTS IN THE MIXTURE.

Definitions of the characteristic lines , C^+ and C^- ;

$$(1) \quad C^+[U+C] : \quad \frac{DX}{DT} S1 = \frac{1}{2} [(U_A + C_A) + (U_B + C_B)]$$

$$(2) \quad C^-[U-C] : \quad \frac{DX}{DT} S2 = \frac{1}{2} [(U_A - C_A) + (U_C - C_C)]$$

Definitions of the characteristic quantities at B and C ;

$$(3) \quad C^+[U+C] : \quad S1 = \frac{Q_0 - Q_B}{Q_0 - Q_1} = \frac{A_0 R_0 U_0 - A_B R_B U_B}{A_0 R_0 U_0 - A_1 R_1 U_1}$$

$$(4-9) \quad S1 = \frac{\xi_0 - \xi_B}{\xi_0 - \xi_1} \quad \xi_B: P_B , B_B , BR_B , D_B , A_B , D_{AB}$$

$$(10) \quad C^-[U-C] : \quad S2 = \frac{Q_0 - Q_C}{Q_0 - Q_2} = \frac{A_0 R_0 U_0 - A_C R_C U_C}{A_0 R_0 U_0 - A_2 R_2 U_2}$$

$$(11-16) \quad S2 = \frac{\xi_0 - \xi_C}{\xi_0 - \xi_2} \quad \xi_C : P_C , B_C , BR_C , D_C , A_C , D_{AC}$$

$$(17-18) \quad R_{B/C} = EB P_{B/C}^{1/BN}$$

$$(19-20) \quad R_{B/C} = (1 - B_{B/C}) R_L + B_{B/C} R_{B/C}$$

$$(21-22) \quad C_{B/C} = FSWP (P_{B/C} , B_{B/C} , R_{B/C} , BR_{B/C} , D_{B/C})$$

MC equations for the characteristic lines C^+ and C^- ;

$$C^+ : \quad \frac{1}{\frac{R_B + R_A}{2} \frac{C_B + C_A}{2}} \frac{P_A - P_B}{DT} + \frac{U_A - U_B}{DT} + \frac{D_{AB} + D_{AA}}{A_B + A_A} \frac{U_B + U_A}{2} \frac{C_B + C_A}{2} \rightarrow$$

$$(23) \quad \rightarrow + \frac{FM}{D_B + D_A} \left| \frac{U_B + U_A}{2} \right| \frac{U_B + U_A}{2} + G \sin \theta = 0$$

$$C^- : \quad \frac{1}{\frac{R_C + R_A}{2} \frac{C_C + C_A}{2}} \frac{P_A - P_C}{DT} - \frac{U_A - U_C}{DT} + \frac{D_{AC} + D_{AA}}{A_C + A_A} \frac{U_C + U_A}{2} \frac{C_C + C_A}{2} \rightarrow$$

$$(24) \quad \rightarrow - \frac{FM}{D_C + D_A} \left| \frac{U_C + U_A}{2} \right| \frac{U_C + U_A}{2} - G \sin \theta = 0$$

Definition of the geometric quantities of the point ;

$$(25-27) \quad A_A = A_0 \quad ; \quad D_A = D_0 \quad ; \quad D_{AA} = D_{A_0}$$

Definition of the particle path characteristic C ;

$$(28) \quad C [U] : \quad \frac{DX}{DT} S0 = \frac{1}{2} (U_A + U_D)$$

$$(29) \quad S0 = \frac{Q0 - QD}{Q0 - Q1} = \frac{A0 R0 U0 - Ad Rd Ud}{A0 R0 U0 - A1 R1 U1}$$

$$(30-34) \quad S0 = \frac{\xi_0 - \xi_D}{\xi_0 - \xi_1} \quad \xi_D : P_D , B_D , BR_D , D_D , A_D$$

Conditions at the point D of the particle trace ;

$$(35) \quad R_{BG,D} = EB P_D^{1/BN}$$

$$(36) \quad R_D = (1 - B_D) R_L + B_D R_{BG,D}$$

$$(37) \quad C_D = FSWP (P_D , B_D , R_D , BR_D , D_D)$$

MC equation for the particle path line C ;

$$(38) \quad \frac{B_A - B_D}{DT} + \frac{1 - \frac{B_D + B_A}{2}}{\frac{R_D C_D^2 + R_A C_A^2}{2}} \frac{P_A - P_D}{DT} = 0$$

Characteristic quantities of the calculation point ;

$$(39) \quad \frac{P_A}{R_{BG,A}^{BN}} = \frac{P_0}{R_{BG,0}^{BN}}$$

$$(40) \quad R_A = R_L - (R_L - R_{BG,A}) B_A$$

$$(41) \quad BR_A = \left(\frac{P_A}{P_0} \right)^{\frac{1}{3 BN}} BR_0$$

$$(42) \quad C_A = FSWP (P_A , B_A , R_A , BR_A , D_A)$$

The wall friction coefficient calculation ;

$$(43) \quad FM = SCFM [Param]$$

Unknowns of the system of equations ;

A : $U_A , C_A , P_A , R_A , B_A , BR_A , D_A , A_A , D_{AA} , R_{BG,A} , FM$
 B : $U_B , C_B , P_B , R_B , B_B , BR_B , D_B , A_B , D_{AB} , R_{BG,B} , S1$
 C : $U_C , C_C , P_C , R_C , B_C , BR_C , D_C , A_C , D_{AC} , R_{BG,c} , S2$
 D : $U_D , C_D , P_D , R_D , B_D , BR_D , D_D , A_D , R_{BG,D} , S0$

There are 43 unknowns and the same number of independent equation. It is obvious that analytical solution is not possible but the numerical solution can be made as accurate as required.

E.2. MC EQUATIONS ; CONTACT SURFACE POINT.

Important points ;

- * Contact surface represents the particle trace which is the particle path characteristic.
- * Supersonic flow condition check is not required ; the gas can not drive the mixture to supersonic speeds.

Boundary condition ; pressure equilibrium on the surface ;

$$(0) \quad P_{S2} = P_{SM2} = P_{SG2}$$

Definitions of the characteristic lines , C^+ and C^- ;

$$(1) \quad C^+[U+C] : \quad \frac{DX}{DT} S1 = \frac{1}{2} [(U_{S2} + C_{SM2}) + (U_B + C_B)]$$

$$(2) \quad C^-[U-C] : \quad - \frac{DX}{DT} S2 = \frac{1}{2} [(U_{S2} - C_{SG2}) + (U_C - C_C)]$$

Definitions of the characteristic quantities at B and C ;

$$(3) \quad C^+ : \quad XCS1 = (S1 - DELX) / DS1X$$

$$(4) \quad XCS1 = \frac{Q_{SM1} - Q_B}{Q_{SM1} - Q_{L1}} = \frac{A_{S1} R_{SM1} U_{S1} - A_B R_B U_B}{A_{S1} R_{SM1} U_{S1} - A_{L1} R_{L1} U_{L1}}$$

$$(5-10) \quad XCS1 = \frac{\xi_{S1/SM1} - \xi_B}{\xi_{S1/SM1} - \xi_{L1}} ; \quad \xi_B : P_B, B_B, BR_B, D_B, A_B, D_{AB}$$

$$(11) \quad R_{BG,B} = E_B P_B^{1/BN}$$

$$(12) \quad R_B = (1 - B_B) R_L + B_B R_{BG,B}$$

$$(13) \quad C_B = FSWP (P_B , B_B , R_B , BR_B , D_B)$$

$$(14) \quad C^- : \quad Y = (DS1X + XDEL) + S2$$

$$(15) \quad XCS2 = Y - |Y|$$

$$(16-17) \quad LCSX = L1 + Y \quad LCSY = LCSX + 1$$

$$(18) \quad XCS2 = \frac{Q_{LCSX} - Q_C}{Q_{LCSX} - Q_{LCSY}} = \frac{(A R U)_{LCSX} - A_C R_C U_C}{(A R U)_{LCSX} - (A R U)_{LCSY}}$$

$$(19-22) \quad XCS2 = \frac{\xi_{LCSX} - \xi_C}{\xi_{LCSX} - \xi_{LCSY}} ; \quad \xi_C : P_C , D_C , A_C , D_{AC}$$

$$(23) \quad R_C = E_G P_C^{1/GN}$$

$$(24) \quad C_C = \sqrt{GN \frac{P_C}{R_C}}$$

The movement and the position of the CS ;

$$(25) \quad \text{DEL} = \frac{Us_1 + Us_2}{2} DT$$

$$(26) \quad \text{HM}_2 = \text{HM}_1 + \text{DEL}$$

$$(27) \quad L_2 = \left\lfloor \frac{\text{HM}_2}{DX} \right\rfloor + 1$$

$$(28) \quad \text{DS}_2 = \text{HM}_2 - (L_2 - 1) DX$$

MC equations for the characteristic lines , C^+ and C^- ;

$$(29) \quad \begin{aligned} C^+ : & \quad \frac{1}{\frac{R_B + R_{SM2}}{2} \frac{C_B + C_{SM2}}{2}} \frac{Ps_2 - P_B}{DT} + \frac{Us_2 - U_B}{DT} + \rightarrow \\ & \quad \rightarrow + \frac{DAB + DAS_2}{AB + AS_2} \frac{U_B + Us_2}{2} \frac{C_B + C_{SM2}}{2} + \rightarrow \\ & \quad \rightarrow + \frac{FM}{DB + DS_2} \left| \frac{U_B + Us_2}{2} \right| \frac{U_B + Us_2}{2} + G \sin \theta = 0 \end{aligned}$$

$$(30) \quad \begin{aligned} C^- : & \quad \frac{1}{\frac{R_C + R_{SG2}}{2} \frac{C_C + C_{SG2}}{2}} \frac{Ps_2 - P_C}{DT} - \frac{Us_2 - U_C}{DT} + \rightarrow \\ & \quad \rightarrow + \frac{DAc + DAS_2}{Ac + AS_2} \frac{U_C + Us_2}{2} \frac{C_C + C_{SG2}}{2} - \rightarrow \\ & \quad \rightarrow - \frac{FG}{Dc + DS_2} \left| \frac{U_C + Us_2}{2} \right| \frac{U_C + Us_2}{2} - G \sin \theta = 0 \end{aligned}$$

Calculation of the void fraction : CS is the C[U] characteristic ;

$$(31) \quad \frac{Bs_2 - Bs_1}{DT} + \frac{1 - \frac{Bs_2 + Bs_1}{2}}{\frac{R_{sm2} C_{sm2}^2 + R_{sm1} C_{sm1}^2}{2}} \frac{Ps_2 - Ps_1}{DT} = 0$$

Characteristic quantities of the calculation point ;

$$(32) \quad \frac{Ps_2}{RG_{BG, S2}^{BN}} = \frac{Ps_1}{RG_{BG, S1}^{BN}}$$

$$(33) \quad R_{SM2} = R_L - (R_L - R_{BG, S2})$$

$$(34) \quad \frac{Ps_2}{RG_{G,S_2}^{GN}} = \frac{Ps_1}{RG_{G,S_1}^{GN}}$$

$$(35) \quad BR_{S_2} = \left(\frac{Ps_1}{Ps_2} \right)^{\frac{1}{3 \cdot BN}} BR_{S_1}$$

$$(36) \quad CSM_2 = FSWP (Ps_2 , Bs_2 , RSM_2 , BR_{S_2} , Ds_2)$$

$$(37) \quad CSG_2 = \sqrt[GN]{\frac{Ps_2}{RG_{S_2}}}$$

Geometric quantities of the CS point ;

$$(38-40) \quad \frac{DS_2}{DX} = \frac{\xi(L_2) - \xi(S_2)}{\xi(L_2) - \xi(L_2+1)} ; \quad \xi_{S_2} : Ds_2 , As_2 , DAs_2$$

The wall friction coefficients calculation ;

$$(41-42) \quad FM = SCFM [Param.] ; \quad FG = SCFG [Param.]$$

S2 : US2 , CSM2 , CSG2 , PS2 , RSM2 , RSG2 , BSM2 , BR_{S2} , RSG_{B2}
 DS2 , AS2 , DAS2 , DEL , HM2 , DS2 , L2
 B : UB , CB , PB , RB , BB , BRB , RGBB
 DB , AB , DAB , S1 , FM , XCS1
 C : UC , CC , PC , RC , S2 , FG
 DC , AC , DAC , XCS2 , LCSX , LCSY , Y

There are 42 unknowns (less than the number for the case of ordinary points due to the missing particle path characteristic !) and the same number of independent equations. It is obvious that analytical solution is not possible but the numerical solution can be made as accurate as required.

E.3. MC SOLUTION ; ORDINARY POINTS IN THE MIXTURE.

A short, step by step summary of the procedures of the MC solution of the set of equations produced in App.E.1. is considered. The format of the program will be used as much as possible ; that is the all indexes were transformed to additional full characters etc. and the index "A" of the calculation point is omitted.

- * Initialization ; all variables - integer and real - related with the application of the numerical method and the loop counters etc. related with the step's calculations are initialized.
- * Initial assignments ; arrayed values of the previous step are to be assigned as the initial values of the new step.

U , C , P , R , B , BR , TEM = U0 , C0 , P0 , R0 , B0 , BR0 , TEM0

- * Initial approximate values of the slopes of the char. lines ;

$$S1 = (C + U) / (DXT + ((C0 - C1) + (U0 - (A1 / A0) U1)))$$

$$S2 = (C - U) / (DXT + ((C0 - C2) - (U0 - (A2 / A0) U2)))$$

* The loop calculations start at this stage ;

* Calculations of the characteristic points B and C ;

$\xi : U, P, B, BR, TEM, D, A, DA$

$$\begin{aligned} \xi_B &= \xi_0 - (\xi_0 - \xi_1) S_1 & \xi_C &= \xi_0 - (\xi_0 - \xi_2) S_2 \quad ; U < C \\ & & \xi_C &= \xi_0 - (\xi_0 - \xi_1) S_2 \quad ; U > C \end{aligned}$$

$$RG-B/C = EB-B/C (P-B/C ** (1/BN))$$

$$R-B/C = (1 - B-B/C) RL + B-B/C RG-B/C$$

$$C-B/C = FSWP (P-B/C, B-B/C, R-B/C, BR-B/C, D-B/C)$$

* Friction coefficient is calculated after the calculation of the physical quantities - viscosity etc. - that used for it.

$$FM = SCFM [Parameters]$$

* The velocity U and the pressure P are calculated with the two MC equation for the characteristic lines of C(+) and C(-) ; the procedure is given below in a simplified format. ($\mp/\pm : B \downarrow / C \uparrow$)

$$Z1-B/C = 0.25 (FM / D-B/C + D0) (U-B/C + U) [(U-B/C + U)]$$

$$Z2-B/C = 0.25 (DA-B/C / A-B/C) + (DA0 / A0) (U-B/C C-B/C + U C)$$

$$X-B/C = (R-B/C C-B/C + CRCBC R C) / (1. + CRCBC)$$

$$Y-B/C = X-B/C (U-B/C - ZB-B/C) \mp P-B/C$$

$$UF-B/C = (U-B/C Z-B/C) \mp ((P-B/C - P) / X-B/C)$$

$$U = (YB + YC) / (XB + XC)$$

$$" \approx 0.5 ((YB / XB) + (YC / XC)) \approx 0.5 (UFB + UFC)$$

$$W-B/C = (U-B/C - U) \pm Z-B/C$$

$$PF-B/C = P-B/C \mp (X-B/C W-B/C)$$

$$P = 0.5 (PFB + PFC) \approx (XB PFB + XC PFC) / (XB + XC)$$

$$" = 0.5 (YB - YC) \approx (XB YB - XC YC) / (XB + XC)$$

* Velocity change is checked against a previously defined limit.

* Physical properties of the gas in the bubble calculated.

$$RG = EB (P ** (1/BN)) \quad ; \quad CSGS = BN (P / RBG)$$

* Calculation of the void fraction can be done at this stage ;

Initialization statement ; $BD = B0$

$$S0 = 0.5 (U + UD) / DXT \quad \xi : U, P, BR, TEM$$

$$\xi_D = \xi_0 - (\xi_0 - \xi_1) S0 \quad U > 0 : \text{Expansion}$$

$$\xi_D = \xi_0 - (\xi_0 - \xi_2) S0 \quad U < 0 : \text{Retraction}$$

$$WD = EB (PD ** BNI) \quad ; \quad XD = BN (PD / WD)$$

$$YD = 0.5 ((1./(WD XD)) + (1./(RG CSGS))$$

$$B0 = 0.25 ((B + BD) (2 - (B + BD))) ZD$$

$$B = BD - B0 (P - PD)$$

* Calculation of the derived physical quantities ;

$$BR = ((PD / P) ** ((1/3) BNI)) BRD$$

$$R = (1 - B) RL + B RG$$

$$C = FSWP (P , B , R , BR , D)$$

* Time step check for staying in the limit ;

$$DT > DX / (C + |U|) : STOP ; \text{ New } DT = 0.5 DT$$

* Loop-stop / Reaching required precision check ;

Done with the U change at the step against a defined limit ,
or with the set loop limit.

$$|(1 - U0 / U)| < DMCML \quad \& \quad \text{Loop Value} > \text{Loop Limit} : \text{ END}$$

* New values of the slopes of the characteristic lines ;

$$S-1/2 = 0.5 ((C \mp U) + (C-B/C \mp U-B/C)) / DXT \quad (\mp/\pm : 1\downarrow/2\uparrow)$$

$$S-1/2 \approx (C-B/C \mp U-B/C) / DXT$$

* Calculations to be repeated until one of the END conditions
mentioned above is satisfied.

END OF APPENDIX E

A P P E N D I X - F

T H E D A T A F I L E

The program , as stated in Chap.1.4 has six data files of the same format which use the same names for corresponding functions. The data files contain about 370 names and about a dozen of them are special multi function names that handle the jobs of up to five independent names. Altogether , about 400 , more or less separate functions needed to be explained for the full and fast use of the data files.

F.1. DIVISION OF THE DATA INTO FUNCTION BASED GROUPS.

For easy comprehension and explanation of their functions, the names - data - in the data files are divided into small groups and further sub groups. the main groups may be defined as given below in tables Table F-1 , F-2 and F-3.

Table F-1 Grouping of the Main and MC Calculations Data.

1. Data in the Heading.
2. Parameters of the Definition of the Vessel Geometry.
3. Initial Conditions Data.
4. Node Number Definition Related Parameters.
5. Time Step Calculation Related Parameters.
6. Special Cases and Output Format Parameters.
7. Parameters on Increasing the Accuracy of the Calculations.
8. NFV to FV Case Transformation Parameters.
9. Physical Characteristics of the Component Fluids.
10. Principal MC Calculation Parameters.
11. Limits of the MC Calculation Loops.
12. Limits for the End of Loop Velocity Difference Values.
13. Speed of Wave Propagation Calculation Parameters.
14. Choked Flow and CPR Calculation Parameters.
15. Opening Conditions and Expulsion Element Parameters.
16. Characteristic Coefficients of the Opening.
17. Rate of Flow of Mixture Expulsion Calculation Parameters.
18. Wall Friction Calculation Parameters.
19. End of Expulsion Way Decision Parameters.
20. Level of Informativeness of the Output Files Parameters.
21. Debugging Works Related Parameter.
22. Time Information Presentation Related Parameters.
23. Full Vessel - Multi Data Cases Special Parameters.

In Chap.F.3 the main and MC calculations data are presented in the order and with the titles given in Table F-1.

Table F-2. Grouping the Shock Front Calculations Related Data.

- S1. SF Calculation Ways Related Parameters.
- S2. SF Pressure Ratio Calculations Related Parameters.
- S3. Precision of the SF Calculations Related Parameters.
- S4. Acceptable Error Level Definitions Related Parameters.
- S5. End of SF Calculations Way Decision Parameters.
- S6. Library Routines Use and Debugging Related Parameters.
- S7. FV-Special Case Created SF related Parameters.

In Chap.F.3 the main and MC calculations data are presented in the order and with the titles given in Table F-2.

Table F-3. Grouping of the Graphics Drawing Related Data.

- G1. Graphics and Output Arrays List Requirement Parameters.
- G2. Quality and the Format of the Graphics Related Parameters.
- G3. Extensiveness of the Graphics Output Related Parameters.

In Chap.F.5 the Graphics Drawing related data are presented in the order and with the titles given in Table F-3.

F.2. THE COMPACT FIELDS OF USAGE INFORMATION FORMAT FOR THE DATA.

The Principal Cases , their descriptive numbers and data files.

Non-Full Vessel	IFL = 1	DNF
Full Vessel	" = 0	DFV / DFM / DMS / DFS
Pressurized Gas Bottle	" = -1	DGB

General and Special Fields of Usage Information Convention ;

IFL : (-1) / (0) / (+1)	+ : Yes - : No
+/- +/- +/-	

Non - Full Vessel Case : (IFL = 1)

I : Initial Calculations.
N : Non-Full Vessel Part Calculations.
G : " " " " ; Gas Region Calculations.
M : " " " " ; Mixture " " "
T : NFV to FV Transformation Calculations.
S : Shock Front Calculations.
F : Full Vessel Condition Calculations Only.

Full Vessel Cases : (IFL = 0)

P : Principal Case	(DFV)	Only..
M : Multi Data Cases	(DFM,DMS)	" .
O : Multi Data - Special Case	(DMS)	" .
N : Standard Multi Data Case	(DFM)	" .
S : Created SF Case	(DFS)	" .

Abbreviations for Frequently Encountered Cases :

A : + + + ; All cases and all parts (Whole program).
B : - + + ; Mixture flow cases only.
C : + - + ; Gas flow cases only.
D : - - + ; Non Full Vessel case only.
E : + P + ; For all single data file cases only.
F : - P + ; NFV and principal FV cases only.
G : + + F ; Full Vessel - mix. or gas filled - cases only.

Dimensions information, if there is any, is given in the usual format. When applicable, the percentage values are clearly indicated with the base value.

F.3. DESCRIPTION OF THE MAIN AND THE METHOD OF CHARACTERISTICS
CALCULATIONS DATA IN FUNCTION BASED GROUPS.

1. Data In the Heading.

1.1. Data as a special message on top of the output.

" *** TRIAL RUN *** " (A) : The message wanted to be printed on top of the output file and the graphics pages may be put into the space provided.

1.2. Principal data on the job and the computer in use.

NDF (A) : Number of data files in the job.

To be appeared on the first data file only.

KDF (A) : Data file identification number. [Table 8.1]

KNC (A) : Code of the computer in use. Used for the adjustments according to the facilities and the restrictions.

LGL (A) : Availability of the GLIB mill-time calc. library par.

1.3. Data on the types of the fluid used.

LLQ (B) : Type of the liquid of the liquid part of the mixture.

LBG (B) : " " " gas in the bubble part of the mixture.

LRG (C) : " " " gas in the gas region.

Examples : LLQ=1 : Water & LBG=1 : Nitrogen & LRG=1 : Air

2. Parameters of the Definition of the Vessel Geometry.

2.1. Principal parameters of the -cylindrical- vessel dimension.

H (A) / [M] : Height / length of the vessel.

DV (A) / [M] : Diameter - at the top of the - vessel.

TETA (A) / [DEG] : Inclination of the axis of the vessel

2.2. Main parameters of the non-cylindrical vessel case.

NCV (A) : Non-cylindrical vessel identification parameter.

ICDA (A) : Diameter change ratio calculation method parameter.

CDAC (A) : " " " " " " factor.

2.3. Parameters of the relative lengths of the sections.

XVRL (A) / [%H] : Relative length of the lower section.

XVRU (A) / [%H] : Relative length of the upper section.
 XVRT " / " : " " " " " top " .
 XVRC = 1 - (XVRL + XVRU + XVRT) : The center section value.
 TDI (A) / [%DV] : Relative length of the open end section.

2.4. Parameters of the relative diameters of the sections.

DBLS (A) / [%DV] : Relative diameter of the lower section.
 DBCS " / " : " " " " " center " .
 DBUS " / " : " " " " " upper " .
 DBTS " / " : " " " " " top " .

2.5. Parameters on the definition of the shape of the vessel.

CSSPL (A) / [%DBCS] : Relative distance of the special point
 in the center section.
 CSSPD (A) / [%DV] : Relative diameter of the special point
 in the center section.
 TSIAB (A) / [%] : (D/Dx)D value at the bottom of top section.
 TSIAT " / " : " " " " " top " " " " .

3. Initial Conditions Data.

3.1. Parameters of the definition of the initial mixture content.

HMI (D) / [m] : Initial mixture height (Priority).
 PHMI (D) / [%] : Initial fullness ratio.

3.2. Params. of the definition of the initial pressure at the top.

PTI (E) / [N/M2] : Initial pressure at the top (Priority).
 PRTI (E) / [%Patm] : " " " ratio at the top.

3.3. Parameters of the definition of the initial β distribution.

BBI (F) / [%] : Initial β at the bottom of the vessel.
 BTI " / " : " " " " top " " " " .
 CBI " : " " distribution constant.

3.4. Parameters of the definition of the initial R_b distribution.

BRBI (F) / [M] : Initial R at the bottom of the vessel.
 BRTI " / " : " " " " top " " " " .
 CBRI " : " bubble size distribution constant.

3.5. Initial temperatures of the component fluids.

TLKO (B) / [K DEG] : Initial temperature of the liquid.
 TBKO " / " : " " " " " gas in bubbles.
 TGKO " / " : " " " " " gas in region.

3.6. Environmental conditions.

PA (A) / [N/M2] : Atmospheric pressure.
 TEK " / [K DEG] : " " temperature.
 G " / [M/S2] : Acceleration of gravity.

4. Node Number Definition Related Parameters.

4.1. Parameters on the initial number of calculation nodes.

MNF (- - I) : Initial number of calculation nodes ; NFV case.
 MF (+ P F) : " " " " " ; FV " .

- 4.2. Special parameters of the NFV case for the node number calc.
 ICL (D) : Max. number of calculation nodes for NFV calc.
 IOMC " : Parameter for the optimization correction request
 on "MNF" value assignment.

- 4.3. Parameters of the application of job time saving measures to
 the mixture region for the non-full vessel case.
 IJTS (D) : Parameter of the request of application.
 MJTS " : Min. node number precondition par. : $M \geq MJTS * MNF$
 LJTSB " : Par.s on the determination of the appl. region.
 LJTST " : $LJTSB \leq [\text{Number of Nodes}] \leq (\text{CS Node} - LJTST)$

5. Time Step Calculations Related Parameters.

- 5.1. Parameters of the initial time step value limit calculations.
 CTDNF (- - I) } NFV case ; Initial time duration and time step.
 CTMNF " } $T \leq (\text{CTMNF} * \text{TCO}) ; \text{DT} \leq (\text{TCO} / \text{CTDNF})$
 CTDF (+ P F) } FV case ; Initial time duration and time step.
 CTMF " } $T \leq (\text{CTMF} * \text{TCO}) ; \text{DT} \leq (\text{TCO} / \text{CTDF})$
 5.2. Parameters of the time step value limitation in MC calcs.
 ENF (D) : NFV Case ; $\text{DT (Max.)} = \text{ENF} * \text{DT (MC Calc.)}$
 EF (A) : FV " ; $\text{DT (Max.)} = \text{EF} * \text{DT (MC Calc.)}$

- 5.3. Parameters on time step reduction or adjustment.
 RDT (A) : Time step adjustment / reduction factor for
 restarts after error condition detection.
 $\text{DT (New)} = \text{RDT} * \text{DT (Old)}$
 PRDT (A) : Low pressure definition and the corresponding time
 DTPR " : step correction parameters for increased accuracy.
 $\text{PR} < \text{PRDT} : \text{DT} = \text{DTPR} * \text{DT (MC Calc.)}$
 IMST (A) : Parameter for the request of the use of
 rounded up MC time step value.
 OFDT (A) / [E-3 S] : Base time interval for rounding up the
 MC time step increment value.
 $\text{DT (Corrected)} / \text{OFDT} = \text{A real number !}$

6. Special Cases and the Output Format Related Parameters.

- 6.1. Parameters for the request of special MC applications and
 the format of the data files.
 IQSF (- + -) : Quasi Steady Flow calculation request parameter.
 JICD (+ P -) : Initial Calculations Data file run request par.
 IWFC (A) : Initial Wave Front calculations request param.
 6.2. Parameters on the general character of the output files.
 ISRUN (A) : Parameter for the request of Short Run.
 Short Run : No heading , no data file list , short
 lists for step's inf. , no fields inf. , very short
 end of job information list.
 ITMFO (A) : Parameter for tidied output listing request.
 6.3. Parameters related with the contents of the output file.
 IPOH (A) : Parameter on the length of the output file request.
 IFDL " : " " on the full data list request.

ITDL (A) : Parameter on extra tidy data file list request.
NOFII " : " " on no fields inf. in output file request.
IPCAL " : " " on precision inf. request in output file.

7. Parameters on Increasing the Accuracy of the Calculations.

7.1. Params. on the initial increase of node number for FV cases.

IDIMF (G) : Par. for using initially increased node number MF.
IMIVF " : Initially increased node number calc. coefficient.
M (Increased) = IMIVF * MF

7.2. Parameters on the determination of the duration of application of the use of initially increased node number for FV cases.

XMIVF (G) : Increased M use ; till : Step Number J = XMIVF * MF
XIDWF " : " " " " ; " : XIDWF % move of the "IWF".
IDWF " : " " " " ; until the end of the "IWF" calc.

7.3. Parameters on limiting the change of the speed of expulsion in initial time steps for increased accuracy.

IULC (A) : Parameter for the request of speed of expulsion limitation at the initial calculation steps.
Application] NFV Case ; $T \leq CTMNF * TCO$
Duration] FV " ; $T \leq CTMF * TCO$

UVLG (C) / [M/S] : Expulsion of gas velocity change limit for the initial calculation steps.

UVLM (B) / [M/S] : Expulsion of mixture velocity change limit for the initial calculation steps.

7.4. Parameters on limiting the change of the speed of expulsion in in the case of full opening. (Valid for duration of expulsion.)

Expressed in terms of the quantity defined below ;
[ΔU (Speed of expulsion change)] / [C (Speed of sound at OE)]

UDCLG (+ - -) : [ΔU / C] limit for the expulsion of gas.

UDCLM (- P -) : " " " " " " " mixture.

7.5. Accuracy related Contact Surface calculations parameters.

DELXL (D) / [DX %] : Max. displacement of the CS in one step.
Absolute limit ; (DELXL)max. = 0.99

JKC (D) : Parameter on the decision that the CS is close enough to the OE and allowing to double the number of calc. nodes for being able to get closer to the OE.

L : Node number of the CS point.

KC : Number of nodes used in MC calc. in gas region.

The condition to be satisfied : $(L+KC) + JKC = M + 1$

Meaning ; the characteristic lines are at least JKC nodes away from the open end.

JJS (D) : Parameter for the distance of the CS to the open end for declaring the vessel full.

Vessel is full if ; $L \geq (M_{max} - JJS)$

8. Parameters on the Non-Full to Full Vessel Transformation.

8.1. Format of the NFV to FV transformation parameters.

LFVT (D) : Parameter of the request and the way of NFV to FV energy transformation calculations.
 A multi data parameter with 1 + 3 defined formats.
 LFVT = 0 : No special action is taken. (Default)
 LFVT > 0 : Energy transformation calc. requested ;
 " = 1 : with ; two-phase energy balance equation.
 " = 2 : " ; single phase " " "
 " = 3 : " ; " " momentum " " "
 IDTRC (D) : Parameter for the request of the residual time for the transformation calculation.
 INFEC (D) : Parameter for the request of the void fraction distribution correction (for the whole vessel).

8.2. Parameters on the time related transformations.

INFFX (D) : Parameter for the request of the use of reduced MC time step for a specified duration.
 TCOX (D) / [S] : Base value for the calculation of the duration and the level of MC time step correction for the NFV to FV transformation calculations.
 CTDX (D)] Par. for the definition of MC time step correction
 CTMX "] and its duration for the NFV to FV transformation.
 $\Delta T < (CTMX * TCOX) : DT \leq (TCOX / CTDX)$

9. Physical Characteristics of the Component Fluids. (SAC : Standard Atmospheric Conditions)

9.1. Parameters on the calculation frequency of the physical characteristics of the regional and component fluids.

Decision of recalculation at all or some steps or the employment of the standard atmospheric conditions value.
 KVPQL (B) : Phys. char. calc. frequency par. for the liquid.
 KVPQB " : " " " " " " " bubble gas.
 KVPQG " : " " " " " " " regional gas.

9.2. Physical characteristics of the liquid phase of the mixture.

RL (B) / [K/M3] : Specific gravity of the liquid at SAC.
 VCL " / [K/M*S] : Dynamic viscosity " " " " "
 BML " / [N/M2] : Bulk modulus " " " " "
 STCL " / [N/M] : Surface tension " " " " "
 CPLQ " / [kJ/K DEG] : Cp Specific heat " " " " "
 CVLQ " / " : Cv " " " " "

9.3. Physical characteristics of the gas phase of the mixture.

RBS (B) / [K/M3] : Specific gravity of the bubble gas at SAC.
 VCB " / [K/M*S] : Dynamic viscosity " " " " "
 BGC " / [MKS] : Gas constant " " " " "
 BN " : Thermodynamic behaviour constant " " " "
 CPBG (B) / [kJ/K DEG] : Cp Specific heat of the gas at SAC.
 CVBG " / " : Cv " " " " "

9.4. Physical characteristics of the regional gas at the top.

RGS (D)	/ [K/M3]	: Specific gravity of the gas at top at SAC.							
VCG	" / [K/M*S]	: Dynamic viscosity	"	"	"	"	"	"	"
GGC	" / [MKS]	: Gas constant	"	"	"	"	"	"	"
GN	"	: Thermodynamic behaviour constant	"	"	"	"	"	"	"

```
CPG (D) / [kJ/K DEG] : Cp Specific heat of gas at top at SAC.  
CVG " / " : Cv " " " " " " "
```

10. Principal Method of Characteristics Calculation Parameters.

10.1. Discrete parameters of the MC calculations.

LCS (A) : Parameter for the way of calculating the inclination of the characteristic lines.

(The use of simple or complex averaging ways.)

KMCCE (A) } Parameter on the request of of the calc. of the
KMCOE " } special points of CE & OE like an ordinary point
with an imaginary additional point / line.

10.2. Par. on the correction jobs related with the MC calculations.

```

CUCBE (A) : Correction coefficient for CE MC "velocity" calc.
CRCBE " : " " " " " the calculation of the
          mean value of the "R * C" quantity.

```

10.3. Parameters of the preferred formats of the mean value calcs. of the U (velocity) and P (pressure) quantities at ordinary and special MC calculation points.

LMCU (A) :	"U"	calc. way	parameter	for	ordinary	MC	points.
ILMCU " :	"	"	"	"	"	special	" "
LMCP " :	"P"	"	"	"	"	ordinary	" "
ILMCP " :	"	"	"	"	"	special	" "

10.4. Parameters of the preferred format of the B (void fraction) and R (specific gravity) calculation ways.

```

JCMB  (B) : "B" calc. way parameter for ordinary MC points.
JCSMB (D) : " " " " " " " the CS point.

```

KBRMC (A) : "B" (mix.) or "R" (gas) calculation way parameter
for the CE point MC calculations.

11. Limits of the Principal and Inner MC Calculation Loops.

11.1. Limits of the Main MC calculation repeat loops.

```

NOEM (B) : Main loop limit for the OE - Mixture MC calcs.
NOEG (C) : " " " " " OE - Gas " "
NM (B) : " " " " " OP - Mixture " "
NG (C) : " " " " " OP - Gas " "
NCE (A) : Main loop limit for the MC calcs. for the CE.
NCS (D) : " " " " " " " " " CS.
NWF (A) : " " " " " " " " " IWF.

```

11.2. Limits of the inner loops for "U" & "P" and "B" / "R" calcs.

```

LMCL  (A) : U & P and B / R calcs. inner loop limit for OPs.
LMCOE  "  : " & " " " / " " " " " " " " " " OE.
LMCCE  "  : " & " " " / " " " " " " " " " " CE.

```

- 11.3. Discrete loop repeat limits for various MC calculations.
 JFC (A) : Absolute limit for all main loops of MC calcs.
 LAL " : Repeat limit for ordinary MC calls due to error.
 NDWF " : Main IWF-MC calcs. loop limit for the IO case.
 IJOEM (B) : Correction par. for OE-Mix. MC calcs. main loop.

12. Limits for the End of Loop Velocity Difference Values.

- 12.1. Parameters on ending MC loop calculations with given limits on the percentage of change on the calculated velocities.

PRDOE (A) : PR limit for OE(Mix.-Gas) calcs. with %U change.

PR < PRDOE : KEOEM (Mix.) & KEOEG (Gas).

KEOEM (B) : Request of MC loop "end" with %AU , OE-Mix. calcs.

KEOEG (C) : " " " " " " " " , OE-Gas " .

KEMCM (B) : " " " " " " " " , OP-Mix. " .

KEMCG (C) : " " " " " " " " , OP-Gas " .

KECE (A) : " " " " " " " " , CE point " .

KECS (D) : " " " " " " " " , CS " " .

KEWF (A) : " " " " " " " " , IWF " " .

- 12.1. Limits of the percentage of change of the calculated velocity values for decisions on ending MC loop calculations.

DOEML (B) : %AU limit for ending MC loop calc. , OE-Mix. calc.

DOEGL (C) : " " " " " " " " , OE-Gas " .

DMCML (B) : " " " " " " " " , OP-Mix. " .

DMCGL (C) : " " " " " " " " , OP-Gas " .

DCEL (A) : " " " " " " " " , CE point " .

DCSL (D) : " " " " " " " " , CS " " .

DWFL (A) : " " " " " " " " , IWF " " .

13. Speed of Wave Propagation (SWP) in the Mixture Calcs. Par.

- 13.1. Principal SWP-Mixture calculation parameter.

KCM (B) : SWP-Mixture calc. method determination parameter.

KCM : [x]XXX ; KCM1 & KCM2 & KCM3 & KCM4

Default (most suitable) value : "7100"

KCM1 = 1 : Simple SWP-Mix. calculation equation use.

= 2 : Basic " " " " " " " " .

KCM1 = 3 : Basic SWP-Mix. calc. equation + STCL effect.

" = 4 : Standard " " " " " " " " .

" = 5 : " " " " " " " " + STCL effect.

" = 6 : Full " " " " " " " " .

" = 7 : " " " " " " " " + STCL effect.

Special formats for small "B" and "BR" values.

KCM1 = 11 : BML only considered.

" = 12 : BML & STCL " " " " .

" = 13 : BML & STCL " " " " + calculated RGB value used.

KCM1 = 14 : BML & STCL + calc. RGB use + Simple DRDP eqn. use.

" = 15 : " & " + " " " " + Full " " " " .

" = 16 : " & " + " " " " + Special " " " " .

KCM2 : Parameter for the calculated BN value use request.

KCM3 : " " " " consideration of "EMVM" value.

KCM4 : " " " " " " " " the slip effect.

(Applicable to the cases of " $\beta < 0.01$ " only !)

- 13.2. Additional SWP-Mixture calculations related parameters.
 - EMVM (B) / [N/M2] : Elasticity module of the vessel material.
 - VWT " / [M] : Thickness of the walls of the vessel.
 - OEA (B) : "r at OE" ; assumed slip ratio at the OE.
 - OEB " : "s at OE" , " acceleration " " " " .
14. Parameters of the Choked (Sonic) Expulsion and the Critical Pressure Ratio (CPR) Calculations.
 - 14.1. Par. for the requested way of choked expulsion of mixture.
 - ICRG (C) : Par. for way of choked expulsion calc. for gas.
 - ICRM (B) : " " " " " " " " " mixture.
 - ICR-G/M = 1 : Calc. with sonic speed equation.
 - " " = 0 : " " ordinary equation and critical PR.
 - 14.2. Principal parameters of the CPR calculations.
 - ICWN (A) : Parameter for the request of the CPR calcs. way.
 - ICWN = -1 ; Approximate value functions use.
 - " = 0 ; Calculation with Newton's method.
 - " = 1 ; " " " NAG library routine.
 - PDPL (A) : Requirement of CPR calcs. decision parameter.
 - (ACPRM / PR) < (1 - PDPL) : CPR calcs. required.
 - 14.3. Special parameters of the CPR calcs. with the Newton's method.
 - DYL (A) : Required limit for calculation error.
 - FFL " : Differential of the F(CPR) function value limit.
 - NPRC " : Parameter of the calculation loop limit.
 - 14.4. Special pars. of the CPR calcs. with the NAG library routine.
 - INAG (A) : Par. for the preferred NAG routine determination.
 - CNRL "] Lower / Upper limits of the calc. region params.
 - CNRU "] Condition : CNRL < 1.0 & CNRU > 1.0
 - ACPRL = CNRL * (ACPRG or ACPRM) for Gas & Mixture.
 - ACPRU = CNRU * (ACPRG or ACPRM) " " & " .
 - EPSN "] Special precision level parameters required in the
 - ETAN "] fixed format CALL list of the NAG routines.
15. Principal Parameters of the Expulsion Element / Opening Conditions and the Expulsion Element Definitions.
 - 15.1. Principal parameters of the opening conditions definition.
 - TCO (E) / [S] : Duration of opening, time reaching to AOF.
 - AOF " / [M2] : Final value of the area of the opening as a dimensioned quantity. (Priority)
 - PHIF " / [% AV] : Final value of the area of the opening as a percentage of the cross-section area.
 - 15.2. Principal parameters of the expulsion element definitions.
 - LDON (A) : Parameter for the type of the opening.
 - LDON = -1 : Non-standard expulsion element.
 - " = 0 : Standard diaphragms.
 - " = 1 : " nozzles.
 - LPHI (A) : Parameter for the definition of the employed area ratio when the actual value is out of set limits.

LXERC (A) : Parameter on the inclusion of the Reynolds effect into the calc. of the characteristic coefficients.
 LXEMC " : Parameters on the inclusion of the minor factors into the calc. of the characteristic coefficients.

16. Characteristic Coefficients of the Opening.

16.1. Parameters for the correction of the coefficients for the pure liquid flow for the expulsion of the bubbly-liquid mixtures.

LCBCM (E) : Parameter for the request of the corrections on the flow coeffs. of the pure liquid discharge for the expulsion of the bubbly liquid with the β .
 CLCAD "] Char. coef. correction for the stdrd. diaphragms.
 CLCBD "] "A": Constant addition / "B": β value coefficient.
 CLCAN "] Char. coef. correction for the standard nozzles.
 CLCBN "] "A": Constant addition / "B": β value coefficient.

16.2. Params. of the flow coeffs. corrections for full opening case.

TFOEM (- + F) : For the mixture & for the expulsion case.
 TGOEG (+ - N) : " " gas & " " " " .
 TFOIM (- + F) : " " mixture & " " back-flow " " .
 TFOIG (+ - N) : " " gas & " " " " " " .

16.3. Flow coefficients correction factors for the back-flow case.

CBIMD (- + F) : For mixture back-flow through std. diaphragms.
 CBIMN (") : " " " " " " nozzles.
 CBIGD (+ - N) : " gas " " " " diaphragms.
 CBIGN (") : " " " " " " nozzles.
 XBFG (") : Percentage of expelled gas in back-flow gas.

16.4. Assigned flow coeffs. of a non-standard expulsion element.

COFM (- + F) : Contraction coeff. , expulsion of mixture.
 TOFM " : Flow " , " " " " .
 CBFM " : Contraction " , back-flow " " .
 TBFM " : Flow " , " " " " .
 COFG (+ - N) : Contraction coeff. , expulsion of gas.
 TOFG " : Flow " , " " " " .
 CBFG " : Contraction " , back-flow " " .
 TBFG " : Flow " , " " " " .

17. Parameters for the Calculation of the Rate of flow of Mixture Through Standard Expulsion Elements.

17.1. Primary param. of the rate of flow of mixture calculations.

IOE (B) : Parameter for the definition of the method /formula to be used for the calc. of rate of flow of mixture.
 IOE : XX ; IOEM (1,2,3-8) & IOEBN (0 / 1)
 IOEM = 1 & 2 ; Bubble - Liquid mixture methods.
 " = 3 - 8 ; Steam - water " " .
 IOEBN : Parameter for the employment of simple (0) or the full (1) format of the "BN" value.
 IOEM = 1 : Standard method ; EVET with slip effect.
 Slip coeffs. : r(Top)=OEA & r(Bottom)=OEB
 " = 2 : Bubble surface energy effect method.

- 17.2. Secondary parameters of the rate of flow of mixture calcs.
 IOEQB (B) : Parameter on the request of the inclusion of the
 void fraction effect to the flow coefficients.
 EXYK " : Parameter used for different functions for the
 IOEM = 4 - 8 case steam-water mixture equations.

18. Wall Friction Calculation Parameters.

- 18.1. Parameters for the calculation of wall friction coefficients.
 IFM (B) : Par. for the cons. of the friction effect ; mixture.
 IFG (C) : " " " " " " " " ; gas.
 ZK (A) / [M] : Measure of the roughness of the vessel walls.
- 18.2. Parameters on the calculation of the "Re" of the mixture.
 JRENC (B) : Par. for requesting "Re-mix" calc. not Re-liquid.
 CRRL " (Re)mix = [RREN / (VRENL + VRENG)] * (D * U)
 CRRB " RREN = CRRL * (1 - B) * RL + CRRB * B * RBG
 CRVL " VRENL = CRVL * (RL / R) * (1 - B) * VCL
 CRVB " VRENG = CRVB * (RBG / R) * B * VCB

19. End of Calculations / Expulsion Way Decision Parameters.

- 19.1. Parameters on the way of deciding to end the calculations.
 IECG (C) : Parameter of the way of ending calcs. ; gas.
 IECM (B) : " " " " " " " " ; mixture.
- IECG / IECM = -1 : End when ; PR < PRLG / PRLM
 " / " = 0 : " " ; 1U (I=1-MP)1 < ULIMG / ULIMM
 " / " = 1 : " " ; 1P (I=1-MP)1 < PRLG / PRLM
 " / " = 2 : "1" with " P + 0.5 * R * U " value use.
- 19.2. Pressure at top and speed of expulsion limits for the end of
 calculations / expulsion decision.
 PRLG (C) : Limit for the "end" pressure ratio for gas.
 PRLM (B) : " " " " " " " " mixture.
 ULIMG (C) / [M/S] } Speed limit for the decision of the end
 ULIMM (B) / " } of expulsion deceleration ; gas / mixture.
- 19.3. Parameters for intentionally ending the calculations.
 KSRLT (A) : Param. for the use of a set job-time limit value.
 JSTOP " : The MC calc. step number that the job to be ended.
 RTLIM (A) / [min] : Run-time limit of the job in real time.
 TMILL " / [S] : Mill-time " " " " or data file.

20. Level of Informativeness of the Output Files Parameters.

- 20.1. Params. on the calc. points information printout interval.
 JGS (- - G) : NFV case ; for the points in the gas region.
 JMS (- - L) : " " ; " " " " " " mixture " .
 JFS (+ + F) : FV " (Both mixture and gas filled vessels.)
- 20.2. Params. on the calc. steps information printout interval.
 JZNF (- - N) : NFV case , up to reaching FV conditions.
 JZF (+ + F) : FV case (Both mixture and gas filled vessels.)

- 20.3. Params. on the level of the calc. steps information printout.
 IPD (A) : Par. for the calc. steps inf. level on printout.
 NCSIP (D) : Par. for the CS region definition for information
 printout. [L (CS node) : (L-NCSIP) - (L+NCSIP)]
- 20.4. Params. on the information printout level for non-MC calcs.
 LPVC (A) : Non-cylinder. vessel case inf. print request param.
 LPFG (C) : Friction coeff. calc. inf. print request for gas.
 LPFM (B) : " " " " " " " " mix.
21. Parameters on the Error Tracing / debugging Work.
- 21.1. Parameters on debugging information request.
 IJK (A) : Par. for debugging inf. on MC calc. print request.
 LIJK " : Param. for the defined mill-time end stop related
 debugging information request.
- 21.2. Params. for the def. of general debugging region or step.
 JJZ (A) } Calc. steps information output region for debugging.
 JJ " } Region : $JL > JJZ \ \& \ JL / JJ = \text{An integer number.}$
- 21.3. Params. for the definition of the extensive information region
 for the debugging purposes.
 JLL (A) } The "step" number limits definition parameters.
 JLU " } (Lower limit) $JLL \leq JL \leq JLU$ (Upper limit)
 ILL " } The "node" number limits definition parameters.
 ILU " } (Lower limit) $JLL \leq JL \leq JLU$ (Upper limit)
- 21.4. Params. of debugging information request on MC calculations.
 LPOEM (B) : Extensive MC calcs. inf. request ; OE - Mix. calc.
 LPOEG (C) : " " " " " " ; OE - Gas " .
 LPMCM (B) : " " " " " " ; OP - Mix. " .
 LPMCG (C) : " " " " " " ; OP - Gas " .
 LPCEC (A) : Extensive MC calc. inf. request ; CE point calc.
 LPCSC (D) : " " " " " " ; CS " " .
 LPWFC (A) : " " " " " " ; IWF " " .
22. Mill-time information request and limits related parameters.
 IOLC : Parameter for requesting the frequent issuing a special
 system message for pushing the job in the batch queue.
- 22.1. Parameters related with the mill time information request.
 JMTP (A) : Par. for requesting mill-time inf. in the output.
 KESR " : " " " " " " on the screen.
 TMTDS (A) / [S] : Mill-time interval for the screen printout.
- 22.2. Mill time limits for the error detection on MC calculations.
 TMSL (A) / [S] : Mill time limit for MC steps calculations.
 TMSFL " / " : " " " " SF " " " .
23. Special Parameters of the Full Vessel , Multi - Data Cases.
- 23.1. Parameters on the size of the FV Multi-data data lists.
 NCAL (- 0 -) : Number of data sets in the list ; DMS case.

NSEC (- N -) : Number of the group of data sets ; DFM case.
 NLSEC " : " " data sets in a group ; " " .

- 23.2. Parameters related with the FV - MD cases MC applications.
 M : Number of calculation nodes used. (Equivalent to MF)
 CTD : Initial time step value limit calc. param. (Eqv. CTDF)
 CTM : " " " " " " " " . (" ")
- 23.3. Parameters related with the FV - MD cases initial conditions.
 PRO : Initial pressure ratio at the top of the vessel.
 BV : " void fraction for the whole vessel.
 BRV : " bubble radius " " " " .

F.4. DESCRIPTION OF THE SHOCK FRONTS AND SPECIAL SF-MC CALCULATIONS RELATED DATA IN FUNCTION BASED GROUPS. [KDF = 1 & 4 / (- S +)]

S1. Parameters for the Definition of the SF Calculations Way.

- S1.1. Principal parameters of the SF calculations.
 INSF : Parameter for requesting SF calculations.
 INSF = 0 / 1 : SF calculations Request ; No / Yes.
 INSF = -1 : SF created but no SF calc. is done.
 LSFIC : Par. for the method of solution of the SF equations.
 -1 : U with EC eqn. & USF with C and MT eqns.
 0 : USF " MT & EC eqns. & U " C eqn.
 1 : U " MT & EC " . & USF " C " .
- S1.2. Discrete parameters on the method of SF calculations.
 KMCSF : Parameter for the MC calcs. method of the SF points.
 With one (C+ or C-) or both (C+ and C-) charac. lines.
 DSFNE : Max. distance of an SF from an end point (CE & OE) for
 close enough / ready to reflect decision. (in % DX !)
- S1.3. Pars. of the time step increment an correction calcs. for SF.
 ESF : MC time increment value correction factor for the SF.
 DT (SF , Max.) = ESF * DT (MC Calc.)
 DSFXL : MC time increment correction factor for "USF" effect.
 DT (SF) = DSFXL * (DX / USF)
 DT (SF) = MIN [DT (ESF) & DT (DSFXL)]

S2. Parameters of the SF pressure Ratio Calculations.

- S2.1. Pars. on the SF PR calculations decision and applications.
 IPRSF : Parameter on the decision to use the calculated or the
 given (PRISF) PR value at the start of the SF calcs.
 PRISF : The given starting starting SF pressure ratio value.
 APISF] The principal and the PR related components of the
 BPISF] calculated initial pressure ratio value.
 PRISF = APISF + BPISF * (A PR related value.)
- S2.2. Pressure ratio increments in various SF calculation Stages.
 RPISF : Initial PR increment in the first SF calcs. step.
 RPSFI : " " " " " ordinary " " " .

RPSRI : Initial PR increment in the reflected SF calcs. step.
 RUSFI : PR increment in the loop for improvement on first estimates of the set of SF equations calculations.

S2.3. Pars. on the calc. of PR increments for an SF calcs. step.

JSFBM : Par. for the method of calcs. of the initial PR increment at the SF calculations of a step.
 0 : Standard value use request. (RPSFI & RPSRI)
 1 : Request of calculation using recent PR values.
 JSFBR : Par. for the job of JSFBM for reflected SF calcs.
 CSFP1/2/3 } Parameters of the simple empirical relation for
 CSFD1/2/3 } the calculation of the starting SF - PR value / increment for the SF calculations of a step.

S2.4. Params. of PR increment calcs. in loop stages of SF steps.

JRPSF } Params. on the decision to use constant or calculated
 JLISF } PR increment correction factor in the loops for the calc. of the PR value of the next stage.
 To be used when the signs of the Old and New precision parameters are different / the same.
 CJRSF } Special SF - PR increment calculation factors related
 DILSF } with the parameters JRPSF and JLISF.

S3. Precision of the SF Calculations Related Parameters.

S3.1. Pars. for requesting SF calcs. with the improved accuracy.

MSFM : Par. for the request of additional procedures for the improvement on the calcs. of an ordinary SF step.
 KSFPC : Par. for the request of SF pressure and PR correction calculations at an SF calculations step.
 CSFPC : Coefficient for the adjustment of the calculated PR correction value.

S3.2. Limits for velocity and pressure changes in SF calc. steps.

UWSFL (M/S) : Velocity value calculation difference for ordinary SF calculations.
 PWSFL (N/M2) : Pressure value calculation difference for reflected SF calculations.

S3.3. Limits of the SF calculations loops.

KSFWL : Limit of the principal loop of the SF point calcs.
 NSFMC : SF point MC calculations loop limit.
 NSFCEI : Loop limit for the SF point calcs. near CE.
 KSFWEI : " " " " " " " " OE.
 LMCSF : Loop limit for the SF-MC (U and P) calculations.
 NSF : Loop limit for all non-specified SF calcs. cases.

S4. Parameters on the SF Calculations Error Levels.

S4.1. Params. on the decision of the error level on SF calcs.

JSFUP : Par. for using U (0) or P (1) value at the SF point for the SF calculations error level checks.
 NRPSF : Par. for the consideration of the relative error levels of the two consecutive runs in SF calc. steps.

KRPSF : Par. on the ways of correcting calculated value with the ratio of two consecutive error levels for the estimation of the new SF pressure ratio value.

S4.2. Principal error level parameters of the SF calculations.

DWISF : Acceptable starting error level parameter for redoing the SF calculations of the step with corrected values.
DUSFL : Limit for the error level calculations with energy balance equation for the end of the calcs. decision.
DSFRP : Very weak SF decision related parameter for deciding to use the PR value or the data RPSFE in a calc. step.

S4.3. Pars. on defining SF calculations errors and related limits.

NDWSF : Par. on the way of defining calc. error of an SF step.
DWSFL } Principal error limit for the ordinary / reflected SF
DWRCL } calculations related with the (U / USF) ratio.
RPDLI : Limit for the PR difference between two consecutive steps for the acceptable error level decision.

S5. Parameters of the End of SF Calculations Way Decision.

S5.1. Principal parameters of ending the SF calculations decision.

JSFCE : Parameter on ending the SF calculations when first reflected front reaches to the OE point (Expelled SF).
JSFEP : Par. for calculating the principal PR value to be used to decide for ending the SF calculations.
RPSFE : Limit PR value for the end of the SF calcs. decision.

S5.2. Parameters on ending SF calcs. near the OE for low PR reasons.

LRPEW : Par. on the way of ending SF calcs. for low PR reason.
RPNSF : Limit PR value for the end of SF decision near the OE.
PRMPS : Limit PR at the top (vessel) for end of SF decision.
PRPSL : Limit SF-PR for the end of the expulsion declaration.
PRMPL : Limit of the corrected pressure ratio at the OE for the end of the SF calcs. declaration with PRPSL.

S6. Params. on Debugging Work and Library Routines Use in SF calc.

S6.1. Parameters of the debugging work on the SF calculations.

LPSFC : Par. for requesting debugging information in SF calcs. Used for establishing principal data in SF-MC loops.
JDSFP : SF calcs. step interval for debugging inform. print.
KDSFP : Lower limit of the step number for SF debugging print.
KSFOP : Par. for the level of informativeness of the debugging work printout for MC steps calcs. at points near SF.
JLLSF } Lower / upper limits in step numbers for the request
JLUSF } of the SF-PR calcs. debugging information printout.

S6.2. Params. on the unsuccessful use of the NAG library routines.

NLSFC : Par. for requesting NAG library use for SF equations.
NLSFT : " " " " " " " " tidying up of the SF calculation steps results.
NSFNC } Parameter for identifying the NAG library routine to
NSFNT } be used for calculation or tidying up.

NRSFB] Parameter on requesting to use NAG library routines at
 NRSFR] the first SF step / reflected SF calculations.
 NRSCE] Distance in number of nodes from CE / OE for defining
 NRSOE] the region in which the NAG library is to be used.
 DWNCL : Error limit for using the NAG routines for tidying up
 the results of an SF calculation step.

S7. Special Parameters of the Created SF of the FV-Special Case.

S7.1. Params. on the way of creating and the strength of the SF.
 JBSFI : Par. on the determination of the way of creating SF.
 -1 : Create when the opening period ends.
 0 : " " " step number reaches equals JBSFJ.
 1 : " " " IWF reaches to the CE.
 JBSFJ : The step number at which an SF is to be created.
 PHSFA] Contracted area of the opening in per-cent of the ;
 PHSFP] area at the top / final value of the opening area.

 S7.2. Params. on the time step correction for the created SF.
 JSFTC : Par. for the request of time step correction.
 RSFTE : Lower PR limit for time step correction calcs.
 ASFTC] Parameters for the time step value correction.
 CSFTC] $DT \text{ (Corrected)} = [CSFTC / (ASFTC * PR)] * DT$

F.5. DESCRIPTION OF THE GRAPHICS WORK DATA IN FUNCTION BASED GROUPS.

G1. Params. on the Graphics and Output Arrays List Requirements.

G1.1. Parameters on the decision to draw graphs.
 JGRC : Par. for the request of the graphics-code production.
 LGRO : Par. for the Graphics Output Only Run request.
 LSGL : Par. for requesting Graphics Output Listing.
 LEGRI : Par. for graph drawing inf. printout for debugging.

G1.2. Par. on the decision to produce Output Arrays Listing.
 IOAL : Par. for the request of the output arrays listing.
 LOLO : Par. for the Output Arrays Listing Only Run request.
 IUOA : Par. for the level of informativeness of the OAL.

G2. Quality and the Format of the Graphics Related Parameters.

G2.1. Parameters on the size of the graphics information data files.
 JSGL : Number of steps skipped after each ordinary step added
 into the output arrays list.
 JALO : Limit of the number of elements in output arrays.

 G2.2. Par. for the format of the graphics output.
 NGDPR : Par. for the data and results list print/draw request.
 NODPR : Par. for the "no" date inf. on graphical output "

 G2.3. Params. for the determination of the line character of graphs.
 ISVC : Par. for the imposition of single valued curve draw.
 LGDPC : Par. for the curve drawing method ; GHOST or GLIB.
 ICOH : Param. for the request of curve drawing or print plot.

IBRCL : Param. for the request of continuous / broken / mixed
line drawing when the choice exist.

G2.4. Params. for the method of drawing of the special graphs.
ISCOP : Par. for the request of curve or point plot drawing.
ISNOC : " " " " " GHOST or GLIB library use.

G3. Extensiveness of the Graphics Output Related Parameters.

G3.1. Principal parameters of the size of the graphical output.
IROGR : Par. for the request of the "Ordinary Set of Graphs".
ISPGR : First Set of the special graphs request parameter.
IRSTG : Second " " " " " " " "

G3.2. Pars. for the request of some additional plots for the Full
Vessel - Multi Data run cases.
KDPE : First dimensionless parameter plot.
KDPT : Second " " " " "
KPLE : Percentage of the liquid expelled plot.
KRPLE : Theoretical / actual amount of liquid expelled " .
KPBVF : Mean void fraction at the end of expulsion " .
KPCAL : Precision of the calculations " .
KDE : Duration of the expulsion " .
KRJME : Number of calculation steps " .

F.6. INDEX OF ALL DATA IN ALL INPUT FILES.

Group Numbers Used in Apps. F.3 & F.4 & F.5 are Indicated.

AOF	15.1	CLCAN	16.1	CSSPL	2.5	DOEML	12.2	H	2.1
APISF	S2.1	CLCBD	16.1	CTD	23.2	DSFNE	S1.2	HMI	3.1
ASFTE	S7.2	CLCBN	16.1	CTDF	5.1	DSFRP	S4.2	IBRCL	G2.3
BBI	3.3	CNRL	14.4	CTDNF	5.1	DSFXL	S1.3	ICDA	2.2
BGC	9.3	CNRU	14.4	CTDX	8.2	DTPR	5.3	ICL	4.2
BML	9.2	COFG	16.4	CTM	23.2	DUSFL	S4.2	ICOH	G2.3
BN	9.3	COFM	16.4	CTMF	5.1	DV	2.1	ICRG	14.1
BPISF	S2.1	CPBG	9.3	CTMNF	5.1	DWFL	12.2	ICRM	14.1
BRBI	3.4	CPG	9.4	CTMX	8.2	DWISF	S4.2	ICWN	14.2
BRTI	3.4	CPLQ	9.2	CUCE	10.2	DWNCL	S6.2	IDIMF	7.1
BRV	23.3	CRCBC	10.2	CVBG	9.3	DWRCL	S4.3	IDTRC	8.1
BTI	3.3	CRRB	18.2	CVG	9.4	DWSFL	S4.3	IDWF	7.2
BV	23.3	CRRL	18.2	CVLQ	9.2	DYL	14.3	IECG	19.1
CBFG	16.4	CRVB	18.2	DBCS	2.4	EF	5.2	IECM	19.1
CBFM	16.4	CRVL	18.2	DBLS	2.4	EMVM	13.2	IFG	18.1
CBI	3.3	CSFD1	S2.3	DBTS	2.4	ENF	5.2	IFM	18.1
CBIGD	16.3	CSFD2	S2.3	DBUS	2.4	EPSN	14.4	IFOL	6.3
CBIGN	16.3	CSFD3	S2.3	DCSL	12.2	ESF	S1.3	IJK	21.1
CBIMD	16.3	CSFP1	S2.3	DECEL	12.2	ETAN	14.4	IJOEM	11.3
CBIMN	16.3	CSFP2	S2.3	DELXL	7.5	EXYK	17.2	IJTS	4.3
CBRI	3.4	CSFP3	S2.3	DILSF	S2.4	FFL	14.3	ILL	21.3
CDAC	2.2	CSFPC	S3.1	DMCGL	12.2	G	3.6	ILMCP	10.3
CJRSF	S2.4	CSFTC	S7.2	DMCML	12.2	GGC	9.4	ILMCU	10.3
CLCAD	16.1	CSSPD	S2.5	DOEGL	12.2	GN	9.4	ILU	21.3

IMIVF	7.1	JMTP	22.1	LBG	1.3	NG	11.1	RPSFE	S5.1
IMST	5.3	JRENC	18.2	LCBCM	16.1	NGDRP	G2.2	RPSFI	S2.2
INAG	14.4	JRPSF	S2.4	LCS	10.1	NLSEC	23.1	RPSRI	S2.2
INFEC	8.1	JSFBM	S2.3	LDON	15.2	NLSFC	S6.2	RSFTE	S7.2
INFFX	8.2	JSFBR	S2.3	LEGRI	G1.1	NLSFT	S6.2	RTLIM	19.3
INSF	S1.1	JSFCE	S2.3	LFVT	8.1	MM	11.1	RUSFI	S2.2
IOAL	G1.2	JSFEP	S5.1	LGDPC	G2.3	NODPR	G2.2	STCL	9.2
IOE	17.1	JSFTC	S7.2	LGL	1.2	NOEG	11.1	TBFG	16.4
IOEBN	17.1	JSFUP	S4.1	LGRO	G1.1	NOEM	11.1	TBFM	16.4
IOEM	17.1	JSGL	G2.1	LIJK	21.1	NOFII	6.3	TBKO	3.5
IOEQ	17.2	JSTOP	19.3	LJTSB	4.3	NPRC	14.3	TCO	15.1
IOLC	22.0	JZF	20.2	LJTST	4.3	NRPSF	S4.1	TCOX	8.2
IOMC	4.2	JZNF	20.2	LLQ	1.3	NRSCE	S6.2	TDI	2.3
IPCAL	6.3	KBRMC	10.4	LMCEE	11.2	NRSFB	S6.2	TEK	3.6
IPD	20.3	KCM	13.1	LMCL	11.2	NRSFR	S6.2	TETA	2.1
IPOH	6.3	KCM1	13.1	LMCOE	11.2	NRSOE	S6.2	TFOEG	16.2
IPRSF	S2.1	KCM2	13.1	LMCP	10.3	NSEC	23.1	TFOEM	16.2
IQSF	6.1	KCM3	13.1	LMCSF	S3.3	NSF	S3.3	TFOIG	16.2
IROGR	G3.1	KCM4	13.1	LMCU	10.3	NSFCI	S3.3	TFOIM	16.2
IRSTG	G3.1	KDE	G3.2	LOLO	G1.2	NSFMC	S3.3	TGKO	3.5
ISCOP	G2.4	KDF	G3.2	LPCEC	21.4	NSFNC	S6.2	TLKO	3.5
ISNOC	G2.4	KDPE	G3.2	LPCSC	21.4	NSFNT	S6.2	TMILL	19.3
ISPGR	G3.1	KDPT	G3.2	LPFG	20.4	NWF	11.1	TMSFL	22.2
ISRUN	6.2	KDSFP	S6.1	LPHI	15.2	OEA	13.2	TMSL	22.2
ISVC	G2.3	KECE	12.1	LPHI	15.2	OEB	13.2	TMTOS	22.1
ITDL	6.3	KECS	12.1	LPMCG	21.4	OFDT	5.3	TOFG	16.4
ITMFO	6.2	KEMCG	12.1	LPMCM	21.4	PDPL	14.2	TOFM	16.4
IULC	7.3	KEMCM	12.1	LPOEG	21.4	PE	3.6	TSIAB	2.5
IUOA	G1.2	KESR	12.1	LPOEM	21.4	PHIF	15.1	TSIAT	2.5
IWFC	6.1	KEOEG	12.1	LPSFC	S6.1	PHMI	3.1	UDCLG	7.4
JALO	G2.1	KEOEM	12.1	LPVC	20.4	PHSFA	S7.1	UDCLM	7.4
JBSFI	S7.1	KESR	22.1	LPWFS	21.4	PHSFP	S7.1	ULIMG	19.2
JBSFJ	S7.1	KEFW	12.1	LRG	1.3	PRO	23.3	ULIMM	19.2
JCF	11.3	KMCCE	10.1	LRPEW	S5.2	PROOR	12.1	UVLG	7.3
JCMB	10.4	KMCOE	10.1	LSFIC	S1.1	PRDT	5.3	UVLM	7.3
JCSMB	10.4	KMCSF	S1.2	LSGL	G1.1	PRISF	S2.1	UWSFL	S3.2
JDSFP	S6.1	KNC	1.2	LXEMC	15.2	PRLG	19.2	VCB	9.3
JFS	20.1	KPBVF	G3.2	LXERC	15.2	PRLM	19.2	VCG	9.4
JGRC	G1.1	KPCAL	G3.2	M	23.2	PRMPL	S5.2	VCL	9.2
JGS	20.1	KPLE	G3.2	MF	4.1	PRMPS	S5.2	VWT	13.2
JICD	6.1	KRJME	G3.2	MJTS	4.3	PRPSL	S5.2	XBFG	16.3
JJ	21.2	KRPLE	G3.2	MNF	4.1	PRTI	3.2	XIDWF	7.2
JJS	7.5	KSFOP	S6.1	MSFM	S3.1	PTI	3.2	XMIWF	7.2
JJZ	21.2	KSFPC	S3.1	NCAL	23.1	PWSFL	S3.2	XVRC	2.3
JKC	7.5	KSFWI	S3.3	NCE	11.1	RBS	9.3	XVRL	2.3
JLISF	S2.4	KSFWL	S3.3	NCS	11.1	RDT	5.3	XVRU	2.3
JLL	21.3	KSRTL	19.3	NCSIP	20.3	RGS	9.4	XVRT	2.3
JLLSF	S6.1	KVPQB	9.1	NCV	2.2	RL	9.2	ZK	18.1
JLU	21.3	KVPQG	9.1	NDF	1.2	RPDLI	S4.3	-----	
JLUSF	S6.1	KVPQL	9.1	NDWF	11.3	RPISF	S2.2		
JMS	20.1	LAL	11.3	NDWSF	S4.3	RPNSF	S5.2		

Table F-4. Index of All Data with Information Reference Numbers.

F.7. INDEX OF ALL NAMES SPECIFIC TO THE OUTPUT FILES.
(PRINTED OUTPUT and GRAPHICS OUTPUT)

Table F-5. Index of All Names Specific to Output Files.

CSN	:	Calculation Step Number.
DSN	:	Data Set Number in the group of data.
T	(%DE)	: Time , % of the duration of expulsion.
T-GE	(%DE-GE)	: Time , in gas expulsion as % of its duration.
T-SF	(%DE-SF)	: Time , in SF phenomena as % of its duration.
BV	(%IV)	: Void Fraction , % of Initial Value.
CEC	:	Precision of expulsion , Expelled / Depleted.
CEC-SF	:	Precision of Expulsion Calculations ; SF.
DE	(MS)	: Duration of Expulsion in Milliseconds.
DEL	(%MV)	: Movement of the CS , % of Mean Value.
DP-E	:	I. Dimensionless Parameter. (Routine SENDEX)
DP-T	:	II. " " " " " " " "
DT	(%MV)	: Time increment , % of Mean Value.
DTRT	:	: Time increment , % of Theoretical value.
DTRT-SF	:	: Time increment , SF , % of Theoretical Value.
DT-SF	(%MV)	: Time increment , SF process , % of Mean Value.
HM	(%HV)	: Height of mixture level , % of Vessel Height.
MCES	(%IV)	: Mass of Contents Expelled , % of Initial Value.
MCES-SF	(%MV)	: Mass of Contents Expelled , SF , % of Mean V.
MCE-S/G	(%MV)	: Mass of Content Expelled, Gas, % of Mean Value.
MG	(%IV)	: Mass of Gas expelled , % of Initial Value.
PBVF	:	: Final Void Fraction , % of Initial Value.
PCAL	:	: Precision of Calcs., overall, up to a time.
PCE	(%FV)	: Per. of Contents Expelled , % of Full Value.
PHM-S	:	: Height of mixture level , % of full value.
PLE	(%IV)	: Per. of Liquid Expelled , % of Initial Value.
PR-T	:	: Pressure at the Top of the Vessel [Atm].
RJME	:	: Ratio, Total number of steps to the nodes.
RPLE	:	: Percentage of Liquid Expelled , % of QSS Value.

END OF APPENDIX F

APPENDIX - G

DESCRIPTION OF THE ROUTINES

G.1. CLASSIFICATION OF THE MAIN JOBS OF THE ROUTINES.

THE "JCN"s : JOB CLASSIFICATION NUMBERS.

- ```

0 - General preparation.
01 - In program file handling statements.
02 - Establishing the principal job parameters.
03 - Determination of the principal constants and standard values.
04 - Principal loop of the multi job runs.

1 - Main part for all cases.

11 - Main job loop of the Non-Full Vessel case.
12 - Main job loop of the Full Vessel cases.
13 - Main mill-time checks.

2 - Preparatory work.

21 - Initialization, creation of constants, establishing limits.
22 - Reading the heading and the principal data.
221 - Reading top part of the data file, related initializations.
222 - " " middle " " " " " " " " " " .
223 - " " bottom " " " " " " " " " " .
224 - Special format data handling. (Very big or small numbers)
23 - Correction of the mismatched data.
24 - Printing the main data on top of the output file.
241 - " " " heading of the data file.
242 - " " " arrayed initial values.
243 - " " " top part of the data list.
244 - " " " middle " " " " " " " " .
245 - " " " bottom " " " " " " " " .

25 - Establishing the arrays of the vessel geometry.
26 - Preparation to the calculations.
261 - Establishing initial β and R distributions. (β_0, R_0)
262 - Establishing all arrayed variables.
263 - Extraction of a step's data from multi-data files.
264 - Naming important initial values.
265 - Opening characteristics related initial values.
266 - Printing important parameters on the special points.

3 - Organizing the case applications.

31 - NFV case initialization, loop and precision calculations.
311 - Gas region MC calculations, related array manipulations.
312 - NFV MC calculations, preparation and organization.
313 - Preparation and checks on the gas region MC calculations.
314 - Calculation of the points in the gas region, debugging work.

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- 315 - Preparation of the next steps data, array assignments.
- 316 - Checks on the precision of the NFV calculations.
- 317 - NFV case ; printing a step's data, mill-time checks.
- 318 - Detailed information, error tracing and precision calc.
- 32 - NFV to FV transformation calculations.
- 321 - Energy balance calculations for the transformation.
- 322 - Error level calculations on the transformation process.
- 323 - Arrangement of the arrays for the new node number value.
- 324 - Establishing the arrays of the Full Vessel calculations.
  
- 33 - Preparation for the filled up vessel conditions.
- 331 - Precision calculations of the NFV to FV transformation.
- 332 - Establishing the new characteristic values at the Open End.
- 333 - Initialization as a preparation to the Full Vessel condition.
  
- 34 - FV case initialization, loop and precision calculations.
- 341 - Preparatory work on the newly created SF calculations.
- 342 - Establishment of the step's data of the loop calculations.
- 343 - End of the SF adjustments.
- 344 - End of the expulsion checks.
- 345 - Time step calculations, adjustments for IWF and SF.
- 346 - Preparation and checks on the FV MC calculations.
- 347 - Checks on the end of the SF calculations.
- 348 - Calculations on the quantities of establishing precision.
- 349 - Preparation of the next step's data, array value assignments.
  
- 4 - Common parts of the MC applications.
- 41 - Initialization for all MC calculations.
- 42 - Establishment of the basis of the U and p calculations.
- 421 - Calculation of the U and p values ; all formats provided.
- 422 - Error tracing statements for U and p calculations.
  
- 43 - Establishment of the basis of the  $\beta$  and R calculations.
- 431 - Void fraction ( $\beta$ ) calculations ; all formats provided.
- 432 - Bubble radius (R) calculations ; all formats provided.
- 433 - Error tracing statements for  $\beta$  and R calculations.
  
- 44 - Movement of the discontinuity surfaces calculations.
- 441 - IWF - Initial Wave Front movement calculations.
- 442 - CS - Contact Surface " " " " " .
- 443 - SF - Shock Front " " " " " .
- 444 - Error tracing on the discontinuity surface movements.
  
- 45 - Changing (doubling / halving) of the M node number calc.
- 451 - Adjustment of the arrays to the changed node number.
- 452 - Evaluation of the position of the discontinuity surface.
- 453 - Determination of special point values.
  
- 5 - Expulsion data calculations.
- 51 - Expulsion of the gas calculations, including back-flow.
- 52 - Mixture expulsion calculations; many different formats.
- 53 - Mixture expulsion calculations with steam-water mix. eqns.
- 54 - Calc. of flow coefficients; standard and other openings.
- 55 - Pressure change for full opening; durationed opening.
  
- 6 - Physical quantities calculations.

- 61 - Shape of the vessel calculations.
- 611 - Functions for creating practical vessel shapes.
- 612 - Total or partial volume or related calculations.
- 613 - Calculation of the coefficients of the shape functions.
- 62 - Speed of Wave Propagation (SWP) calculations.
- 621 - SWP calculation with all known formats.
- 622 - SWP calculation for very low  $\beta$  and / or R cases.
- 63 - CPR - critical pressure ratio calculation for both phases.
- 64 - Calculation of wall friction coefficient.
- 641 - Wall friction coefficient for the gas phase calculations.
- 642 - " " " " " " " " mixture " " " " " " .
- 65 - Calculation of the physical properties of the phases.
- 651 - " " " " " " " " ; gas phase.
- 652 - " " " " " " " " ; mixture " " .
- 653 - " " " " " " " " ; liquid in mixture.
- 654 - " " " " " " " " ; gas " " " " .
- 7 - Method of characteristics calculations.
- 71 - Ordinary points MC calculations.
- 711 - " " " " " " " " ; in the gas.
- 712 - " " " " " " " " ; " " mixture.
- 72 - Closed end point MC calculations.
- 721 - " " " " " " " " ; in the gas.
- 722 - " " " " " " " " ; " " mixture.
- 723 - CE MC calc. in the mixture with ordinary or reflected SF.
- 73 - Open end point MC calculations.
- 731 - " " " " " " " " ; in the gas.
- 732 - " " " " " " " " ; " " mixture.
- 733 - OE MC calculations in gas with initial wave front IWF.
- 734 - " " " " " " " mixture " " " " " " " " .
- 735 - " " " " " " " gas " contact surface CS.
- 736 - " " " " " " " mixture " shock front SF.
- 737 - " " " " " " " gas for quasi-steady flow QSF.
- 738 - " " " " " " " mixture " " " " " " .
- 74 - Contact surface point MC calculations.
- 75 - MC calculations of the special points near CS.
- 751 - " " " " " " " " " " " " ; in gas.
- 752 - " " " " " " " " " " " " ; " mixture.
- 76 - MC calculations for initial wave front IWF.
- 761 - MC " " " points near IWF ; in gas.
- 762 - MC calc. points near IWF in gas ; def. of char. values.
- 763 - MC calculations for points near IWF ; in mixture.
- 764 - MC calc. points near IWF in mixture ; def. of char. values.
- 77 - MC calculations for the shock front SF point.
- 771 - MC calc. for the low pressure side / after point of the SF.
- 772 - MC calculations on the characteristic points of the SF.
- 773 - MC calc. for the high pressure side / before point of the SF.

- 774 - MC calculations for points near and before the SF.
- 775 - MC calc., points near and before SF ; def. of char. values.
- 776 - MC calculations for points near and after the SF.
- 777 - MC calc., points near and after SF ; def. of char. values.
  
- 8 - SF shock front calculations.
- 81 - Initialization and organizing work for the SF calc.
- 82 - Determination of the starting PR , SF PR calculations.
- 83 - Reflection of the SF at closed end calculations.
- 84 - Solving the SF equations ; different starting formats.
- 85 - Calc. error level checks with SF conservation equations.
- 86 - Precision of the SF definitions and error level checks.
- 87 - Adjusted , new PR value calculations of the SF loop.
  
- 9 - Graphics drawing work.
- 91 - Establishing the format of the graphics pages parameters.
- 92 - Preparation of the heading and the listing pages.
- 921 - Printing the title and the and organizing the print pages.
- 922 - Printing the first half of the main data file.
- 923 - " " " last " " " " " " " " .
- 924 - Printing the main results of the run.
- 93 - Common procedures ; used by the principal job routines.
- 931 - Format for printing data file and main results lines.
- 932 - " " " " " arrayed information.
- 933 - Preparation of a page for graphics work.
- 934 - Allocation of physical space for graphics drawing.
- 935 - Common procedures ; typing scale and and recognition inf.
- 936 - Axes annotation intervals calculation.
- 937 - FV - MD cases common calculations.
- 938 - Correction on formatted printing work.
- 94 - Organization of the graphics for NFV case.
- 941 - Drawing first part of the graphics for NFV case.
- 942 - " " second " " " " " " " " " " .
- 95 - Graphics work on FV cases.
- 951 - Organization of the graphics for FV case.
- 952 - Drawing " " " " " " " " .
- 96 - Graphics work on FV - MD cases.
- 961 - Organization of the graphics for the FV - MD cases.
- 962 - Drawing " " " " " " " " " " .
- 97 - Graphics work on FV - MD Special case.
- 971 - Organization of graphics for FV - MD Special case.
- 972 - Drawing graphics for FV - MD Special case ; first quarter.
- 973 - " " " " " " " " " " " ; second " " " .
- 974 - " " " " " " " " " " " ; third " " " .
- 975 - " " " " " " " " " " " ; last " " " .
- 98 - Graphics work on the GB gas bottle case.
- 981 - Organization of the graphics for the GB case.
- 982 - Drawing " " " " " " " " " " .
- 99 - Graphics work on FV - Special case.

- Table G-1. Classification of the Main Jobs of the Routines.  
The "JCN" - Job Classification Numbers - Listing.

Table G-1. Classification of the Main Jobs of the Routines.  
The "JCN" - Job Classification Numbers - Listing.

G.2. LISTING OF THE ROUTINES IN JOB CLASSIFICATION NUMBER ORDER.

| JCN       | NAME   | ROUTINES CALLED |        |        |        |        |        |  |
|-----------|--------|-----------------|--------|--------|--------|--------|--------|--|
| 01 - 04   | MAIN   | SEBLFV          |        |        |        |        |        |  |
| 11 - 13   | SEBLFV | SRAIV           | SWAIV  | SCIVF  | SCIVL  | SNFVC  | SNFFT  |  |
|           |        | SFVC            | SCMT   | SENDEX | SGRAOL |        |        |  |
| 21 + 23   | SRAIV  | SREAD           | SVPQM  | SVPOG  |        |        |        |  |
| 22        | SREAD  | SREADF          | SREADS | SREADT | FREAD  |        |        |  |
| 221       | SREADF |                 |        |        |        |        |        |  |
| 222       | SREADS |                 |        |        |        |        |        |  |
| 223       | SREADT |                 |        |        |        |        |        |  |
| 224       | FREAD  |                 |        |        |        |        |        |  |
| 24 - 25   | SWAIV  | SWRITE          | SVES   |        |        |        |        |  |
| 241 - 242 | SWRITE | SWRDFF          | SWRDFS | SWRDFT |        |        |        |  |
| 243       | SWRDFF |                 |        |        |        |        |        |  |
| 244       | SWRDFS |                 |        |        |        |        |        |  |
| 245       | SWRDFT |                 |        |        |        |        |        |  |
| 261 - 263 | SCIVF  | SVES            |        |        |        |        |        |  |
| 264 - 266 | SCIVL  |                 |        |        |        |        |        |  |
| 31        | SNFVC  | SNFMC           | SNFVCE |        |        |        |        |  |
| 311       | SNFGR  | SPHIV           | SOEGS  | SMDS   | SWOEG  | SOEG   | SCSOE  |  |
|           |        | SNFGRE          |        |        |        |        |        |  |
| 312       | SNFMC  | STWOM           | SCSC   | SIWF   | SNFMCC | SNFMCE |        |  |
| 313       | SNFMCC | SNFGR           | SCEM   | SCEG   | SWMCM  | SPNCSM | SMCM   |  |
| 314       | SNFGRE | SWMCG           | SPNCSG | SMCG   |        |        |        |  |
| 315       | SNFVCE | SNFWR           |        |        |        |        |        |  |
| 316       | SNFMCE |                 |        |        |        |        |        |  |
| 317 - 318 | SNFWR  | SCMT            |        |        |        |        |        |  |
| 321 - 324 | SNFFT  | SNFFTE          |        |        |        |        |        |  |
| 331 - 333 | SNFFTE | SOEMS           |        |        |        |        |        |  |
| 341 - 344 | SFVC   | SFVMC           | SFVCE  |        |        |        |        |  |
| 345       | SFVMC  | SPHIV           | SSFR   | SIWF   | SFVMCC | SFVMCE |        |  |
| 346       | SFVMCC | SOEMS           | SMDS   | SWOEM  | SOEM   | SSFR   | SCEM   |  |
|           |        | SWMCM           | SMCM   |        |        |        |        |  |
| 347 - 348 | SFVMCE |                 |        |        |        |        |        |  |
| 349       | SFVWR  | SCMT            |        |        |        |        |        |  |
| 41        | SIFMC  |                 |        |        |        |        |        |  |
| 42        | SMCUAP | SVPQM           | SVPQG  | SCFM   | SCFG   | SMCUPC | SMCUPE |  |
| 421       | SMCUPC |                 |        |        |        |        |        |  |
| 422       | SMCUPE |                 |        |        |        |        |        |  |
| 431 - 433 | SMCBOR |                 |        |        |        |        |        |  |
| 441 - 444 | SMDS   |                 |        |        |        |        |        |  |
| 451 - 453 | STWOM  | SVES            |        |        |        |        |        |  |
| 51        | SGED   | SFCDN           |        |        |        |        |        |  |
| 52        | SMED   | SFCDN           | SMEDS  |        |        |        |        |  |
| 53        | SMEDS  |                 |        |        |        |        |        |  |
| 54        | SFCDN  |                 |        |        |        |        |        |  |
| 55        | SPOEFO |                 |        |        |        |        |        |  |

| JCN       | NAME   | ROUTINES CALLED |        |        |        |       |        |  |
|-----------|--------|-----------------|--------|--------|--------|-------|--------|--|
| 611 - 612 | SVES   | FNCV            | FSHV   |        |        |       |        |  |
| 613       | FNCV   |                 |        |        |        |       |        |  |
| 614       | FSHV   |                 |        |        |        |       |        |  |
| 621 - 622 | FSWP   |                 |        |        |        |       |        |  |
| 63        | SCPR   | (NAG)           |        |        |        |       |        |  |
| 641       | SCFG   |                 |        |        |        |       |        |  |
| 642       | SCFM   |                 |        |        |        |       |        |  |
| 651       | SVPQG  |                 |        |        |        |       |        |  |
| 652       | SVPQM  | SVPQL           | SVPQB  |        |        |       |        |  |
| 653       | SVPQL  |                 |        |        |        |       |        |  |
| 654       | SVPQB  |                 |        |        |        |       |        |  |
| 711       | SMCG   | SIFMC           | SMCUAP | SMCBOR |        |       |        |  |
| 712       | SMCM   | "               | "      | "      |        |       |        |  |
| 721       | SCEG   | "               | "      | "      |        |       |        |  |
| 722       | SCFM   | "               | "      | "      |        |       |        |  |
| 723       | SFCE   | "               | "      | "      |        |       |        |  |
| 731       | SOEG   | SIFMC           | SMCUAP | SMCBOR | SCPR   | SGED  | SPOEFO |  |
| 732       | SOEM   | "               | "      | "      | "      | SMED  | "      |  |
| 733       | SWOEG  | "               | "      | "      | "      | SGED  | "      |  |
| 734       | SWOEM  | "               | "      | "      | "      | SMED  | "      |  |
| 735       | SCSOE  | "               | "      | "      | "      | SGED  |        |  |
| 736       | SFOE   | "               | "      | "      | "      | SMED  |        |  |
| 737       | SOEGS  | "               | "      | "      | "      | SGED  |        |  |
| 738       | SOEMS  | "               | "      | "      | "      | SMED  |        |  |
| 74        | SCSC   | SIFMC           | SMCUAP | SMCBOR | SMDS   | SVES  |        |  |
| 751       | SPNCSG | "               | "      | "      |        |       |        |  |
| 752       | SPNCSM | "               | "      | "      |        |       |        |  |
| 76        | SIWF   | SMDS            |        |        |        |       |        |  |
| 761       | SWMCG  | SIFMC           | SWGMC  | SMCBOR |        |       |        |  |
| 762       | SWGMC  | SMCUAP          |        |        |        |       |        |  |
| 763       | SWMCM  | SIFMC           | SWMMC  | SMCBOR |        |       |        |  |
| 764       | SWMMC  | SMCUAP          |        |        |        |       |        |  |
| 771       | SSFMC  | SIFMC           | SMCSF  | SMCBOR | SMCUAP |       |        |  |
| 772       | SMCSF  | SMCUAP          |        |        |        |       |        |  |
| 773       | SSFP   | SIFMC           | SMCUAP |        |        |       |        |  |
| 774       | PNSFB  | SIFMC           | SPNSBM | SMCBOR |        |       |        |  |
| 775       | SPNSBM | SMCUAP          |        |        |        |       |        |  |
| 776       | PNSFA  | SIFMC           | SPNSAM | SMCBOR |        |       |        |  |
| 777       | SPNSAM | SMCUAP          |        |        |        |       |        |  |
| 81        | SSFR   | SCSF            | SFRC   | SPNSFB | SPNSFA | SFOE  | DFCE   |  |
| 82        | SCSF   | SIFMC           | SMDS   | SSFMC  | SSFE   | SFCEQ | SOEMS  |  |
|           |        | SDWSF           | SSFP   | SRPSF  | SNLSF  |       |        |  |
| 83        | SFRC   | SIFMC           | SSFE   | SFCEQ  | SDWSF  | SRPSF | SMDS   |  |
|           |        | SSFMC           |        |        |        |       |        |  |
| 84        | SSFE   | SNLSF           | SCMT   | SFCEQ  |        |       |        |  |
| 85        | SFCEQ  |                 |        |        |        |       |        |  |
| 86        | SDWSF  |                 |        |        |        |       |        |  |
| 87        | SRPSF  | SCMT            |        |        |        |       |        |  |

| JCN         | NAME   | ROUTINES CALLED |        |        |       |       |       |
|-------------|--------|-----------------|--------|--------|-------|-------|-------|
| 91          | SGRD   | SDGR            | SVPQM  | SVPQG  | SGRDW | SGRMR | SGRNF |
|             |        | SGRFV           | SGRFM  | SGRMD  | SGRFS | SGRGB |       |
| 921         | SGRDF  | SGRDFF          | SGRDFL | SGRLTS | SDGR  |       |       |
| 922         | SGRDFF | SGRLT           |        |        |       |       |       |
| 923         | SGRDFL | SGRLT           |        |        |       |       |       |
| 924         | SGRMR  | SGRLT           | SGRLTS | SDGR   |       |       |       |
| 931         | SGRLT  | SGRTE           |        |        |       |       |       |
| 932         | SGRLTS |                 |        |        |       |       |       |
| 933         | SDGR   |                 |        |        |       |       |       |
| 934         | SPS    |                 |        |        |       |       |       |
| 935         | SGRCP  |                 |        |        |       |       |       |
| 936         | GRAI   |                 |        |        |       |       |       |
| 937         | SGRFMC |                 |        |        |       |       |       |
| 938         | SGRTE  |                 |        |        |       |       |       |
| 94          | SGRNF  | SGRNFF          | SGRNFS |        |       |       |       |
| 951         | SGRFV  | SGRFVD          |        |        |       |       |       |
| 952         | SGRFVD | SDGR            | SPS    | SGRCP  |       |       |       |
| 961         | SGRMD  | SGRMDD          |        |        |       |       |       |
| 962         | SGRMDD | SDGR            | SPS    |        |       |       |       |
| 971         | SGRFM  | SGRFMD          | SGRFMS |        |       |       |       |
| 972         | SGRFMD | SGRFMC          | SDGR   | SPS    |       |       |       |
| 973         | SGRFMS | SGRFMX          | SGRFMY | SDGR   |       |       |       |
| 974         | SGRFMX | SPS             |        |        |       |       |       |
| 975         | SGRFMY | SDGR            |        |        |       |       |       |
| 981         | SGRGB  | SGRGBD          |        |        |       |       |       |
| 982         | SGRGBD | SDGR            | SPS    | SGRCP  |       |       |       |
| 991         | SGRFS  | SGRFSF          | SGRFSS |        |       |       |       |
| 992         | SGRFSF | SDGR            | SPS    |        |       |       |       |
| 993         | SGRFSS | SDGR            | SPS    | SGRCP  |       |       |       |
| 101         | SCMT   | GLIB            |        |        |       |       |       |
| 1021 - 1022 | SGRAOL | SGRD            | SCMT   | SOAL   |       |       |       |
| 103         | SOAL   | SOALF           | SOALL  |        |       |       |       |
| 1031        | SOALF  |                 |        |        |       |       |       |
| 1032        | SOALL  |                 |        |        |       |       |       |
| 104         | SENDEX |                 |        |        |       |       |       |
| 105         | SPHIV  |                 |        |        |       |       |       |
| 1061        | FCPR   | (NAG)           |        |        |       |       |       |
| 1062        | SNLSF  | SFNFN           | (NAG)  |        |       |       |       |
| 1063        | SFNJA  | "               | "      |        |       |       |       |
| 1064        | SFNFN  | (NAG)           |        |        |       |       |       |

Table G-2. Listing of the Routines Called in "JCN" Order.

G.3. INDEX OF ALL ROUTINES AND THEIR JOB CLASSIFICATION NUMBERS.

| NAME   | JCN         | NAME   | JCN       | NAME    | JCN       |
|--------|-------------|--------|-----------|---------|-----------|
| FCPR   | 1061        | SGRFM  | 971       | SNLSF   | 1062      |
| FNCV   | 613         | SGRFMC | 937       | SOAL    | 103       |
| FREAD  | 224         | SGRFMD | 972       | SOALF   | 1031      |
| FSHV   | 614         | SGRFMS | 973       | SOALL   | 1032      |
| FSWP   | 621 - 622   | SGRFMX | 974       | SOEG    | 731       |
| GRAI   | 936         | SGRFMY | 975       | SOEGS   | 737       |
| MAIN   | 01 - 04     | SGRFS  | 991       | SOEM    | 732       |
| PNSFA  | 776         | SGRFSF | 992       | SOEMS   | 738       |
| PNSFB  | 774         | SGRFSS | 993       | SPHIV   | 105       |
| SCEG   | 721         | SGRFV  | 951       | SPNCSG  | 751       |
| SCEM   | 722         | SGRFVD | 952       | SPNCSM  | 752       |
| SCFG   | 641         | SGRGB  | 981       | SPNSAM  | 777       |
| SCFM   | 642         | SGRGBD | 982       | SPNSBM  | 775       |
| SCIVF  | 261 - 263   | SGRLT  | 931       | SPOEFO  | 55        |
| SCIVL  | 264 - 266   | SGRLTS | 932       | SPS     | 934       |
| SCMT   | 101         | SGRMD  | 961       | SRAIV   | 21 - 23   |
| SCPR   | 63          | SGRMDD | 962       | SREAD   | 22        |
| SCSC   | 74          | SGRMR  | 924       | SREADF  | 221       |
| SCSF   | 82          | SGRNF  | 94        | SREADS  | 222       |
| SCSOE  | 735         | SGRTE  | 938       | SREADT  | 223       |
| SDGR   | 933         | SIFMC  | 41        | SRPSF   | 87        |
| SDWSF  | 86          | SIWF   | 76        | SSFE    | 84        |
| SEBLFV | 11 - 13     | SMCBOR | 431 - 433 | SSFMC   | 771       |
| SENDEX | 104         | SMCG   | 711       | SSFP    | 773       |
| SFCDN  | 54          | SMCM   | 712       | SSFR    | 81        |
| SFCE   | 723         | SMCSF  | 772       | STWOM   | 451 - 453 |
| SFCEQ  | 85          | SMCUAP | 42        | SVES    | 611 - 612 |
| SFNFN  | 1064        | SMCUPC | 421       | SVPQB   | 654       |
| SFNJA  | 1063        | SMCUPE | 422       | SVPQG   | 651       |
| SFOE   | 736         | SMDS   | 441 - 444 | SVPQL   | 653       |
| SFRC   | 83          | SMED   | 52        | SVPQM   | 652       |
| SFVC   | 341 - 344   | SMEDS  | 53        | SWAIV   | 24 - 25   |
| SFVMC  | 345         | SNFFT  | 321 - 324 | SWGMC   | 762       |
| SFVMCC | 346         | SNFFTE | 331 - 333 | SWMCG   | 761       |
| SFVMCE | 347 - 348   | SNFGR  | 311       | SWMCM   | 763       |
| SFVWR  | 349         | SNFGRE | 314       | SWMMC   | 764       |
| SGED   | 51          | SNFMC  | 312       | SWOEG   | 733       |
| SGRAOL | 1021 - 1022 | SNFMCC | 313       | SWOEM   | 734       |
| SGRCP  | 935         | SNFMCE | 316       | SWRDFF  | 243       |
| SGRD   | 91          | SNFVC  | 31        | SWRDFFS | 244       |
| SGRDF  | 921         | SNFVCE | 315       | SWRDFT  | 245       |
| SGRDFF | 922         | SNFWR  | 317 - 318 | SWRITE  | 241 - 242 |
| SGRDFL | 923         | -      | -         | -       | -         |

Table G-3. Index of All Routines with "JCN" Numbers.

END OF APPENDIX G

## A P P E N D I X - H

### R O U T I N E S   C A L L   D I A G H R A M S

Due to the number of routines involved , it was not possible to draw the Routines Call Diagram of the program as a whole on a single page. Instead , the program has been divided into three characteristic cases in respect to the related MC calculations and two characteristic program parts that when combined together creates the whole routines call diagram of a case.

The routines call diagrams listed below are prepared ;

- H1. Non - Full Vessel Case , MC calc. routines call diagrams.
- H2. Full Vessel Cases , " " " " " " " " .
- H3. Gas Bottle Case , " " " " " " " " .
- H4. Shock Front Calculations routines call diagram.
- H5. Graphics Drawing work " " " " " " .

The full routines call diagrams of the cases can be created by the combination of the case and calculation group diagrams listed above in the format given in Table. H-1. ;

Table H-1. Routines Call Diagram Combinations.

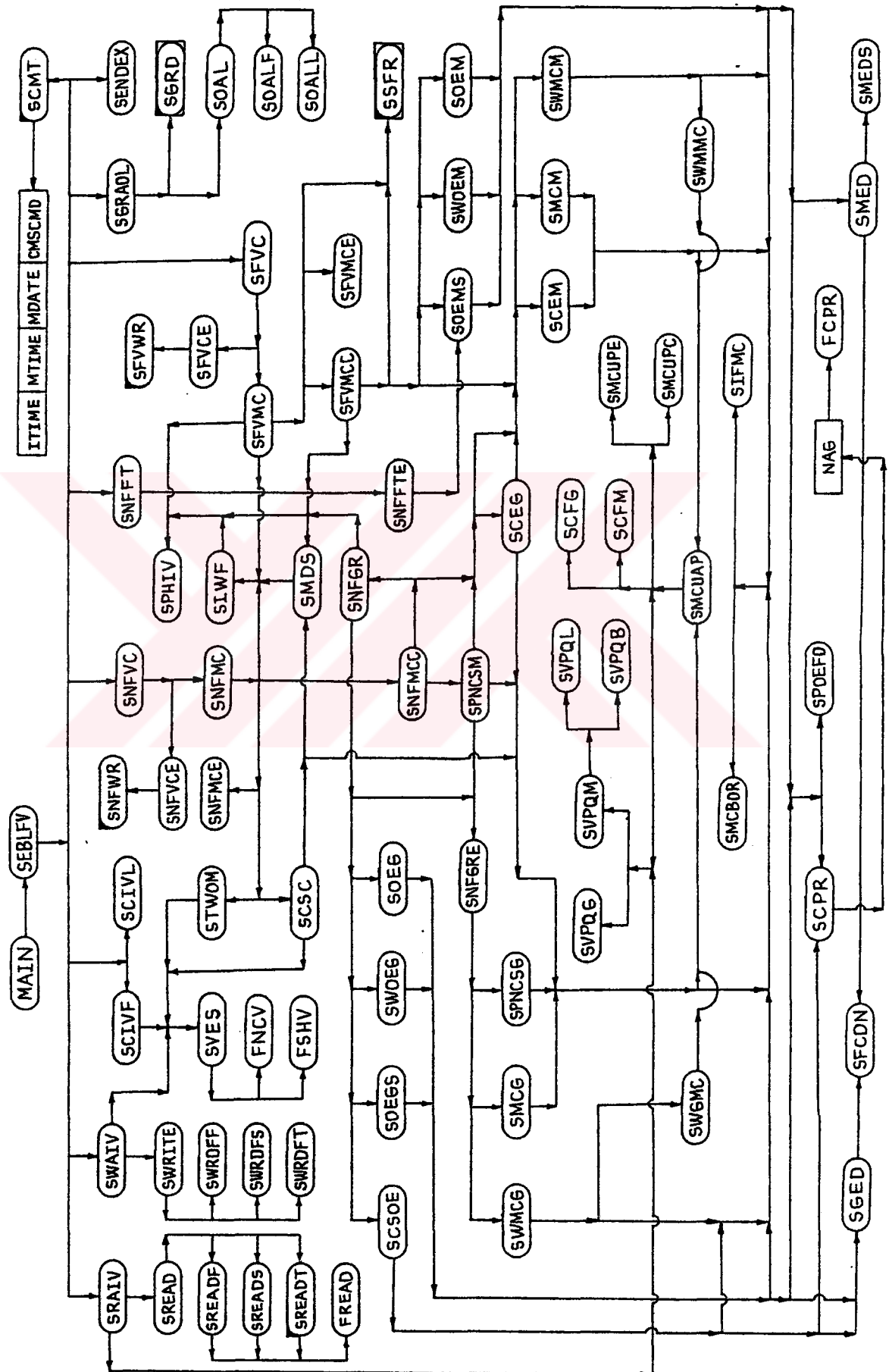
|                        | Chapter No : | H1 | H2 | H3 | H4 | H5 |
|------------------------|--------------|----|----|----|----|----|
| Non - Full Vessel      | :            | X  | -  | -  | X  | X  |
| Full Vessel            | }            | -  | -  | -  | -  | -  |
| " " " - Multi Data     |              | -  | X  | -  | -  | X  |
| " " " - " " - Special  |              | -  | -  | -  | -  | -  |
| " " " - Special        | :            | -  | X  | -  | X  | X  |
| Pressurized Gas Bottle | :            | -  | -  | X  | -  | X  |

#### Notes :

- \* The run time calculation routine SCMT is called by many MC and SF calculation routines which are indicated by the right - angled drawing of their boxes on the up-left corner.
- \* The speed of wave propagation calculation routine FSWP is called by all MC calculations routines and . it was found very unpractical to include it into the already complex routines call diagrams.

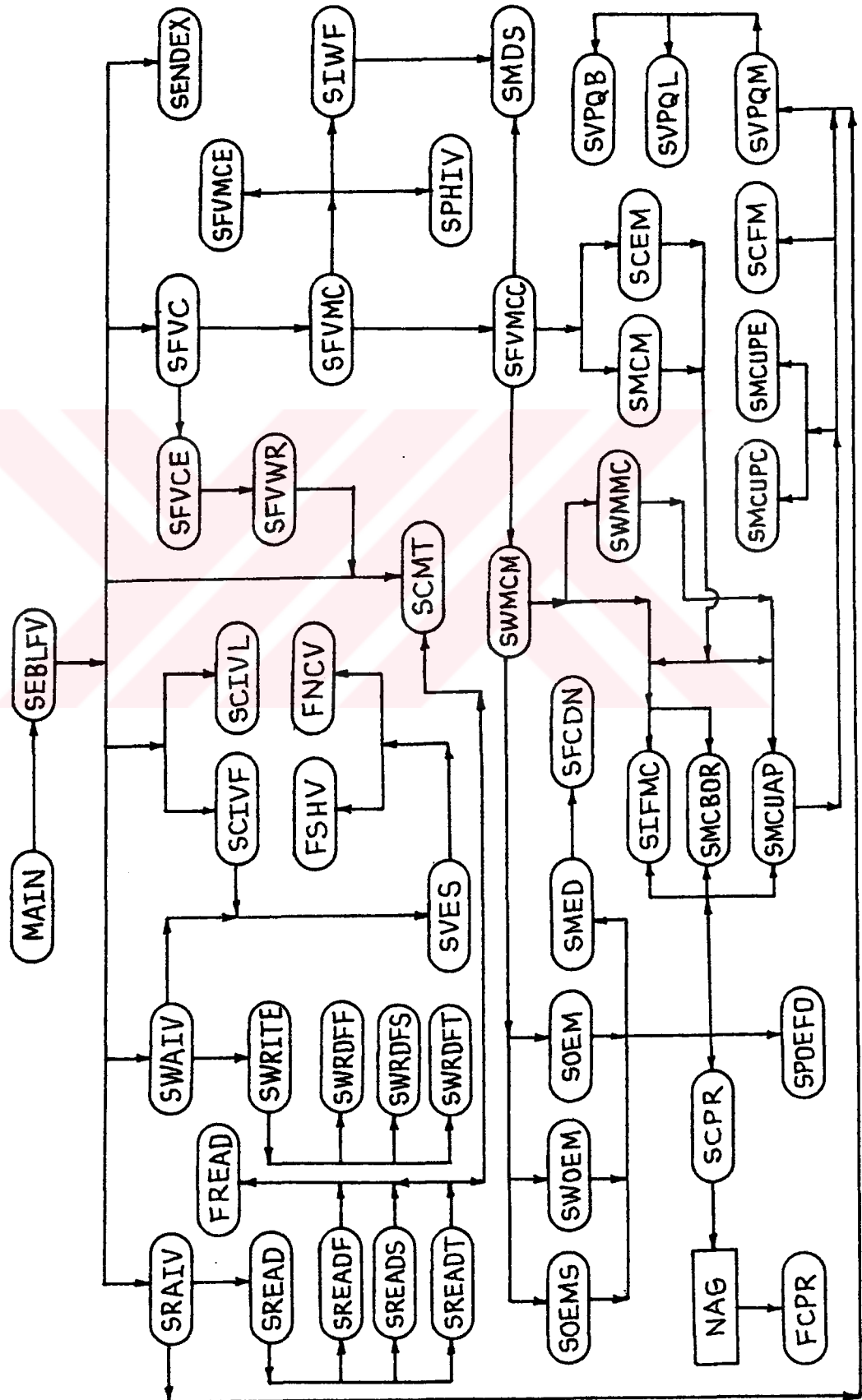
H.1 NON-FULL VESSEL CASE, MC CALCULATIONS ROUTINES CALL DIAGRAM.

### Table H-2 Routines Call Diagrams of the Non-Full Vessel Case.



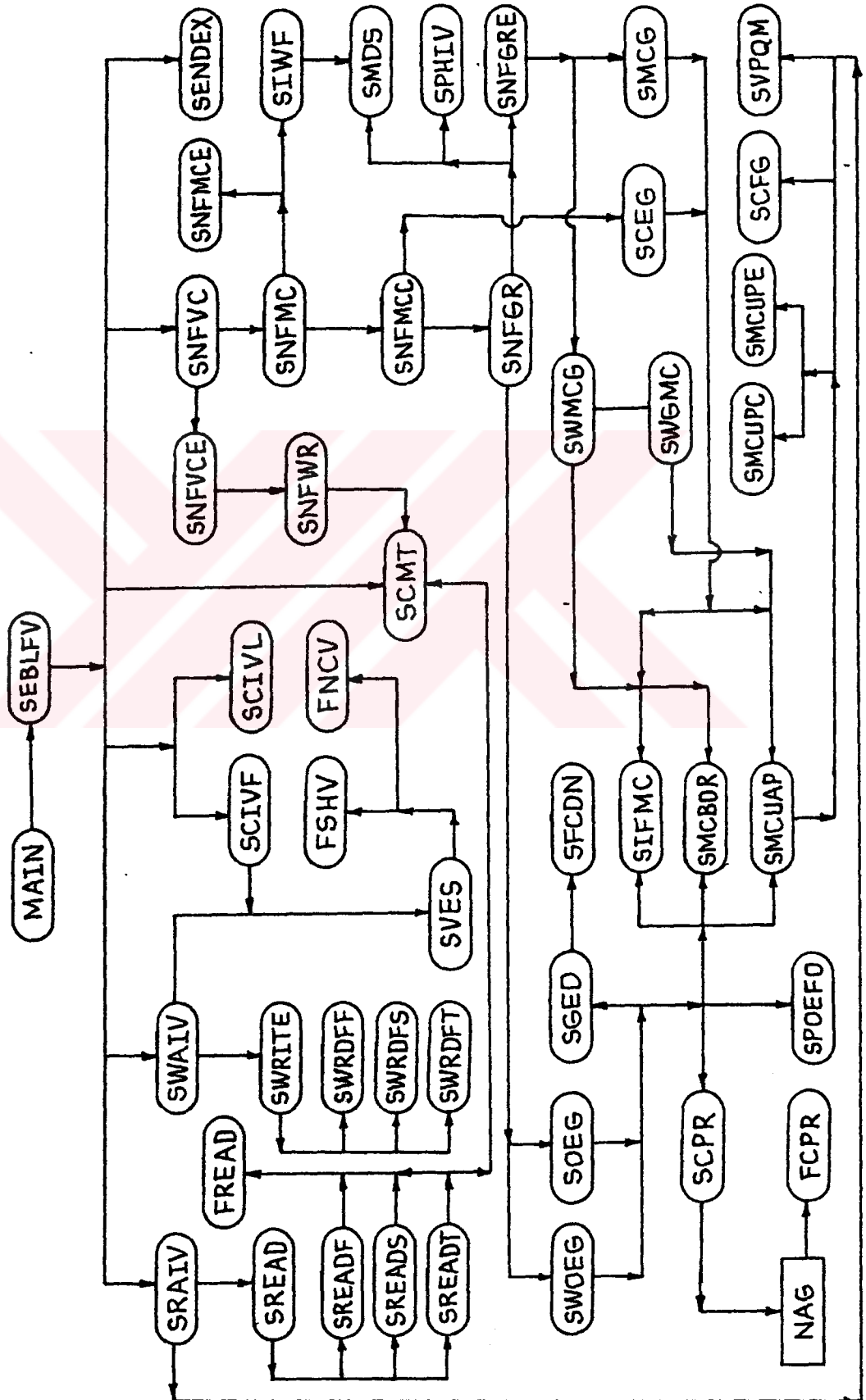
H.2 FULL VESSEL CASES, MC CALCULATIONS ROUTINES CALL DIAGRAM.

Table H-3 Routines Call Diagrams of the Full Vessel Case.



H.3 GAS BOTTLE CASE, MC CALCULATIONS ROUTINES CALL DIAGRAM.

Table H-4 Routines Call Diagrams of the Gas Bottle Case.







## A P P E N D I X - I

### T H E   P R O G R A M M E

### S T A T I S T I C S   A N D   R E Q U I R E M E N T S

#### I.1. STATISTICAL INFORMATION.

Total File Statistics ; are given on the Table I-1.

Table I-1. Total File Statistics of the Program.

|                                       |                 |
|---------------------------------------|-----------------|
| Lines ; Including empty comment lines | ≈ 45500 [Lines] |
| Without the Graphics part             | ≈ 36200 [ " " ] |
| Blocks ; (1 K size blocks)            | ≈ 3550 [Blocks] |
| Without the graphics part             | ≈ 2850 [ " " ]  |
| For the full vessel cases             | ≈ 29750 [Lines] |
| and without the graphics              | ≈ 2350 [Blocks] |

Individual File Statistics ; are given on the Table I-2.

Table I-2. Sizes and the Functions of the Program Parts.

| Order<br>No: | Name | Length<br>[Line] | Function                         |
|--------------|------|------------------|----------------------------------|
| 1            | PFS  | ≈ 8450           | Main part + Data read and write. |
| 2            | NAF  | ≈ 7700           | Case settings and outputting.    |
| 3            | MAR  | ≈ 7950           | Common MC etc. calculation jobs. |
| 4            | SMC  | ≈ 5750           | MC frame calculation routines.   |
| 5            | SSF  | ≈ 6450           | SF and SF-Mc calculations.       |
| 6            | SGR  | ≈ 9300           | Graphics drawing routines.       |

The line numbers include full and empty comment lines.

#### Arrays Size Information.

The sizes of arrays very much depends on the two special variables of array dimensioning listed and defined below ;

IAL ; Maximum number of MC calculation nodes that can be used.  
Required for all runs. Can be very small for the FV cases.

IALO ; Maximum number of calculation steps that can be handled.  
Required for Graphics and Output Arrays List jobs only.

---

(\*) Including ; Sample Data Files , Three short programs use for the curve fitting .. jobs , Some MC grid drawings and A shape of the functions explanation drawing in some parts for safe keeping.

The Total Array Dimensions Requirement (TADR) - excluding small multi data run arrays - may be calculated as below ;

$$\text{TADR} = 26 * (\text{IAL} \approx 801) + 21 * (\text{IALO} \approx 2000) \approx 43.000$$

Only very extreme max. IAL numbers and corresponding IALO values that require TADR > 300 K may create problem on some small machines.

## I.2. COMMON BLOCKS INFORMATION.

Statistics on COMMON blocs ; are given on the Table I-3.

Table I-3. Statistical Information of the COMMON Blocks.

|                                            |   |   |       |
|--------------------------------------------|---|---|-------|
| Total number of names ; ordinary and array | : | ≈ | 1330  |
| Number of Real and Integer variables       | : | ≈ | 1270  |
| Number of Array variables ; Ordinary runs  | : | ≈ | 20850 |
| " " " " " " ; Graphics runs                | : | ≈ | 65000 |

### Individual COMMON Blocks Information.

The principal descriptive information on all named COMMON blocks is given on Table I-4. as a compact listing.

Table I-4. Characteristics of the COMMON Blocks.

| Name | Main place(s) of use.                          | No of Names |
|------|------------------------------------------------|-------------|
| NC01 | Character variables (Time,Date,Heading)        | 85          |
| " 02 | Main job arrays. (IAL * 26 +)                  | ~ 20850     |
| " 03 | FV-MD cases I/O arrays. (IALV * 20 +)          | ~ 1000      |
| " 04 | Graphics & OAL arrays. (IALO * 21 +)           | ~ 42000     |
| NC05 | Vessel Geometry calculations parameters.       | 58          |
| " 06 | MC calc. principal param. & Physical prop.     | 92          |
| " 07 | Mill-time, stop and end condition calcul.      | 63          |
| " 08 | Wave front calculations parameters.            | 69          |
| " 09 | Time-step & Error stop calculations param.     | 85          |
| NC10 | MC calculations, Integer variables.            | 90          |
| " 11 | Expulsion & Opening calculations parameters.   | 101         |
| " 12 | SF calculations ; Main variables.              | 36          |
| " 13 | Precision of the run calculations parameters.  | 85          |
| " 14 | Contact surface calculations parameters.       | 63          |
| NC15 | NFV case , Gas region calculations parameters. | 27          |
| " 16 | SF calculations ; Loop limit etc. parameters.  | 80          |
| " 17 | Points near SF , MC calculations parameters.   | 81          |
| " 18 | SF point MC calculations parameters.           | 66          |
| " 19 | Graphics work for single data run cases param. | 58          |
| NC20 | Graphics work for multi data run cases param.  | 104         |
| " 21 | MC calc. ; Central & calculation point param.  | 39          |
| " 22 | MC calc. ; Points on the characteristic lines. | 70          |

### I.3. STATISTICAL DATA ON SF CALCULATIONS.

SF calculations, in many respects, has a special place in the work and the statistical data on Table I-5. may be of interest.

Table I-5. Statistical Data on the SF calculations.

|                                                     |                      |   |     |
|-----------------------------------------------------|----------------------|---|-----|
| Total number of SF related                          | Data File parameters | : | 79  |
| " " " " " "                                         | Integer " " "        | : | 41  |
| " " " " " "                                         | Real " " "           | : | 38  |
| Empty - no help given 0/1 - Data File               | " " "                | : | 4   |
| Number of SF calculations related variables (Min.). |                      | : | 283 |
| Main variables of the SF calculations.              |                      | : | 36  |
| SF point MC calculations related variables.,        |                      | : | 66  |
| SF calculation loops related variables.             |                      | : | 80  |
| Points near SF calculations variables.              |                      | : | 81  |

### I.4. PROGRAMMING REQUIREMENTS.

#### Disk Space and Virtual Machine Size.

The program (FORTRAN) files , the compiled (TEXT / BINARY) files , the input (DATA) files and the essential usage programme (EXEC / MACRO) files require the spaces listed below ;

Table I-6. Components of the Machine Size Requirements.

| Type of File | Requirement ; Normal / Compacted |   |      |              |
|--------------|----------------------------------|---|------|--------------|
| FORTTRAN     | 3580                             | / | 900  | [1 K Blocks] |
| DATA         | 110                              | / | 30   | " " "        |
| TEXT         | 1385                             |   | 1385 | " " "        |
| EXEC         | 450                              |   | 200  | " " "        |
| Workspace    | 1000                             |   | 1000 | " " "        |

For high occupation ratio, the normal -comfortable work- and minimum - compacted format storage , frequent time consuming file transformations - disk space requirements may be given as below ;

Normal disk space requirement : 7 [Mb]  
Minimum " " " " : 5 "

With the additional space required for the other related programmes, old versions and all usage programs ; the normal disk space requirement increases to 10 [Mb]. When temporary work disk call is possible ; the absolute minimum requirement is only 2 [Mb].

Virtual machine sizes of 3 [Mb] would be enough for all cases but if no library is required only 2 [Mb] would be satisfactory. For simple FV cases, only 1 [Mb] virtual machine size is required.

#### Compiler Requirements.

Under the headings of compatibility and portability, the compiler requirements are considered in Chap.8 ; a concise list of the

critical points that were mentioned may be given as below ;

Table I-7. Compilar Requirements of the Programme.

Absolute Requirements :

- \* Multiple PARAMETER statements use in every routine.
- \* Large ( $\geq 1500$ ) total number of names in COMMON blocks.

Req. that may create problems if (more than one) is not satisfied.

- \* Large ( $\geq 25$ ) number of named COMMON blocks.
- \* Large ( $\geq 120$ ) number of names in COMMON blocs.
- \* Large ( $\geq 15$ ) number of continuation lines in COMMON blocks.
- \* Large ( $\geq 50$  K Real variables) space for individual COMMON blocks.

Hardware and Operating System Requirements.

The programme does not contain any standard Double Precision statement but especially the SF calculations needed to be done in DP mode with at least 10 significant decimal digits , therefore the hardware must satisfy either of the conditions mentioned below ;

- \* Standard 48 / 64 bits machine with minimum 10+ decimal digits.
- \* Standard 32 bits machine with AUTODOUBLE future.

I.5. LIBRARY ROUTINES USE.

Subroutines from tree library routines are used.

- GLIB : CPU time and actual time - date information library.
- NAG : Numerical calculations routines library for equation(s) solving, curve fitting and other mathematical jobs.
- GHOST : Graphics drawing routines library ; essential without alternative for the graphics drawing part (Chap. 9).

Data files contain parameters for the availability of these libraries which allow to overriding related parameters and switch to an alternative way if available ; like producing OAL output if the graphics output can not be produced.

The GLIB library routines MDATE , ITIME and MTIME ; are all called in the same routine, the routine SCMT only ; which allows easy switching to the equivalent routines of an another package. These routines are useful but not essential, but still the CPU time checks are used in SF part for error tracing and at batch jobs for time run-out prevention which are somewhat essential functions.

The NAG library use is not essential, as stressed in the related parts of Chap. 4.7.4 and Chap. 5.11 ; they are kept in the programme as a matter of reference only. Some curve fitting routines of this library (PCFWN and PACPR) were used for the production of the equations of the tabled information in the program. (Stored in the program as comments for safe keeping.)

END OF APPENDIX I

## A P P E N D I X - J

### T H E   C O M P U T E R S A N D   T H E C O M M A N D S   U S A G E   P R O G R A M S

The development of the program, in different proportions and at some period in parallel format, were carried out on four mainframe computers ; three on-site and one remote access. User support at the computer laboratory was satisfactory but all usage programs were, without any exception, prepared as original with very little help if any at all.

It was absolutely essential to employ at least some user developed , custom made , high level system commands usage programs - the CUP's - for a programme development task of the proportions that is under consideration ; for at least saving a lot of time and resources.

#### J.1. THE COMPUTERS.

Principal characteristics of the computers used are listed below in a compact format ;

- \* ICL 1900 Series ; used in the beginning, for basic Full Vessel case programme with a size of less than 3000 lines.
- \* CDC 7600 Series (Cyber 176) ; remote access and batch mode use. Used for error tracing with Waterloo FORTRAN compiler only and before IBM machines were made available.

Table J-1 A Short Comparison of the Computers Used.

|                    | ICL                          | CDC                           | IBM                              |
|--------------------|------------------------------|-------------------------------|----------------------------------|
| Operating System   | GEORGE 4                     | SCOPE                         | VM ; SP - HPO                    |
| CUP Language       | MACRO L.                     | (MACRO & EXEC)                | EXEC L.                          |
| FORTTRAN Compiler  | Extended F.<br>(FORTRAN 66+) | FTN & WATFIV<br>(FORTRAN 66+) | FORTHX - FORTVS<br>(FORTRAN 77+) |
| Machine Type       | 48 Bits                      | 64 Bits                       | 32 Bits                          |
| Precision S/D/E    | 11/20/-                      | 14/29/60                      | 6/16/32                          |
| AUTODOUBLE Future  | No                           | Yes                           | No - Yes                         |
| Compiler debugging | Poor                         | Good                          | Very Good                        |
| Run-Time " "       | Good                         | Very Good                     | Poor                             |
| On-line Use        | Poor                         | None                          | Very Good                        |
| Batch-Job Use      | Satisfactory                 | Good                          | Very Good                        |
| Relative Power     | 1                            | 25 ~ 30                       | 4 ~ 6 - 10 ~ 15                  |

- \* The IBM VM system machines ; 4300 Series and 3080 Series.  
These are the principal machines of the work and the only ones that meet the requirements listed in App. I. They are fast on-line work VM machines with very good batch job facilities. Their main drawback was their very limited error tracing abilities , ties, which is the reason for the in built debugging facilities.

Approximate use of the computers mentioned above ; in respect to the real and CPU time spent with them as a percentage of the total is given in Table J-2.

Table J-2 Time Spent With the Computers Used.

| Computer<br>Name | Total<br>[%] | On - Line<br>[%] | Batch Mode<br>[%] |
|------------------|--------------|------------------|-------------------|
| ICL-1906         | 12           | 5                | 7                 |
| CDC-7600         | 3            | -                | 3                 |
| IBM-4341         | 25           | 20               | 5                 |
| IBM-3080         | 60           | 45               | 15                |
| TOTAL            | 100          | 70               | 30                |

#### J.2. THE COMMANDS USAGE PROGRAMS (CUPs).

The development of the programme, required a lot of effort for the production of custom made commands usage programs. Although only a couple of the CUPs that were written can be considered absolutely essential, but they were the ones that consumed most of the effort.

Most of the CUPs were written for the prevention of tedious and boring repetitive work that otherwise must be done manually. But some of the small CUPs were written for the sake of creating as complete a CUPs library as possible, even if no saving was due. The jobs that CUPs were prepared for, may be summarized - from basics to the complex jobs - as seen on the Table J-3. ;

Table J-3 List of the Jobs of the Command Usage Programs.

- \* Virtual machine use, temporary disk call, common identifications.
- \* File storage, virtual reader use, archiving, magnetic tape use.
- \* File characteristics change and transfer, in & between machines.
- \* File editing, including with generation number usage.
- \* Editing Fortran programs, COMMON and PARAMETER blocs editing.
- \* Printing ; line numbered print , multiple files print, etc.
- \* Tidying ; FORTRAN files , compiler listings etc.
- \* Text libraries ; generation , handling.
- \* Debugging help ;automatic dummy statements creation etc.
- \* Graphics Drawing , simple and full list formats.
- \* Compiling FORTRAN files, basic and full list - debugging formats.
- \* Running FORTRAN jobs ; on-line , batch and remote access cases.

Table J-4 Statistics on the Command Usage Programs.

|                                        |                      |                  |
|----------------------------------------|----------------------|------------------|
| Total number of EXEC and XEDIT files   | :                    | 71               |
| Number of "Absolutely Essential" EXECs | :                    | 18               |
| " " " "Very Important" " "             | :                    | 17               |
| " " " "Important" " "                  | :                    | 13               |
| " " " EXECs ; over 300 lines long      | :                    | 8                |
| " " " " " with full parameters list    | :                    | 10               |
| Sizes ;                                | Min. - Max / Average | : 29 - 677 / 152 |
| Number of parameters ; " " " "         | :                    | 1 - 14 / 5+      |
| Number of listed Par.; " " " "         | :                    | 9 - 77 / 36      |

Table J-4 gives statistical information on the CUP's called EXEC and XEDIT , prepared for the IBM machines, in a compact format. Compact information on the CUP's prepared for the ICL computer, called MACRO is given below.

|                                              |   |                |
|----------------------------------------------|---|----------------|
| Total number of MACRO files                  | : | 9              |
| Number of MACRO files for running jobs       | : | 5              |
| File sizes ; Min. - Max. / Average [Lines]   | : | 70 - 360 / 190 |
| Number of parameters ; Min. - Max. / Average | : | 3 - 29 / 18    |

END OF APPENDIX J

## A P P E N D I X - K

### G R A P H I C A L   O U T P U T

#### E X A M P L E S

Some examples of the graphical output of the principal cases of the program are given. As stated in Chap.9 , all of the cases considered has many pages long, very detailed graphical output facility but only the three principal cases of ;

- \* The Full Vessel Case ;  
    With some Multi Data run examples.
- \* The Non-Full Vessel Case.
- \* The Gas Bottle Case.

are considered here due to not only the space limitations but also the very limited interest that the full multi-data and special conditions output may draw.

The runs that the graphs were drawn were not professional jobs with increased accuracy conditions but rather ordinary jobs that job time saving measures may make themselves felt quite heavily. Accuracy is not a simple concept and the mathematical formulation of it that was used in the programme - the ratio between the amount of liquid expelled that of calculated through rate of expulsion and of through the initial amount and the amount that was left.- can not be taken as a complete measure of it at all.

Due to the format and the plotting character of the examples, it was not possible to present them in a tidier format and due to their unsuitability of reproduction - large but quite thinly and not very clearly drawn high speed plotter output - , much larger amount of probably better representative cases and their plots could not be considered.

The complete case plots contain all the principal input parameters and results , and no extra case data information are given for them. Concise data are also provided for the compact, full page, all inclusive plots of the principal cases of NFV and FV. The aim of these all inclusive plots is only to give a general idea on the results that enable to see some basic relationships and draw simple conclusions.

All the parameters used in the graphics and the principal data and the results files parameters on the numerical data lists of the full format examples are explained below in a compact format.

# GRAPHICS ABBREVIATIONS :

## The Abscissa Parameters.

T (%) : Time , % of the duration of expulsion.  
T-GE (%) : Time , in gas expulsion as % of its duration.  
T-SF (%) : Time , in SF phenomena as % of its duration.  
CSN : Calculation Step Number.  
DSN : Data Set Number in the group of data.

## Single Data Cases Common Parameters.

PCAL : Precision of Calculations, overall, up to a time.  
CEC : Precision of expulsion , Expelled / Depleted.  
DT (%MV) : Time increment , % of Mean Value.  
DTRT : Time increment , % of Theoretical value.  
PCE (%FV) : Percentage of Contents Expelled , % of Full Value.  
BV (%IV) : Void Fraction , % of Initial Value.  
MG (%IV) : Mass of Gas expelled , % of Initial Value.  
MCES (%IV) : Mass of Contents Expelled , % of Initial Value.  
PR-T : Pressure at the Top of the Vessel [Atm].

## Non-Full Vessel Case Parameters.

HM (%HV) : Height of mixture level , % of Vessel Height.  
PHM-S : Height of mixture level , % of full value.  
DEL (%MV) : Movement of the CS , % of Mean Value.  
MCE-S/G (%MV) : Mass of Content Expelled, Gas, % of Mean Value.

## Full Vessel Special Case Parameters.

CEC-SF : Precision of Expulsion Calculations ; SF.  
DT-SF (%MV) : Time increment , SF process , % of Mean Value.  
DTRT-SF : Time increment , SF , % of Theoretical Value.  
MCES-SF (%MV) : Mass of Contents Expelled , SF , % of Mean V.

## Multi Data Cases Ordinary and Floating Parameters.

PCAL : Overall Precision of the Calculations.  
RPLE : Percentage of Liquid Expelled , % of QSS Value.  
PLE (%) : Percentage of Liquid Expelled , % of Initial Value.  
PBVF : Final Void Fraction , % of Initial Value.  
DE [MS] : Duration of Expulsion in Milliseconds.  
RJME : Ratio , Total number of steps to number of nodes.  
DP-E : I. Dimensionless Parameter. (Routine SENDEX)  
DP-T : II. " " " " " " " "  
  
PRO : Initial Pressure Ratio.  
PHIF : Final Area of Opening Ratio.  
BVO : Initial Void Fraction.  
BRVO : Initial Mean Bubble Radius.  
TCO [MS] : Time Constant (Duration) of Opening.  
M : Number of Calculation Nodes Used.

Single Data Cases Common Principle Plots.

PR T+M+B (%) - T (%) : Pressure Ratio at the Top / Mid Point / Bottom , % of the Initial Value at top.

PR T+M+B (%) + PCAL + CEC + DTRT + PCEP - T (%) : Multi Plot.

Special Plots of the Full Vessel - Multi Data Case ; Example.

|      |   |     |   |      |   |      |      |   |      |   |     |   |      |
|------|---|-----|---|------|---|------|------|---|------|---|-----|---|------|
| DE   | - | PRO | / | PHIF | = | Cst. | DE   | - | PHIF | / | PRO | = | Cst. |
| PLE  | - | "   | / | "    | " | "    | PLE  | - | "    | / | "   | " | "    |
| PCAL | - | "   | / | "    | " | "    | PCAL | - | "    | / | "   | " | "    |
| RPLE | - | "   | / | "    | " | "    | RPLE | - | "    | / | "   | " | "    |
| PBVF | - | "   | / | "    | " | "    | PBVF | - | "    | / | "   | " | "    |
| DP-E | - | "   | / | "    | " | "    | DP-E | - | "    | / | "   | " | "    |
| DP-T | - | "   | / | "    | " | "    | DP-T | - | "    | / | "   | " | "    |
| RJME | - | "   | / | "    | " | "    | RJME | - | "    | / | "   | " | "    |

#### ABBREVIATIONS FOR THE PRINCIPAL DATA :

H / HV [M] : Height of the Vessel.  
D / DV [M] : Diameter of the Vessel.  
TETA [DEG] : Inclination of the vessel axis.  
HMO [M] : Initial Height of the Mixture.  
PHMO : " " " " " " " " ; in Percentage.  
PRO : Initial Pressure Ratio at the Top of the Vessel.  
PHIF : Final Value of the Area of the Opening Ratio.  
MNF : Number of MC Calc. Points ; NFV - Initial Value.  
MF : " " " " " " " " ; FV Cases.  
BBO : Initial Void Fraction ; at the Bottom.  
BTO : " " " " " " " " ; " " Top.  
BRBO [M] : Initial Mean Bubble Radius ; at the Bottom.  
BRT0 [M] : " " " " " " " " ; " " Top.

#### ABBREVIATIONS FOR THE PRINCIPAL RESULTS :

DE [S] : Duration of Expulsion.  
DGE [S] : " " " " " " of Gas.  
DME [S] : " " " " " " of Mixture.  
PCALF : Final Value of the Precision of the Calculations.  
RPLE : Ratio to QSS Value of the % of Liquid Expelled.  
PLEF : Percentage of the Liquid Expelled ; Final Value.  
PLF : " " " " " " " " Left ; " " " " .  
BVF : Final Value of the Volume Averaged Void Fraction.  
PBVF : Final to Initial Mean Void Fractions Ratio.  
JEND : Total Number of the Calculation Steps.  
RJME : Number of Steps to Number of Nodes Ratio.

END OF THE GRAPHICS ABBREVIATIONS LIST

# K.1. THE FULL VESSEL CASE EXAMPLES.

## K.1.1. A Full Graphics Output - Five Sheets.

Sheet 1 / 5 : Main Data and Results.

P.1/5

### FULL VESSEL

|                       |                           |                          |                         |
|-----------------------|---------------------------|--------------------------|-------------------------|
| HL... = 2.000 (M)     | DV... = 0.250 (M)         | TETA. = 90.0 (DEG)       | NCV.. = 0               |
| PRO.. = 5.00          | PHIF. = 0.250             | TCO.. = 0.500E-03 (S)    | IVFC. = 1               |
| BBD.. = 0.500E-01     | BTO.. = 0.500E-01         | CBQ.. = 1.00             | LDON. = 0               |
| BRBO. = 1.00E-04 (M)  | BRTQ. = 0.50E-03 (M)      | CBRO. = 1.00             | KVPQM = 1               |
| MF... = 20            | CTDF. = 15.0              | CTMF. = 3.0              | IFC.. = 0               |
| RL... = 998.3 (KG/M3) | VCL.. = 0.10E-02 (KG/M=3) | BML.. = 0.189E+10 (N/M2) | STCL. = 0.729E-03 (N/M) |
| RBS.. = 1.205 (KG/M3) | VCB.. = 0.18E-04 (KG/M=3) | BN... = 1.00             | BGC.. = 286.9 (MKS)     |
| IOE.. = 11            | IOEQ. = 0                 | IJDEM = 1                | JCMB. = 1               |
| KCM.. = 7100          | EMVM. = 0.120E+11 (N/M2)  | VVT.. = 0.0030 (M)       | ICVN. = 0               |
| LCS.. = 0             | KMCCE = 0                 | KMCOE = 0                | CRCBC = 1.00            |
| LMCU. = 2             | LMCP. = 1                 | ILMCU = 0                | ILMCP = 4               |
| IECM. = 1             | PRLM. = 1.0080            | ULIMM = 0.050 (M/S)      | ICRML = 1               |

### MAIN RESULTS

|                   |                     |                     |                     |
|-------------------|---------------------|---------------------|---------------------|
| DE... = 0.230 (S) | PCALF = 1.0070      | RPLE. = 0.9494      | PLEF. = 0.160       |
| PLF.. = 0.840     | BVF.. = 0.202       | PBVF. = 4.031       | PHIF. = 0.250       |
| JEND. = 219       | RJME. = 10.95       | RNONE = 18.608      | RNDT = 2.968        |
| JGLE. = 219       | VLF.. = 0.0785 (M3) | MLF.. = 78.251 (KG) | MLEF. = 14.852 (KG) |

Fig. K.1. List of Main Data And Results  
of the Full Vessel Case Example.

Sheet 2 / 5 ; Four Plots.

PCAL - T (%)  
CEC - T (%)  
DT (%MV) - T (%)  
DTRT - T (%)

P.2/5

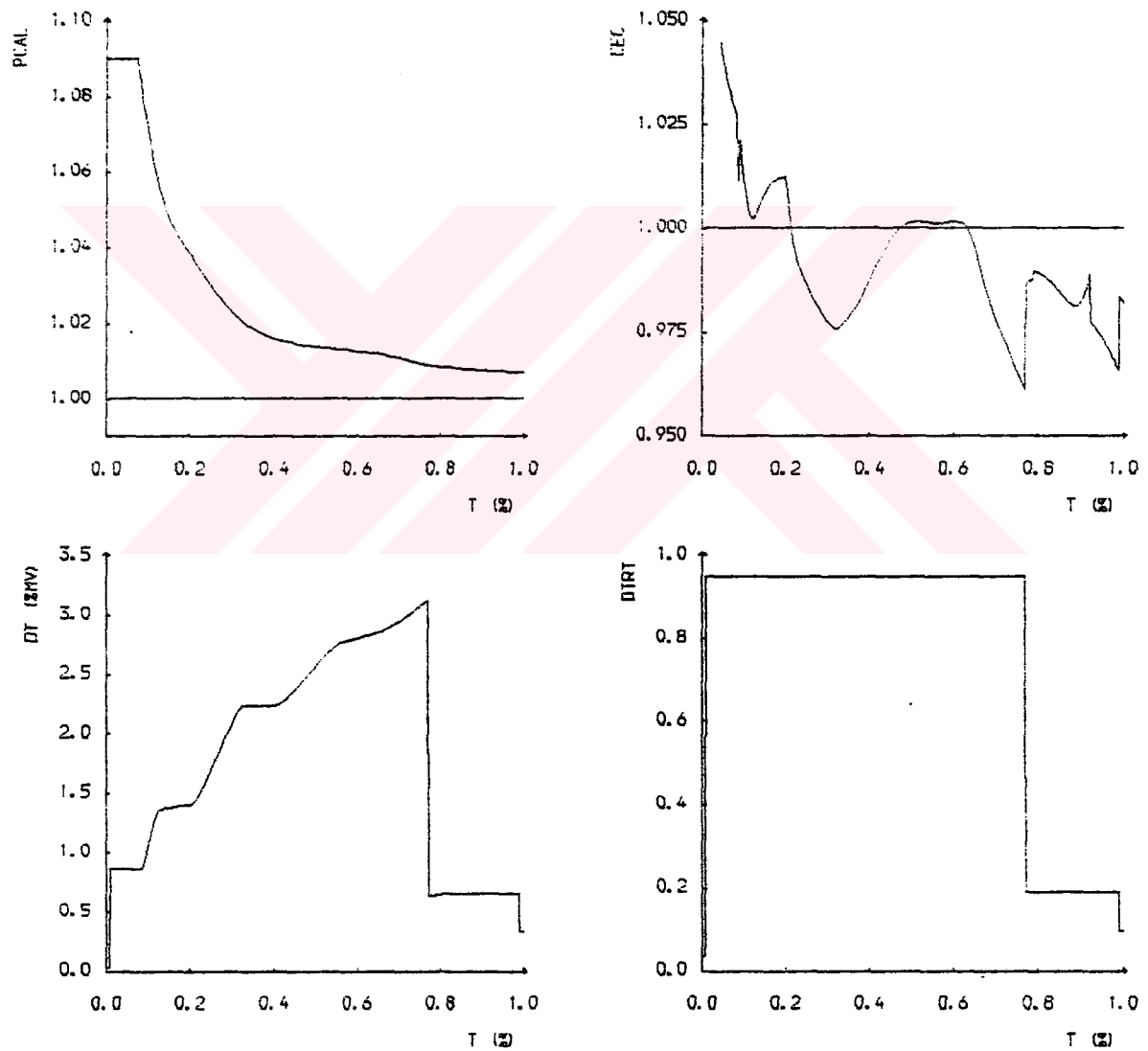


Fig. K.2. First Detailed Plot Page of  
the Full Vessel Case Example.

Sheet 3 / 5 ; Four Plots.

PCE - T (%)

BV (%IV) - T (%)

MCE-S (%IV) - T (%)

PR-T - T (%)

P.3/5

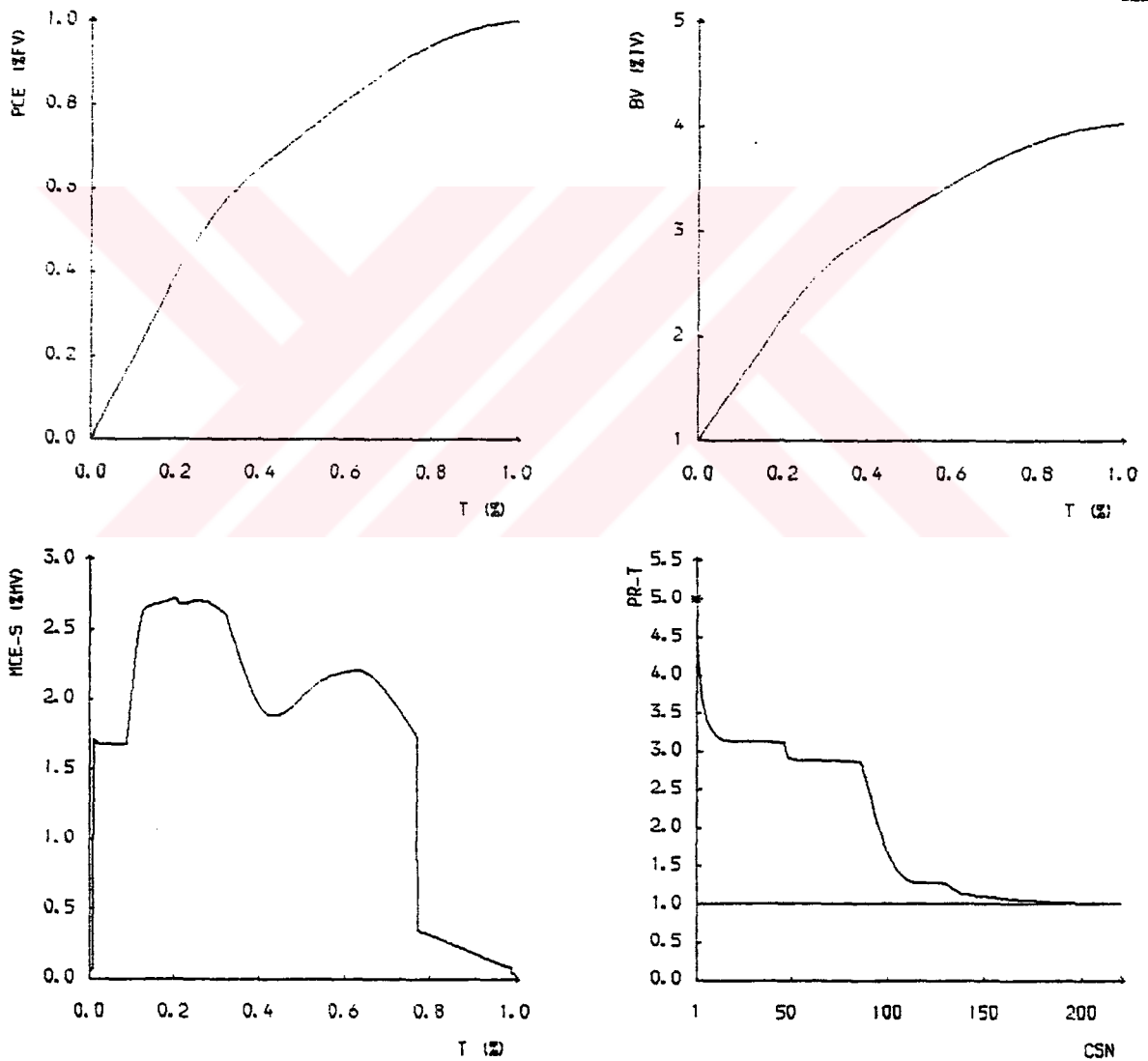


Fig. K.3. Second Detailed Plot Page of  
the Full Vessel Case Example.

Sheet 4 / 5 ; Pressure History Plot.

PR - T (Top) - T (%) [Start ; 1.0]  
PR - M (Middle) - T (%) [ " " ; 1.0+ ]  
PR - B (Bottom) - T (%) [ " " ; 1.0++]

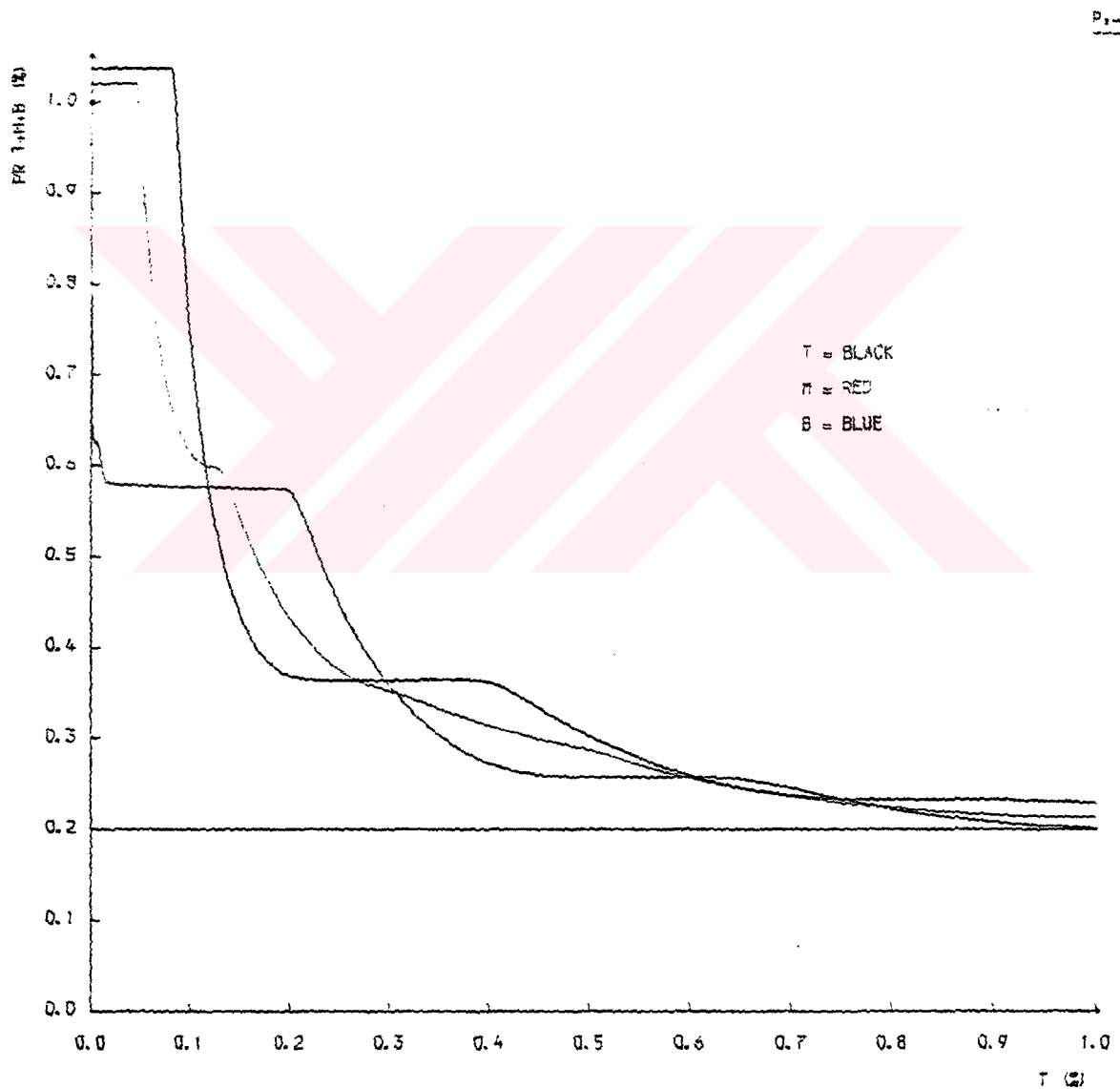


Fig. K.4. Pressure History Plot  
of the Full Vessel Case Example.

Sheet 5 / 5 ; Multi Parameter Plot.

PR - T & M & B - T (%) [Not Signed]  
PCEP & CEC & PCAL & DTRT - T (%) [Not Scaled]

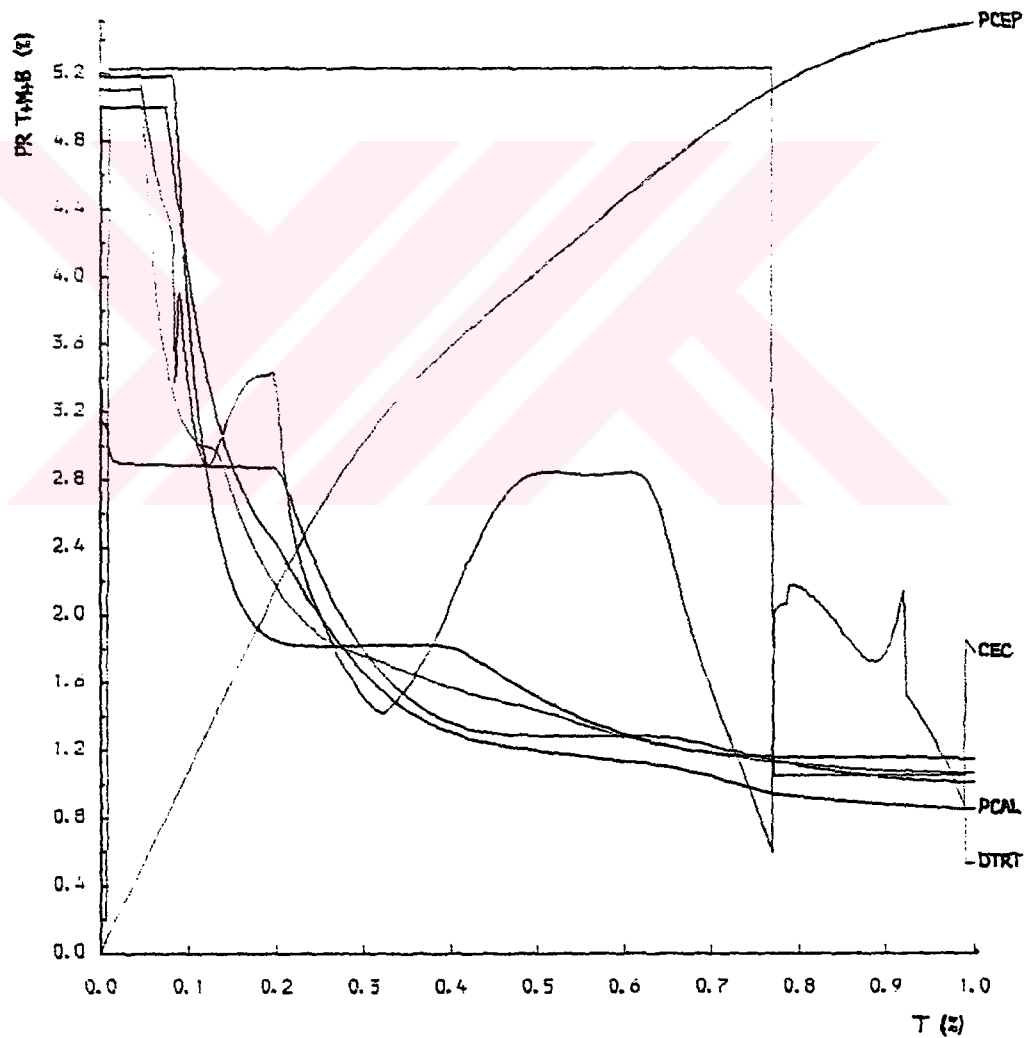


Fig. K.5. Multi Parameter Plot  
of the Full Vessel Case Example.

K.1.2. Compact Outputs - Three Examples.

PR - T & M & B - T (%) [Not Signed]  
PCEP & CEC & PCAL & DTRT - T (%) [Not Scaled]

|       |          |               |
|-------|----------|---------------|
| H     | = 1.5    | [m]           |
| DV    | = 0.35   | [m]           |
| PRO   | = 25     |               |
| TCO   | = 0.5    | $10^{-3}$ [s] |
| PHIF  | = 0.10   |               |
| BBO   | = 0.010  |               |
| BBT   | = 0.015  |               |
| BRBO  | = 0.1    | $10^{-3}$ [m] |
| BRT0  | = 0.5    | $10^{-3}$ [m] |
| TETA  | = 90     | [°]           |
| ===== |          |               |
| DE    | = 0.5962 | [s]           |
| RPLE  | = 0.946  |               |

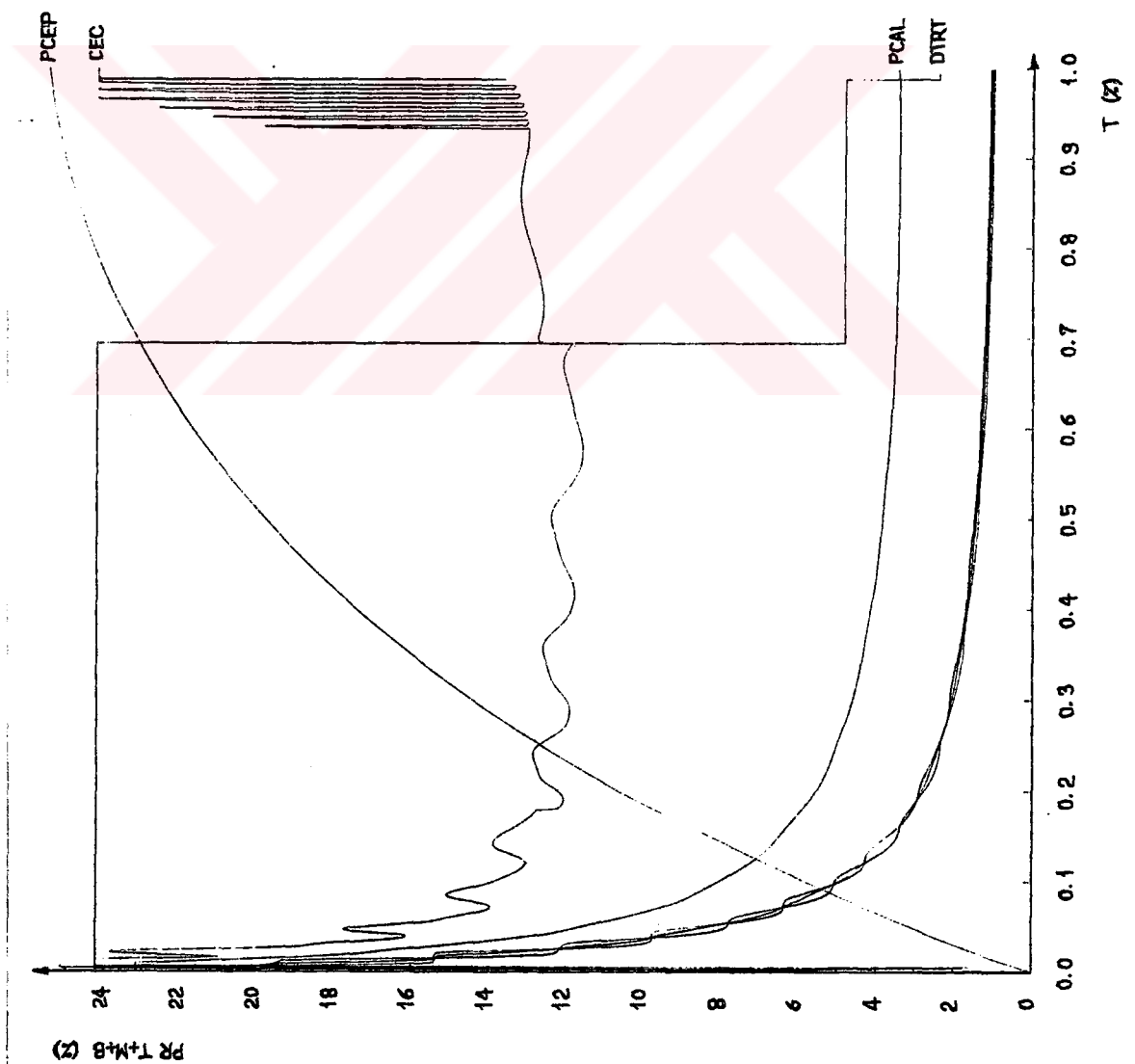


Fig. K.6. First of the Compact  
Full Vessel Case Examples.

PR - T & M & B - T (%) [Not Signed]  
PCEP & CEC & PCAL & DTRT - T (%) [Not Scaled]

H = 1.2 [m]  
DV = 0.25 [m]  
PRO = 10  
TCO =  $0.5 \cdot 10^{-3}$  [s]  
PHIF = 0.30  
BB0 = 0.035  
BBT = 0.050  
BRB0 =  $0.1 \cdot 10^{-3}$  [m]  
BRT0 =  $0.5 \cdot 10^{-3}$  [m]  
TETA = 90 [°]  
=====  
DE = 0.2007 [s]  
RPLE = 0.981

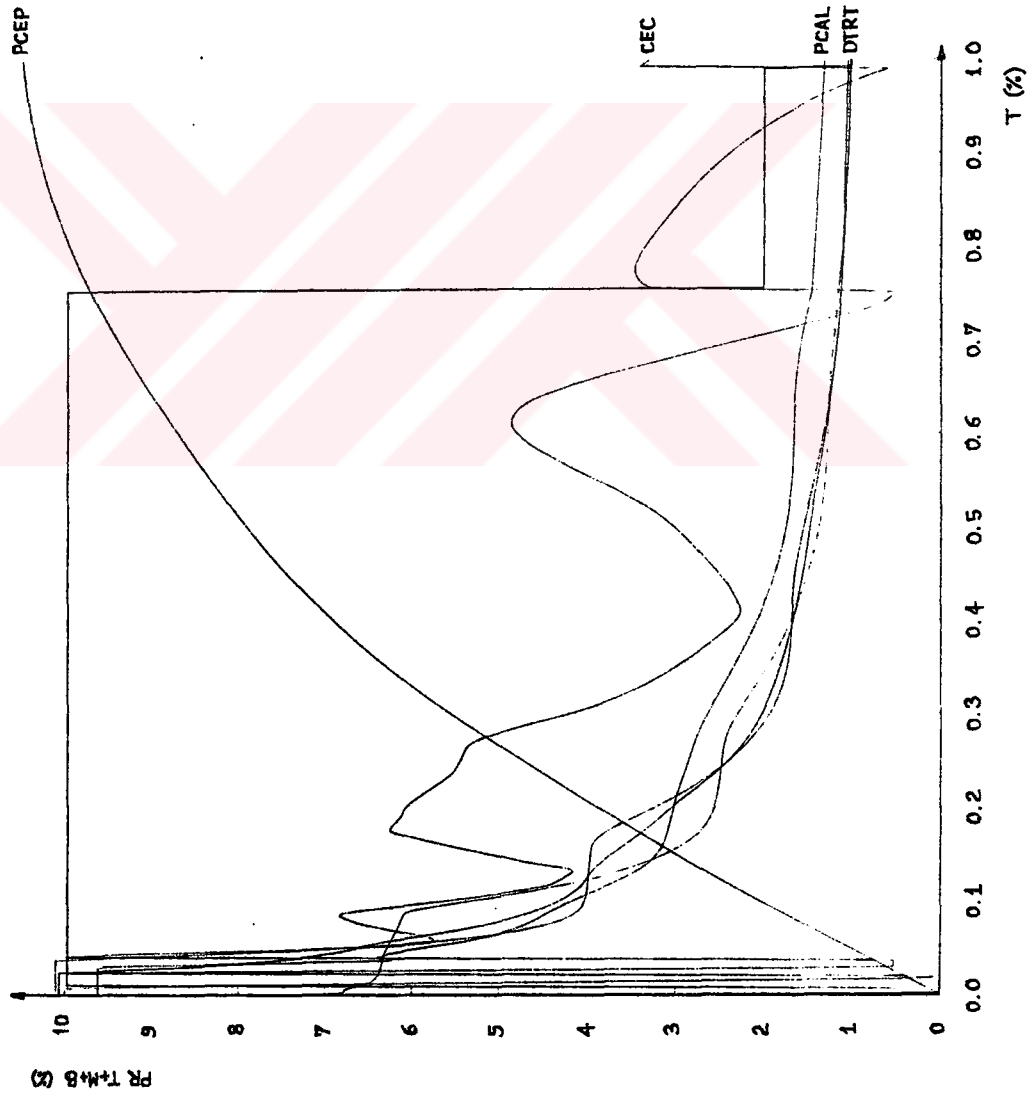


Fig. K.7. Second of the Compact  
Full Vessel Case Examples.

PR - T & M & B - T (%) [Not Signed]  
PCEP & CEC & PCAL & DTRT - T (%) [Not Scaled]

H = 100 [m]  
DV = 0.05 [m]  
PRO = 15  
TCO =  $0.5 \cdot 10^{-3}$  [s]  
PHIF = 0.25  
BBO = 0.04  
BBT = 0.04  
TETA = 0 [°]  
=====  
DE = 30.35 [s]  
RPLE = 0.993

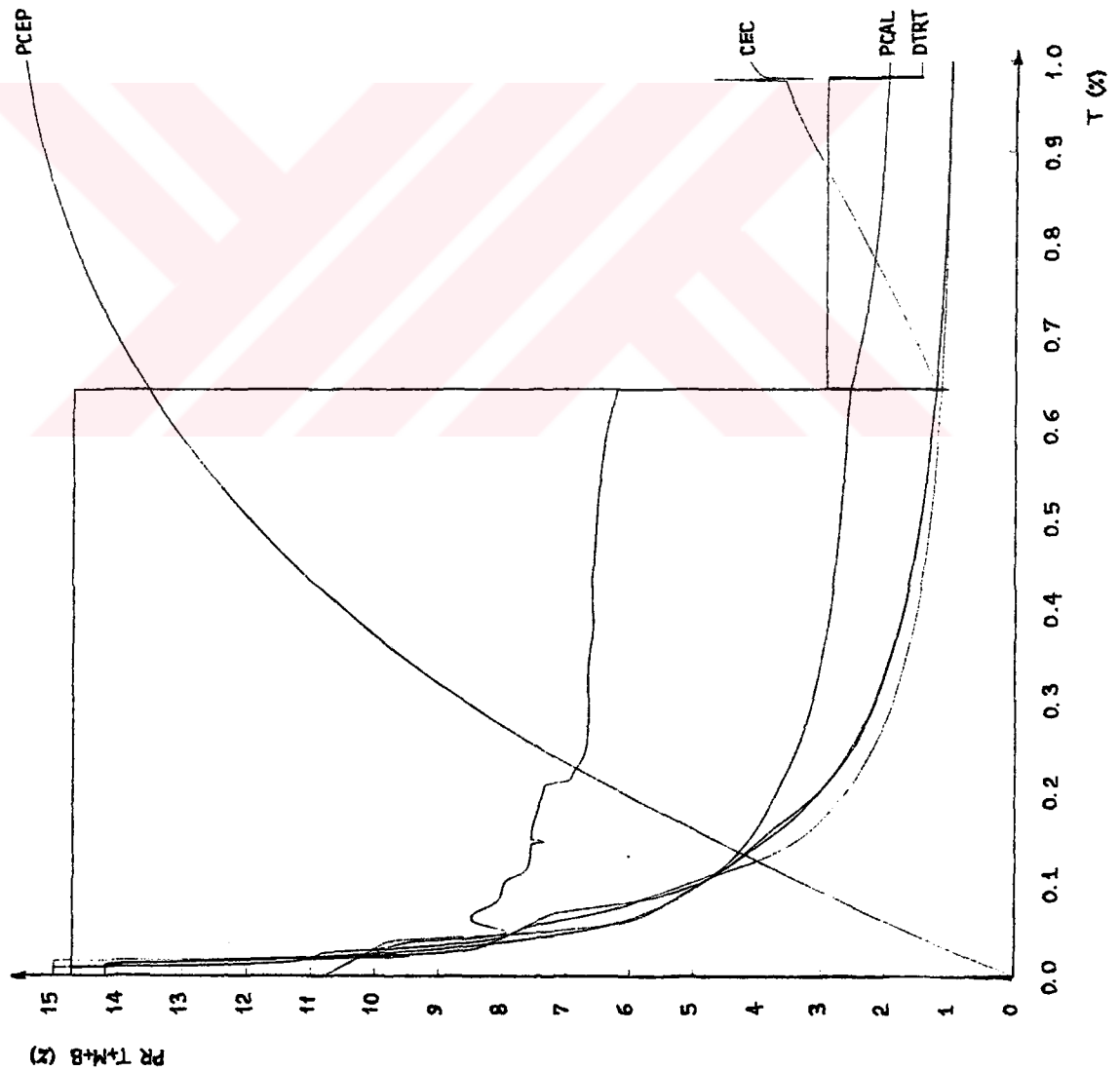


Fig. K.8. Third of the Compact  
Full Vessel Case Examples.

K.1.3. The Multi Data Run Plots - Eight Sheets.

Sheet 1 / 8 : " PLE (%) - PRO / PHIF " Plot.

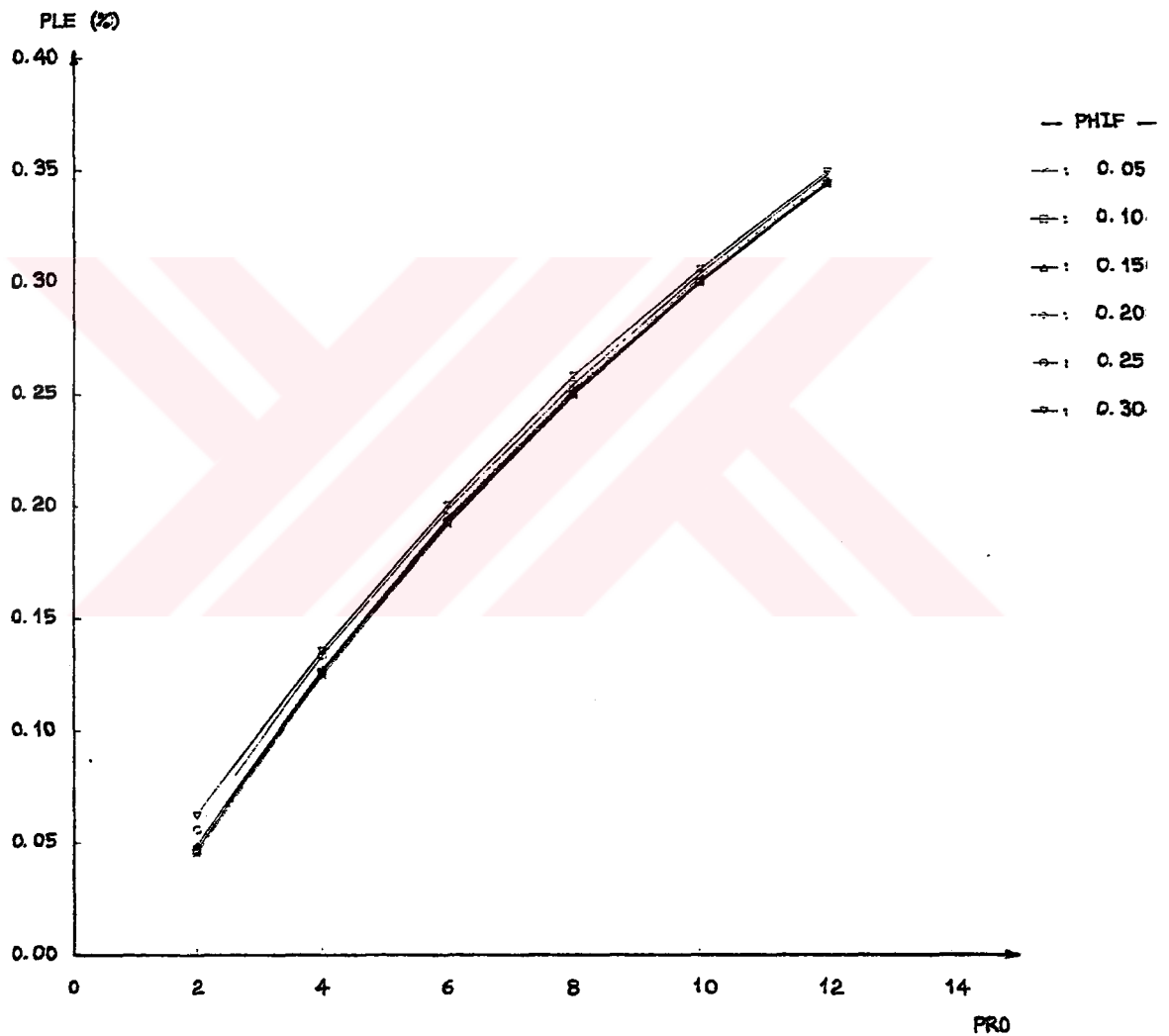


Fig. K.9. First Page of the  
FV - MD Case Plots.

Sheet 2 / 8 : " RPLE - PRO / PHIF " Plot.

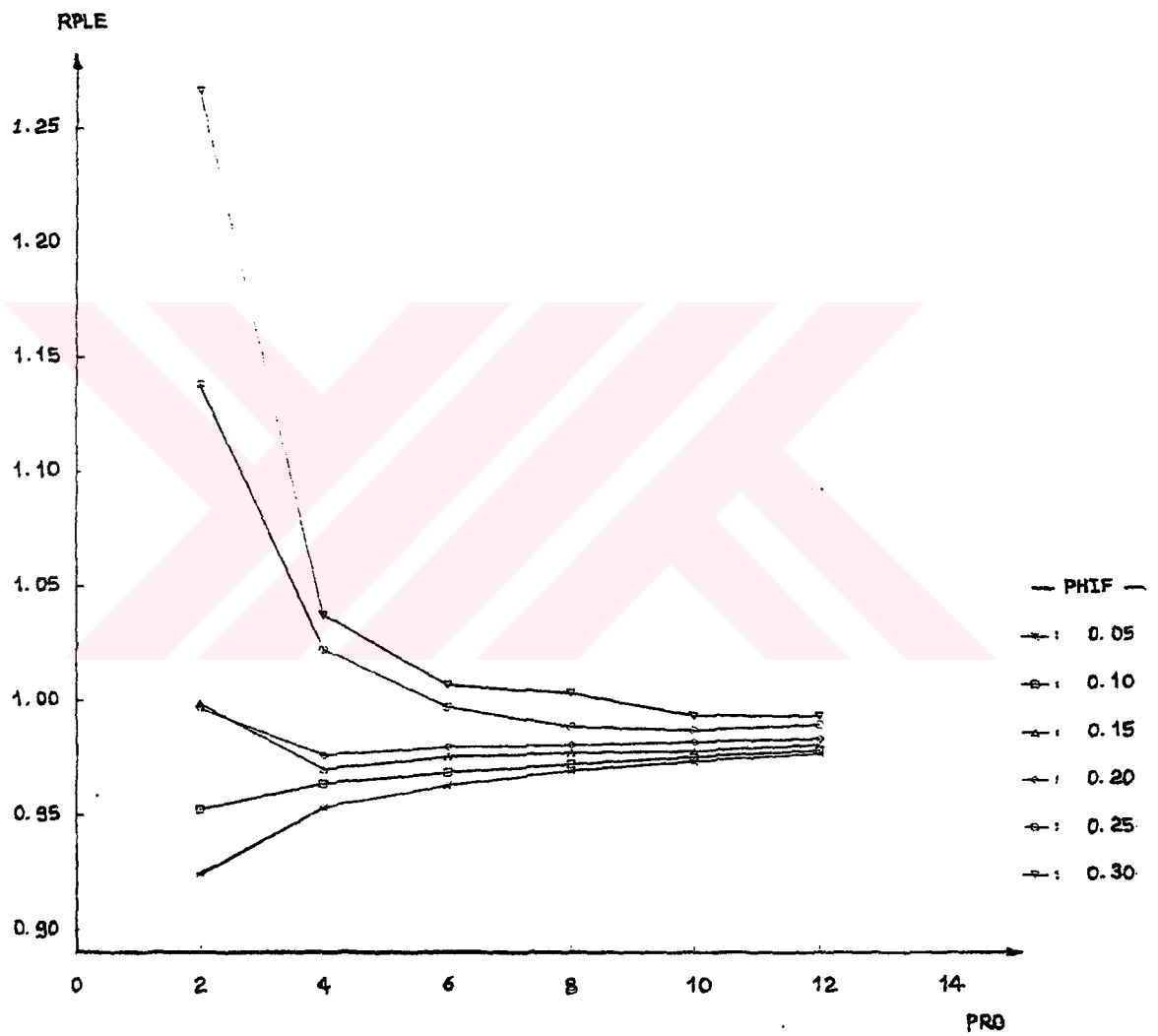


Fig. K.10. Second Page of the  
FV - MD Case Plots.

Sheet 3 / 8 : " PBVF - PRO / PHIF " Plot.

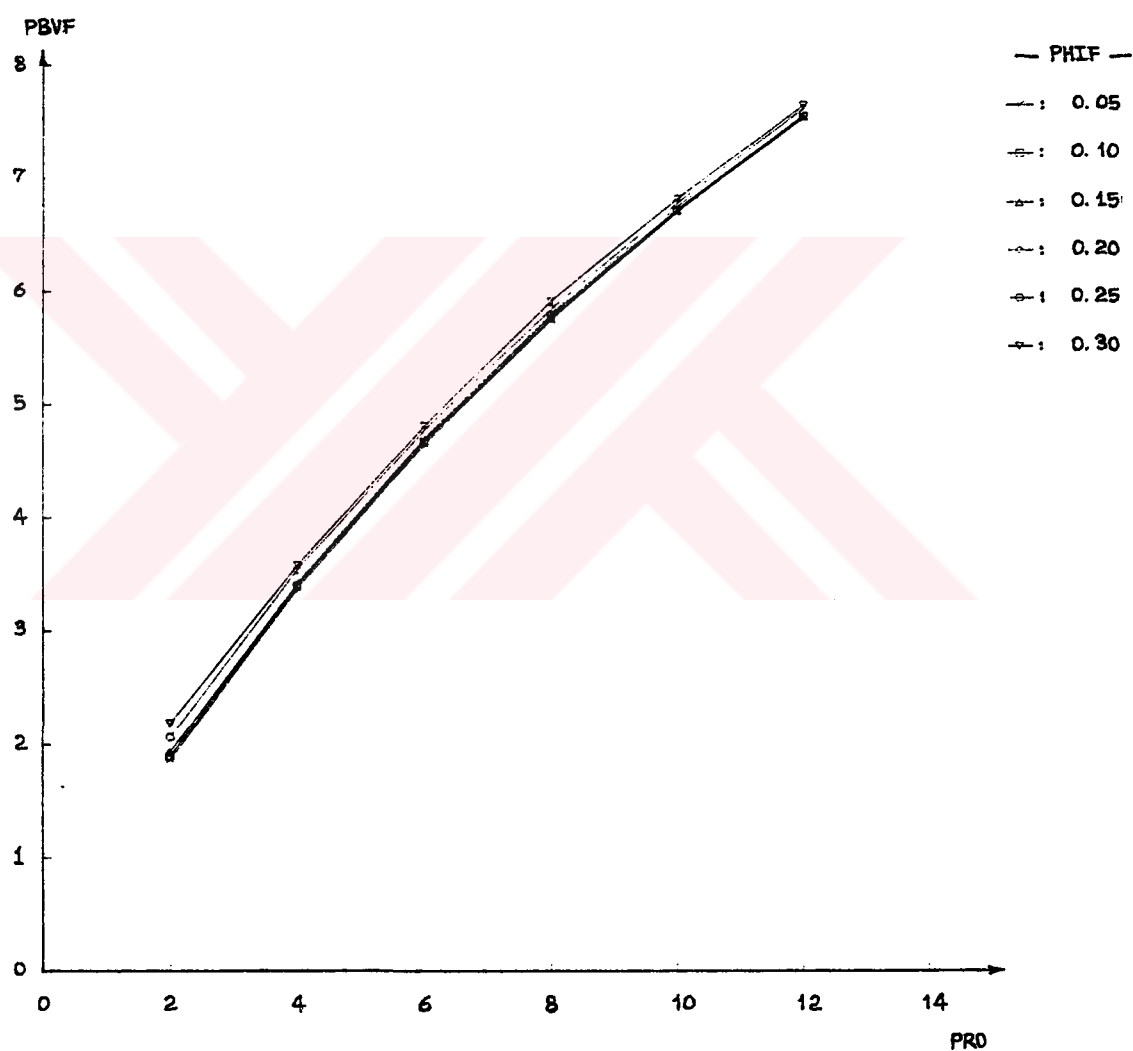


Fig. K.11. Third Page of the  
FV - MD Case Plots.

Sheet 4 / 8 : " PBVF - BV / PRO " Plot.

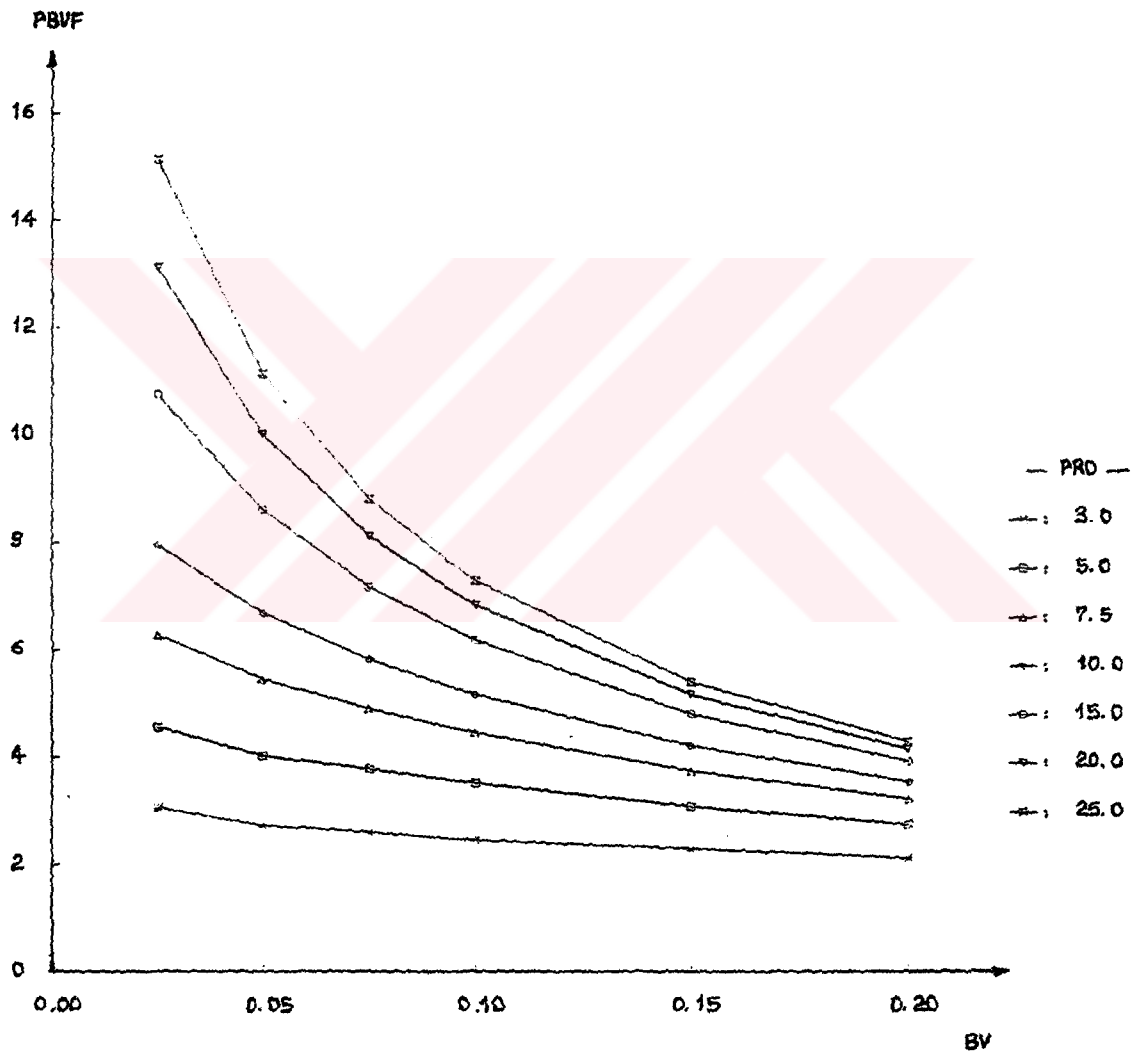


Fig. K.12. Forth Page of the  
FV - MD Case Plots.

Sheet 5 / 8 : " DP-T - PRO / PHIF " Plot.

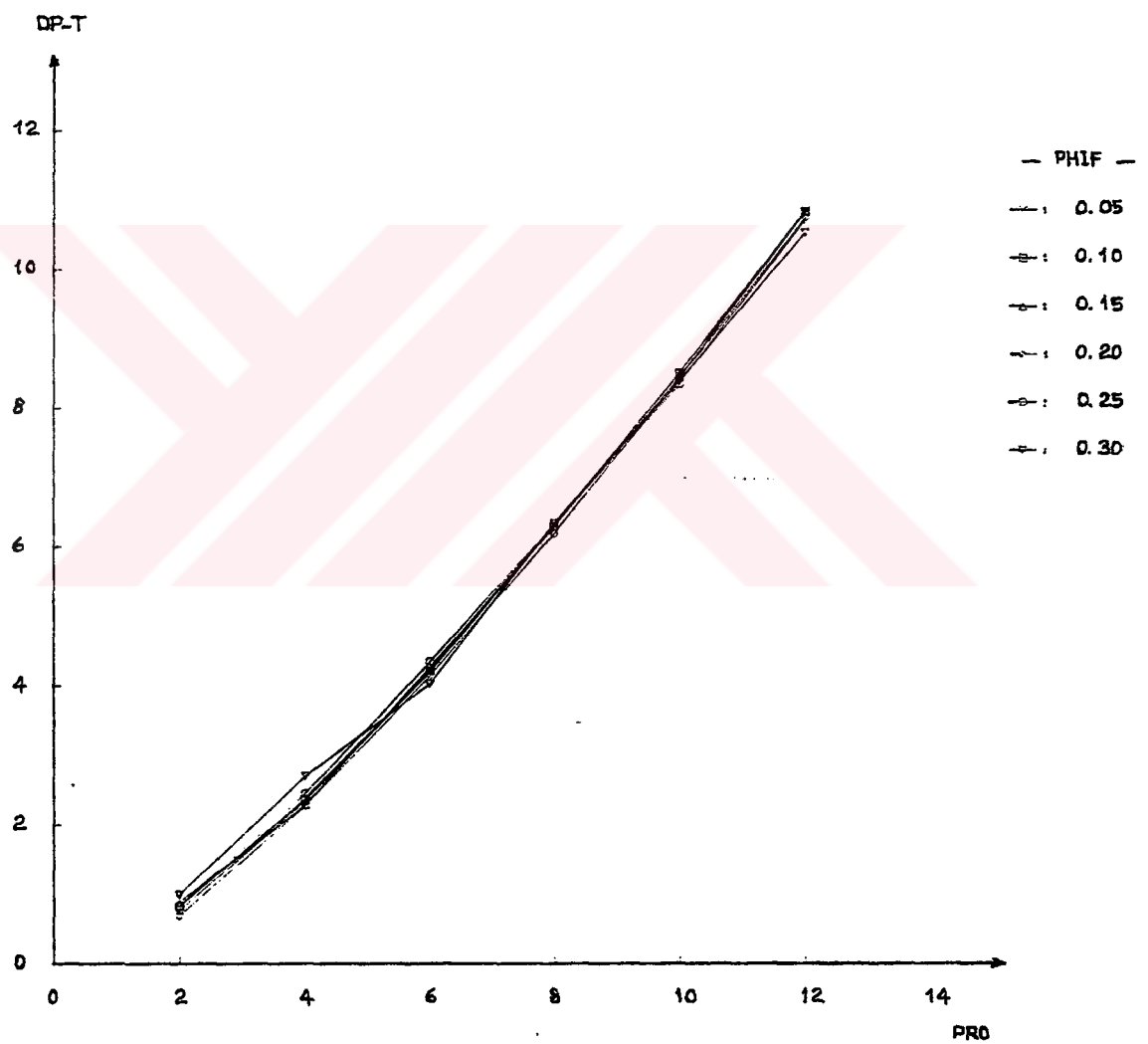


Fig. K.13. Fifth Page of the  
FV - MD Case Plots.

Sheet 6 / 8 : " DP-E - PRO / PHIF " Plot.

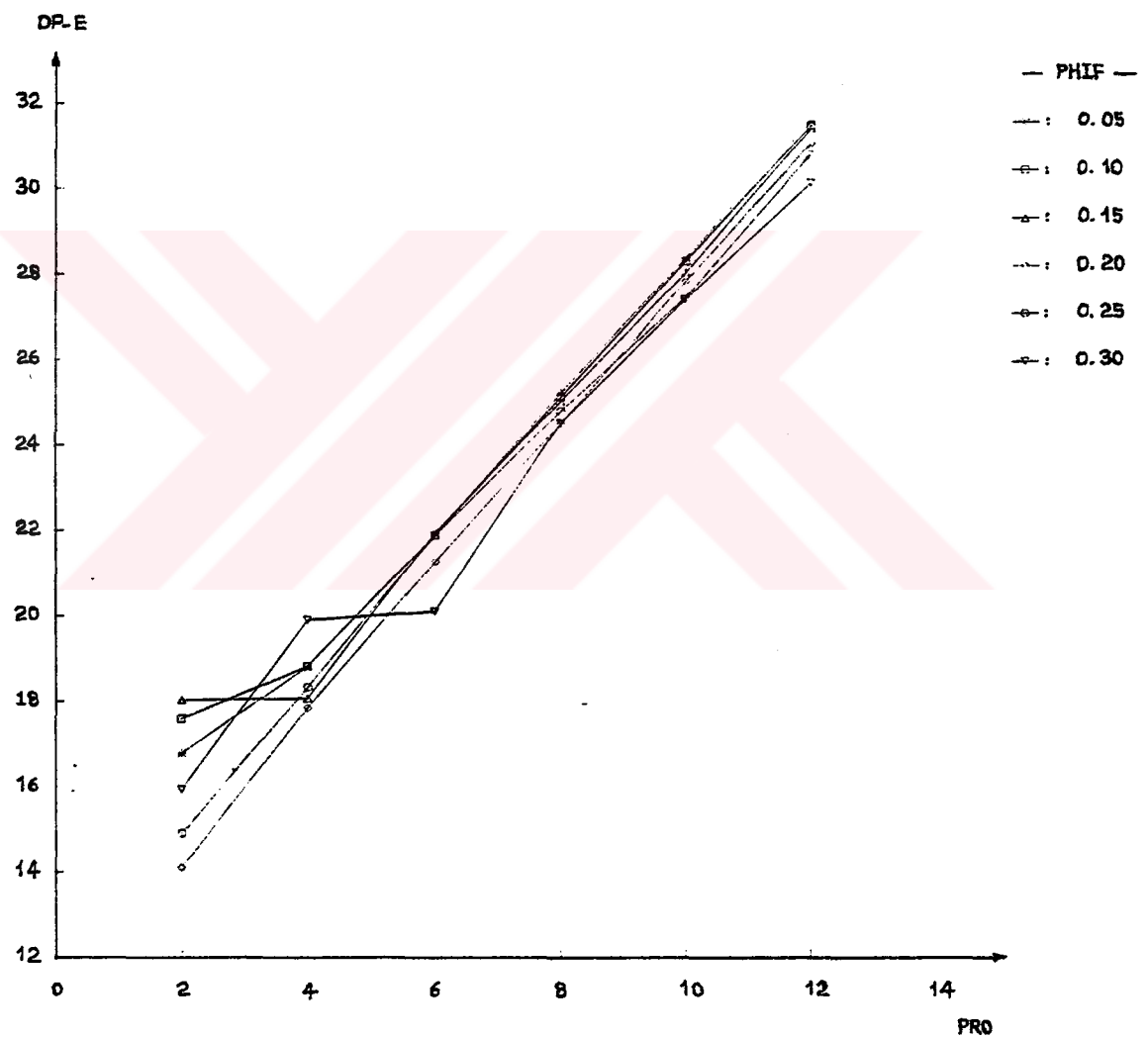


Fig. K.14. Sixth Page of the  
FV - MD Case Plots.

Sheet 7 / 8 : " DE [ms] - PRO / PHIF " Plot.

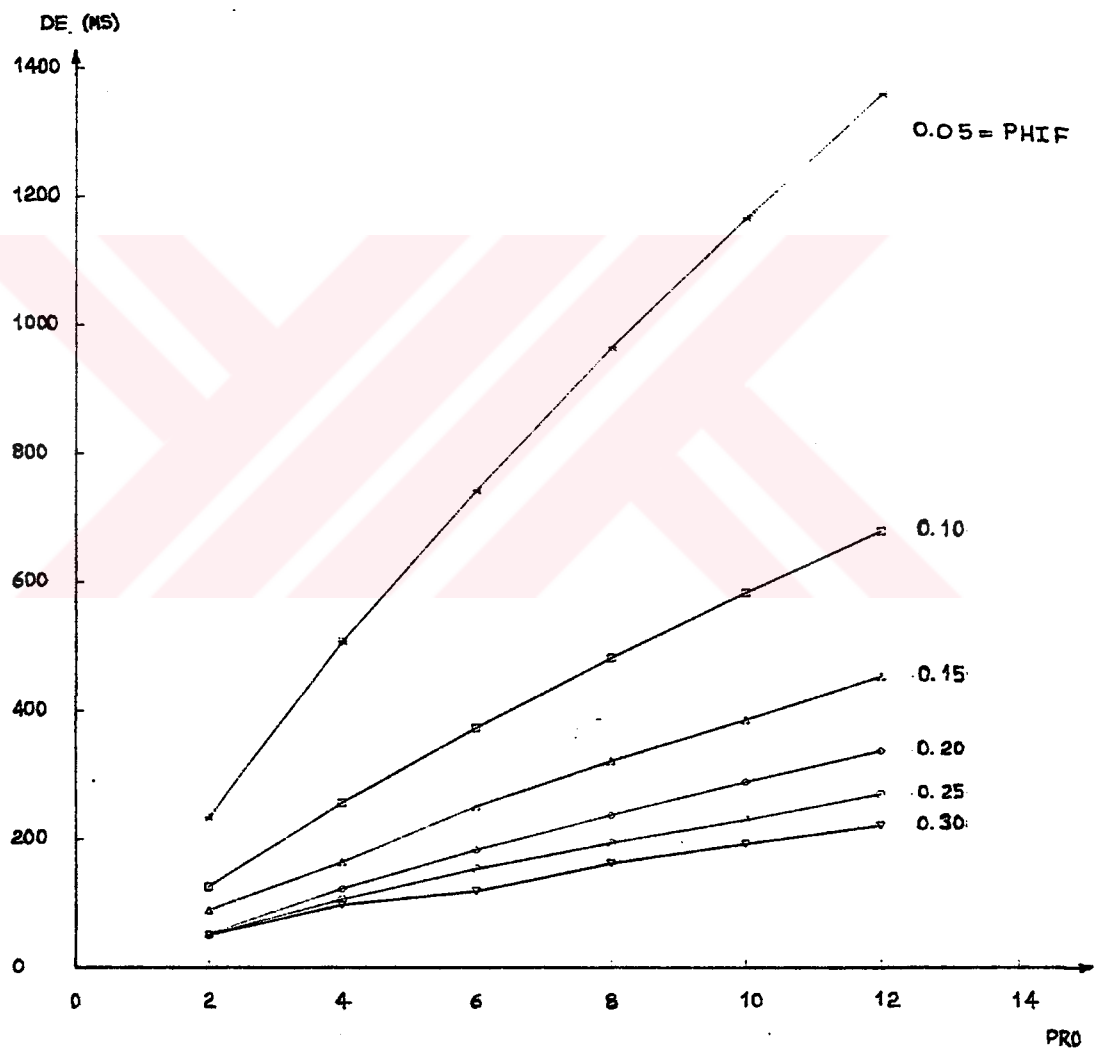


Fig. K.15. Seventh Page of the  
FV - MD Case Plots.

Sheet 8 / 8 : " PLE (%) - PHIF / PRO " Plot.

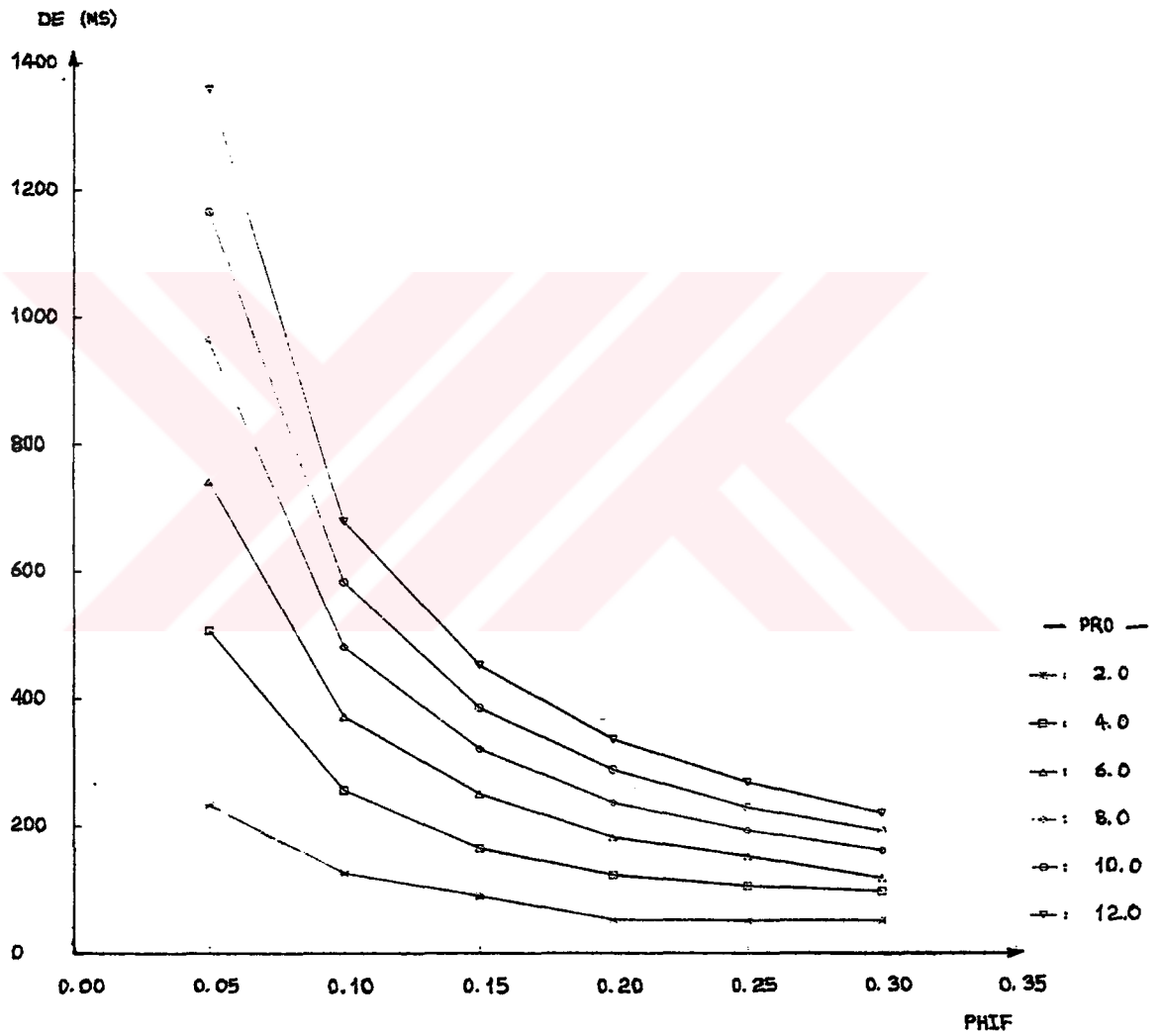


Fig. K.16. Eighth Page of the  
FV - MD Case Plots.

END OF THE FV CASE PLOTS

## K.2. THE NON - FULL VESSEL CASE EXAMPLES.

### K.2.1. The First Full Graphics Output - Six Sheets.

Sheet 1 / 6 : Main Data And Results.

| NON - FULL VESSEL      |                          |                         |                         | P.1/6 |
|------------------------|--------------------------|-------------------------|-------------------------|-------|
| H... = 1.500 (M)       | DV... = 0.300 (M)        | TETA. = 90.0 (DEG)      | NCV... = 0              |       |
| PRO... = 15.00         | PHIF. = 0.200            | TCL. = 1.000E-03 (S)    | IVFC. = 1               |       |
| PHMO. = 0.850          | ICL. = 800               | INF. = 40               | MF... = 20              |       |
| BBQ... = 0.300E-01     | STD. = 0.400E-01         | CBQ. = 1.00             | LDON. = 0               |       |
| BRBO. = 1.00E-04 (M)   | BRTQ. = 0.50E-03 (M)     | CBRO. = 1.00            | KVPQM. = 1              |       |
| CTDNF. = 15.0          | CTMNF. = 3.0             | CTDF. = 0.0             | CTMF. = 0.0             |       |
| RL... = 998.3 (KG/M3)  | VCL. = 0.10E-02 (KG/M3)  | BNL. = 0.189E+10 (N/M2) | STCL. = 0.729E-03 (N/M) |       |
| RBS... = 1.205 (KG/M3) | VCB. = 0.18E-04 (KG/M3)  | BN... = 1.00            | BGC... = 286.9 (MKS)    |       |
| RGS... = 1.205 (KG/M3) | VCG. = 0.18E-04 (KG/M3)  | GN... = 1.40            | GGC... = 286.9 (MKS)    |       |
| IDMC. = 1              | JKS... = 1               | JJS... = 0              | IFC... = 0              |       |
| LFVT. = 0              | INFFX. = 0               | LCBCH. = 0              | XBFG. = 0.70            |       |
| IDC... = 11            | IDC... = 0               | IJOEM. = 1              | JCHB. = 1               |       |
| KCH... = 7100          | ENVH. = 0.120E+11 (N/M2) | VWT... = 0.0030 (M)     | ICVN. = 0               |       |
| LCS... = 0             | KMCCE. = 0               | KMCCE. = 0              | CRCBC. = 1.00           |       |
| LMCU. = 2              | LMCP. = 1                | ILMCU. = 0              | ILMCP. = 4              |       |
| IEDG. = 1              | PRLG. = 1.0080           | ULING. = 5.000 (M/S)    | ICRG. = 1               |       |
| IEDL. = 1              | PRLM. = 1.0100           | ULIM. = 0.050 (M/S)     | ICRM. = 1               |       |
| INSF. = 1              | NSPIL. = 0               | LSFTIC. = 1             | JSFUP. = 0              |       |
| UNSF. = 1.00E-06       | PVSFL. = 0.50E-02        | KRPSF. = 1              | NDVSF. = 1              |       |
| DVSFL. = 1.00E-11      | DVRCL. = 1.00E-11        | RPDLI. = 1.00E-13       | DUSFL. = 1.00E-06       |       |
| JSFBH. = 1             | CSFP1. = 0.990           | CSFP2. = 0.500          | CSFP3. = 0.000          |       |
| JSFBR. = 1             | CSFD1. = 0.200           | CSFD2. = 0.000          | CSFD3. = 0.000          |       |
| JSFCE. = 1             | RPSFE. = 1.0350          | KMCSF. = 0              | DVMSF. = 0.50E-02       |       |
| MAIN RESULTS           |                          |                         |                         |       |
| DE... = 0.394 (S)      | DGE... = 0.025 (S)       | DME... = 0.370 (S)      | PCALF. = 1.035          |       |
| PLF... = 0.804         | PLEF. = 0.196            | PBVF. = 1.922           | PHIF. = 0.200           |       |
| JEND. = 809            | RJME. = 40.450           | RPLEX. = 0.819          | RPLEY. = 0.300          |       |
| JGLE. = 809            | VLFE. = 0.0709 (M3)      | MLF... = 70.155 (KG)    | MLEF. = 17.124 (KG)     |       |

Fig. K.17. List of Main Data and the Results  
of the First NFV Case Example.

Sheet 2 / 6 ; Four Plots.

PCAL - T (%)

CEC - T (%)

DT (%MV) - T (%)

DTRT - T (%)

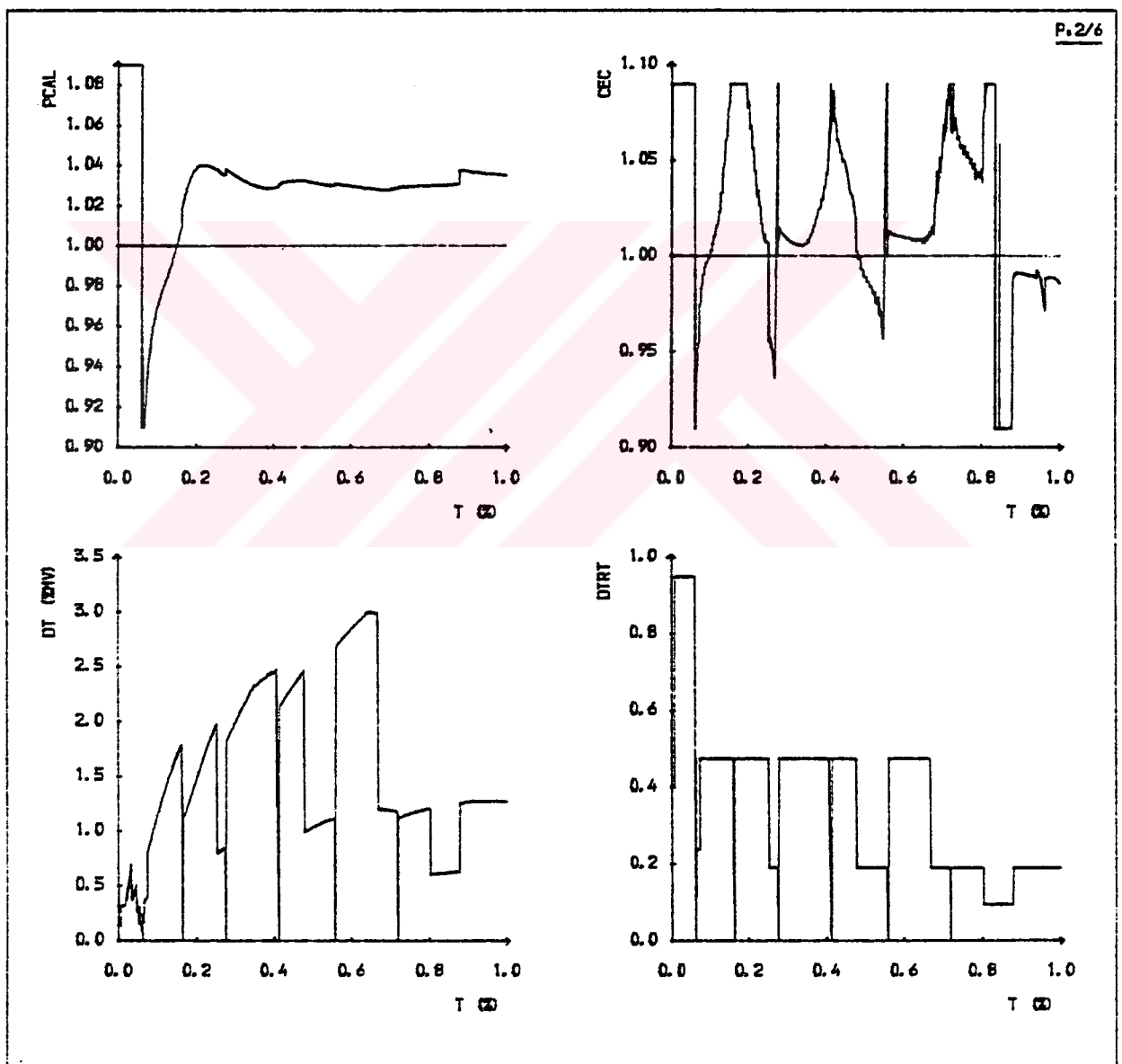


Fig. K.18. First Detailed Plots Page  
of the First NFV Case Example.

Sheet 3 / 6 ; Four Plots.

PCE - T (%)

BV (%IV) - T (%)

MCE-S (%IV) - T (%)

PR-T - CSN

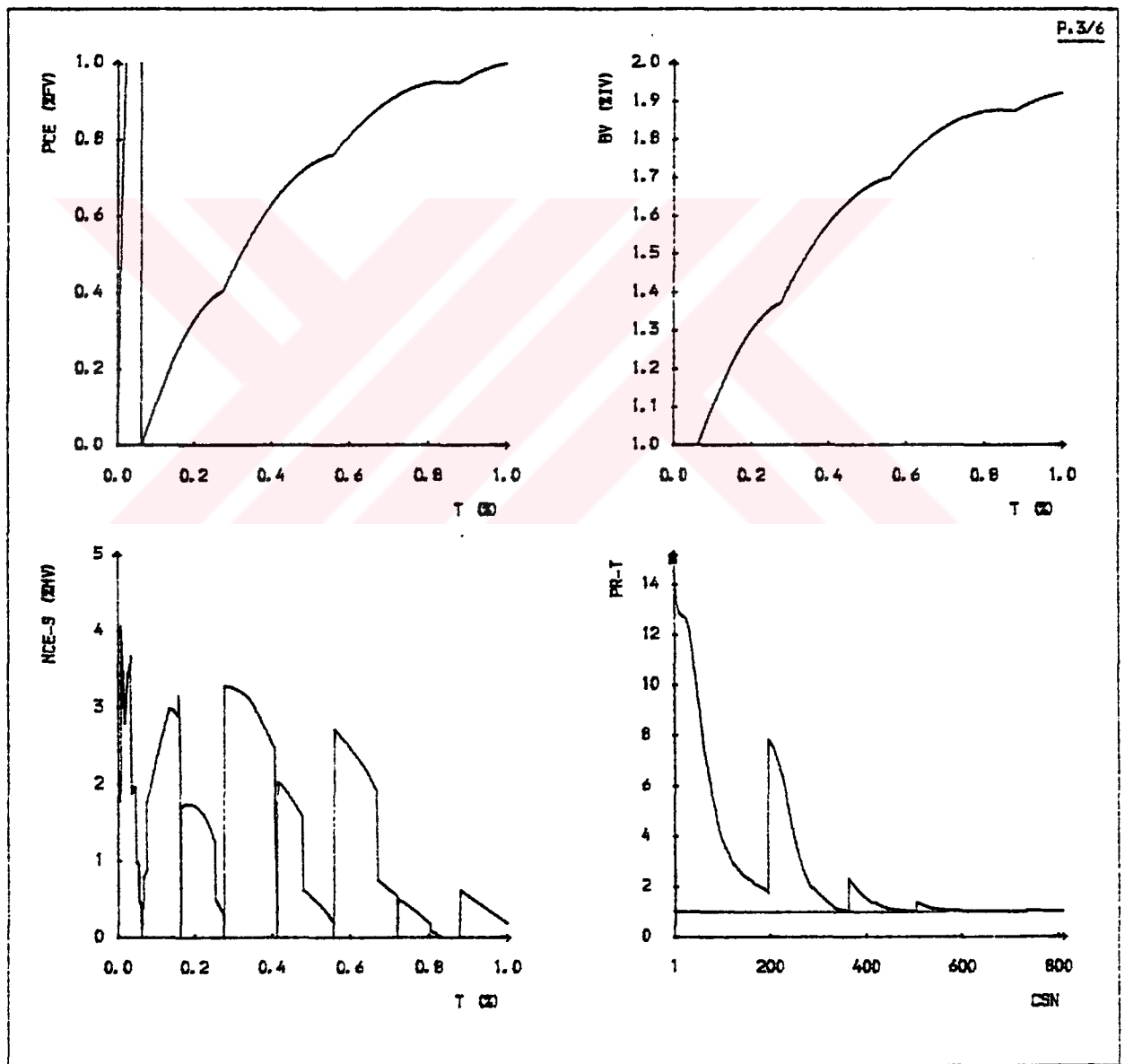


Fig. K.19. Second Detailed Plots Page  
of the First NFV Case Example.

Sheet 4 / 6 ; Four Plots.

HM (%HV) - T-GE (%)

PHM-S (%IV) - T-GE (%)

DEL (%MV) - T-GE (%)

MCE-S/G (%MV) - T-GE (%)

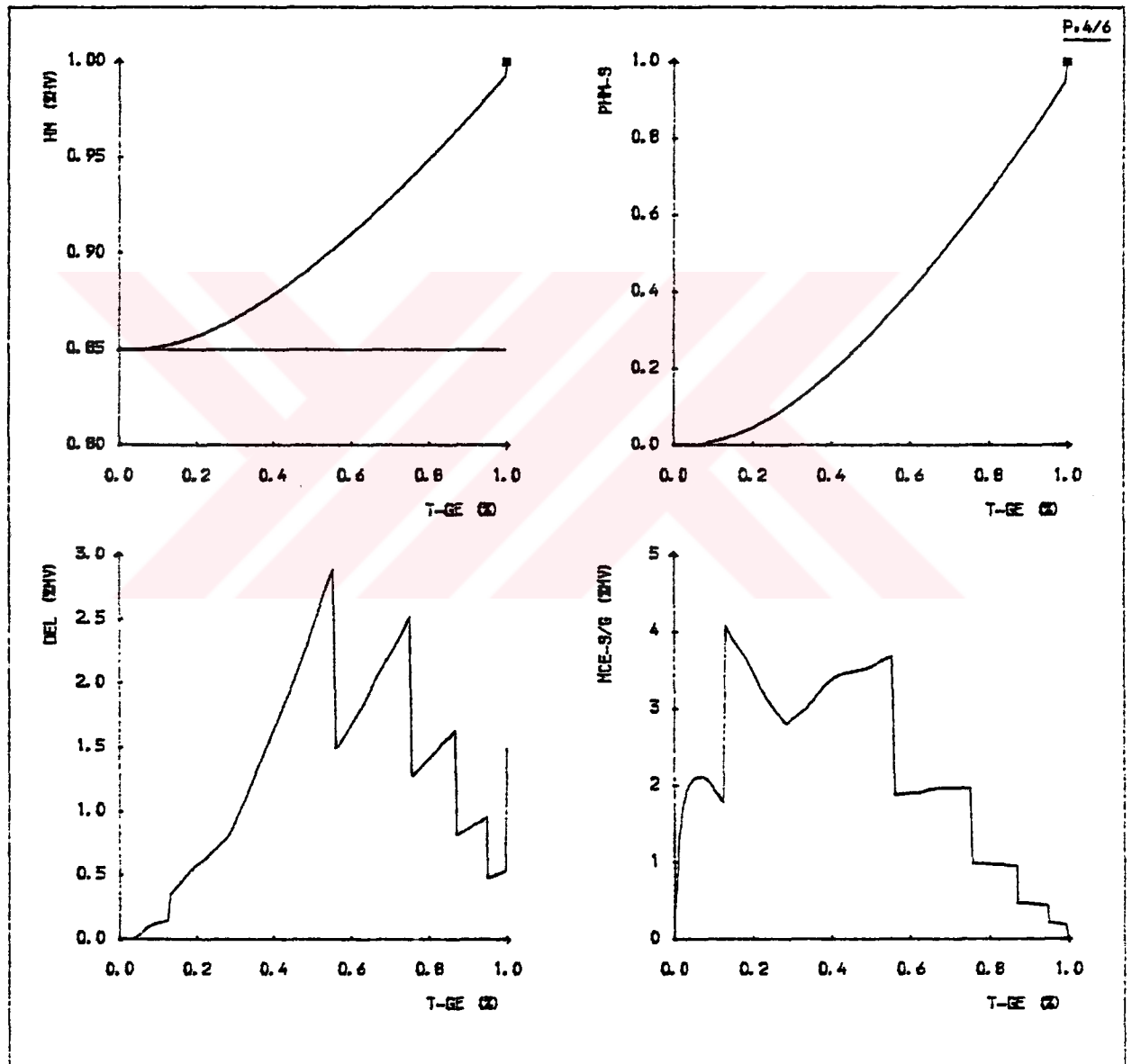


Fig. K.20. Third Detailed Plots Page  
of the First NFV Case Example.

Sheet 5 / 6 ; Pressure History Plot.

PR - T (Top) - T (%) [Start ; 1.0]

PR - M (Middle) - T (%) [ " " ; 1.0+ ]

PR - B (Bottom) - T (%) [ " " ; 1.0++]

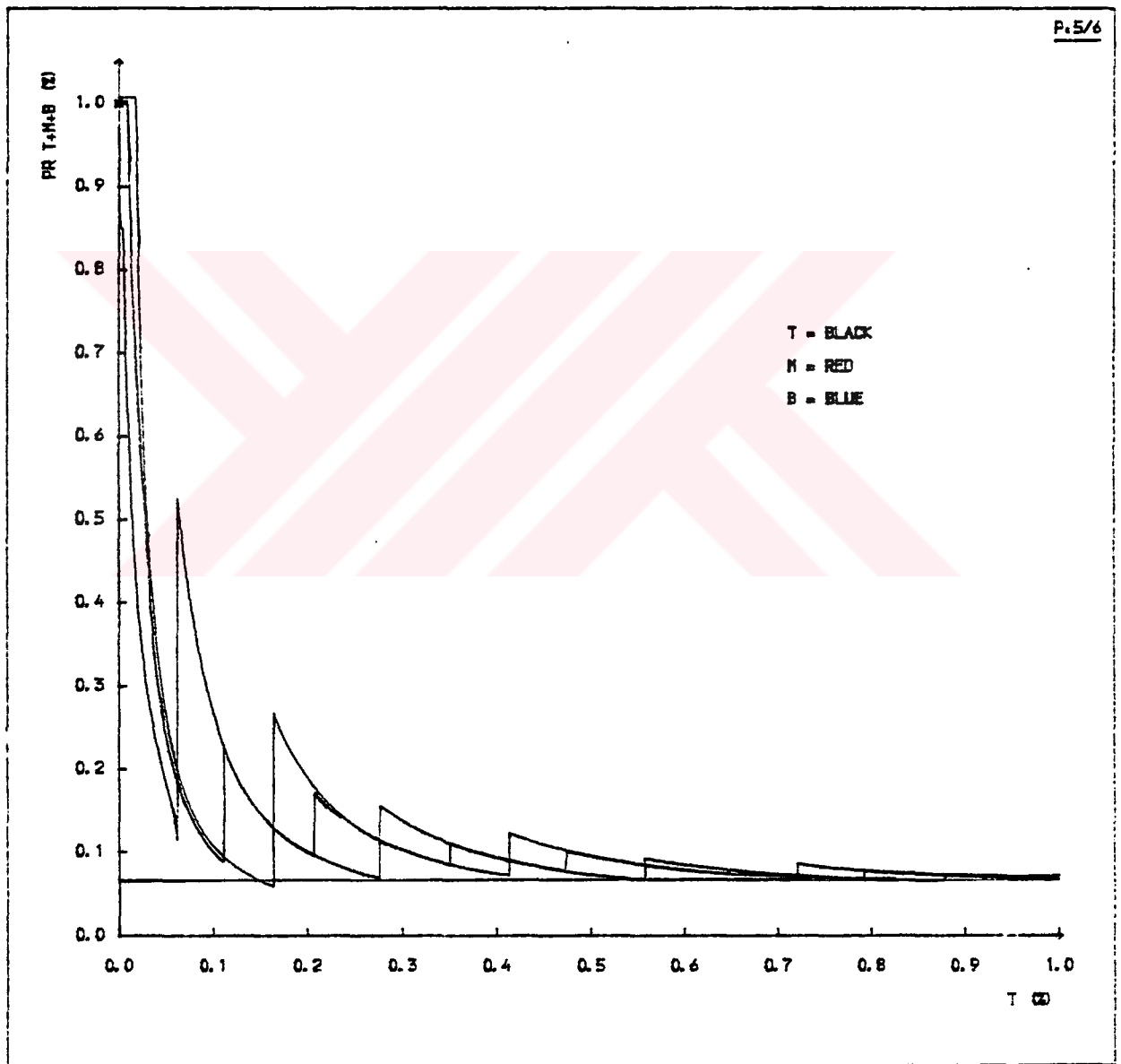


Fig. K.21. Pressure History Plot  
of the First NFV Case Example.

Sheet 6 / 6 ; Multi Parameter Plot.

PR - T & M & B - T (%) [Not Signed]  
PCEP & CEC & PCAL & DTRT - T (%) [Not Scaled]

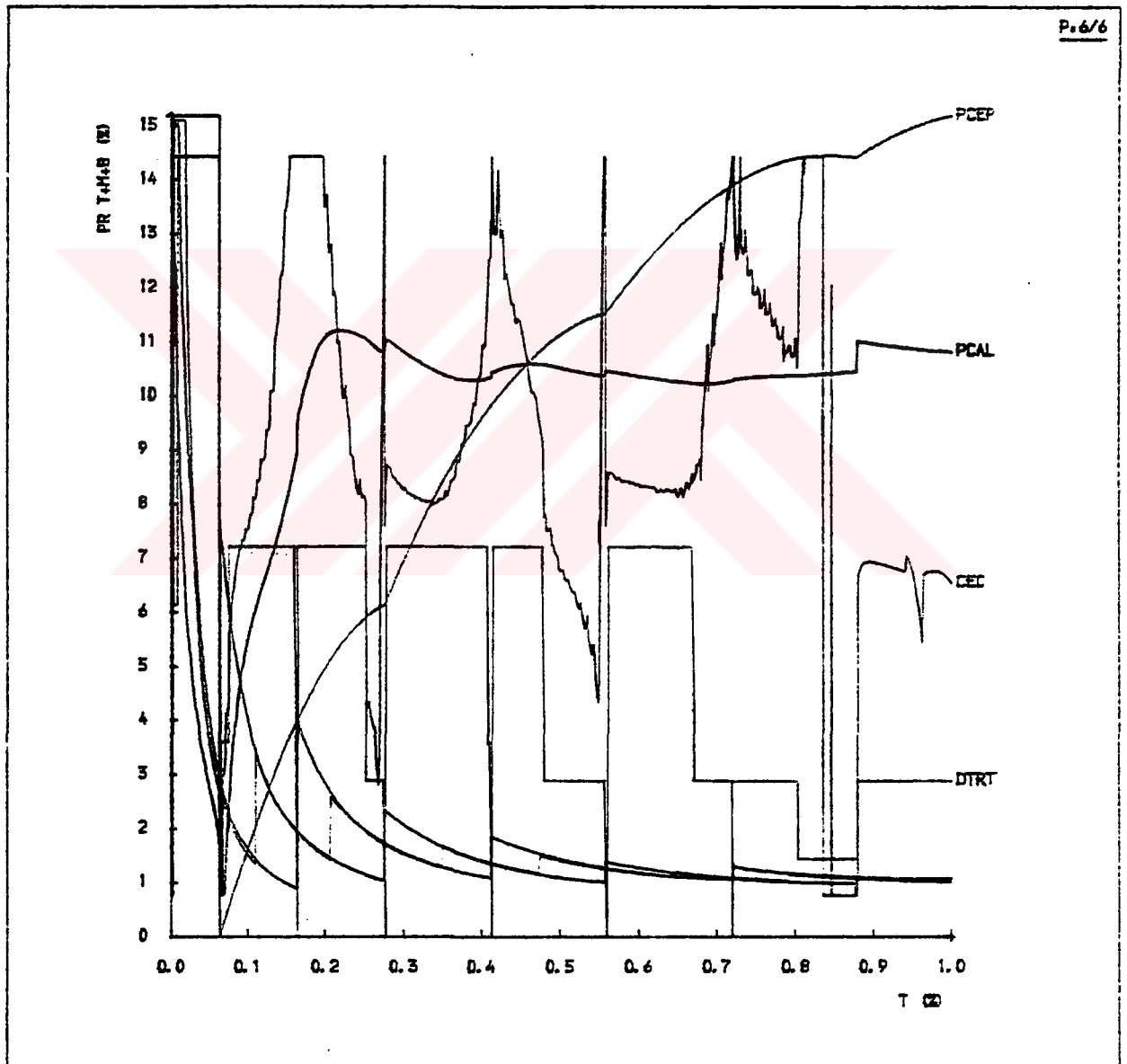


Fig. K.22. Multi Parameter Plot  
of the First NFV Case Example.

### K.2.2. The First Full Graphics Output - Six Sheets.

#### Sheet 1 / 6 : Main Data And Results.

P+1/a

| NON - FULL VESSEL      |                            |                           |                           |
|------------------------|----------------------------|---------------------------|---------------------------|
| M... = 2.500 (M)       | DV... = 0.250 (M)          | TETA = 90.0 (DEG)         | NCV... = 0                |
| PRO... = 5.00          | PHIF... = 0.250            | TCO... = 1.000E-05 (S)    | WFC... = 1                |
| PHMO... = 0.350        | ICL... = 300               | MNF... = 50               | MF... = 20                |
| BBO... = 0.500E-01     | STO... = 0.500E-01         | CBO... = 1.00             | LDON... = 0               |
| BRBO... = 1.00E-04 (M) | BRTO... = 0.50E-05 (M)     | CBRO... = 1.00            | KVPGM... = 1              |
| CTDNF... = 15.0        | CTMNF... = 3.0             | CTDF... = 0.0             | CTMF... = 0.0             |
| RL... = 998.3 (KG/M3)  | VCL... = 0.10E-02 (KG/M3)  | BML... = 0.189E+10 (N/M2) | STCL... = 0.729E-03 (N/M) |
| RBS... = 1.205 (KG/M3) | VCS... = 0.18E-04 (KG/M3)  | BN... = 1.00              | BGC... = 286.9 (MKS)      |
| RGS... = 1.205 (KG/M3) | VCG... = 0.18E-04 (KG/M3)  | GN... = 1.40              | GGC... = 286.9 (MKS)      |
| ICMC... = 1            | JKS... = 1                 | JJS... = 0                | IFC... = 0                |
| LFVT... = 0            | INFFX... = 0               | LCBCM... = 0              | XBFG... = 0.70            |
| IOE... = 11            | IOEQ... = 0                | IJOEM... = 1              | JCMB... = 1               |
| KCM... = 7100          | EMVM... = 0.120E+11 (N/M2) | VVT... = 0.0030 (M)       | ICVN... = 0               |
| LCS... = 0             | KMCCE... = 0               | KMCDE... = 0              | CRCBC... = 1.00           |
| LMCU... = 2            | LMCP... = 1                | ILMCU... = 0              | ILMCP... = 4              |
| IECG... = 1            | PRLG... = 1.0080           | ULING... = 5.000 (M/S)    | ICRG... = 1               |
| IECM... = 1            | PRLM... = 1.0100           | ULIMM... = 0.050 (M/S)    | ICRM... = 1               |
| INSF... = 1            | MSFM... = 0                | LSFIC... = 1              | JSFUP... = 0              |
| UWSFL... = 1.00E-06    | PVSFL... = 0.50E-02        | KRPSF... = 1              | NQWSF... = 1              |
| DWSFL... = 1.00E-11    | DWRCL... = 1.00E-11        | RPDLI... = 1.00E-13       | DUSFL... = 1.00E-06       |
| JSFBM... = 1           | CSFP1... = 0.990           | CSFP2... = 0.500          | CSFP3... = 0.000          |
| JSFBR... = 1           | CSFD1... = 0.200           | CSFD2... = 0.000          | CSFD3... = 0.000          |
| JSFCE... = 1           | RPSFE... = 1.0350          | KMCSF... = 0              |                           |

| MAIN RESULTS      |                      |                      |                      |
|-------------------|----------------------|----------------------|----------------------|
| DE... = 0.147 (S) | DGE... = 0.050 (S)   | DME... = 0.097 (S)   | PCALF... = 1.000     |
| PLF... = 0.928    | PLEF... = 0.072      | PBYF... = 1.314      | PHIF... = 0.250      |
| JEND... = 301     | RJME... = 15.050     | RPLEX... = 1.309     | RPLEY... = 0.223     |
| JGLE... = 301     | VLF... = 0.0928 (M3) | MLF... = 92.609 (KG) | MLEF... = 7.140 (KG) |

Fig. K.23. List of Main Data and the Results  
of the Second NFV Case Example.

Sheet 2 / 6 ; Four Plots.

PCAL - T (%)  
CEC - T (%)  
DT (%MV) - T (%)  
DTRT - T (%)

P.2/6

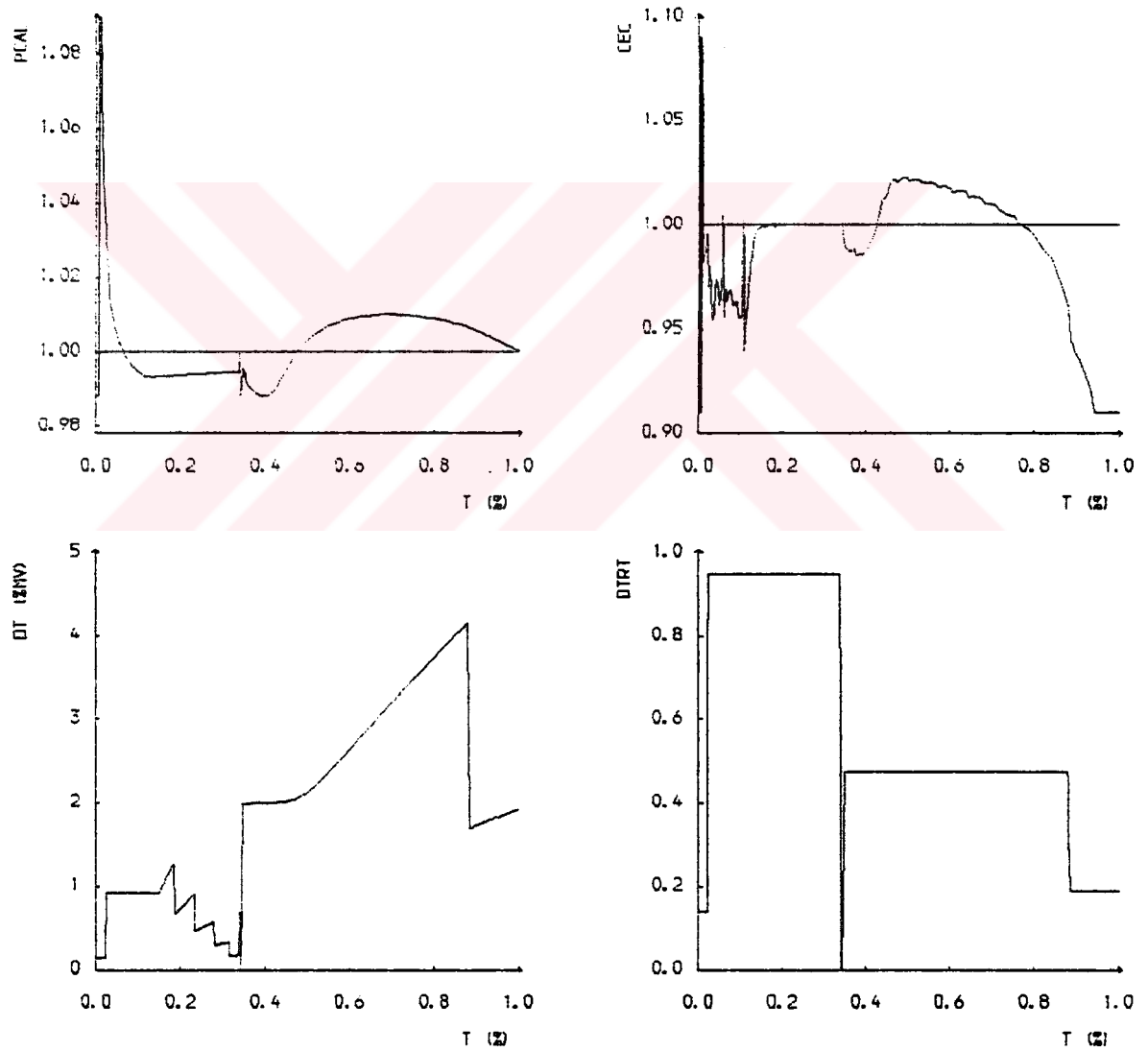


Fig. K.24. First Detailed Plots Page  
of the Second NFV Case Example.

Sheet 3 / 6 ; Four Plots.

PCE - T (%)

BV (%IV) - T (%)

MCE-S (%IV) - T (%)

PR-T - CSN

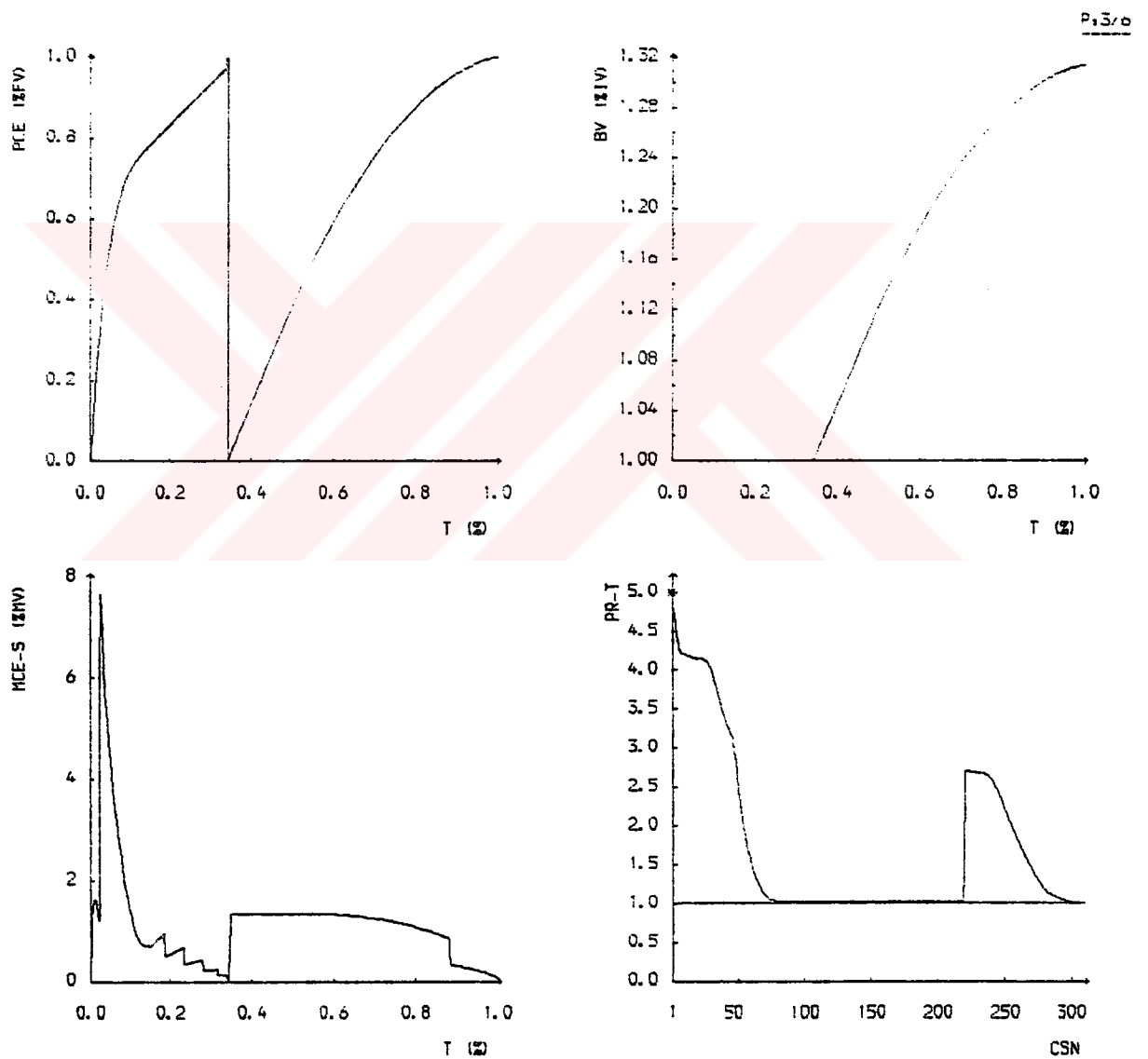


Fig. K.25. Second Detailed Plots Page  
of the Second NFV Case Example.

Sheet 4 / 6 ; Four Plots.

HM (%HV) - T-GE (%)

PHM-S (%IV) - T-GE (%)

DEL (%MV) - T-GE (%)

MCE-S/G (%MV) - T-GE (%)

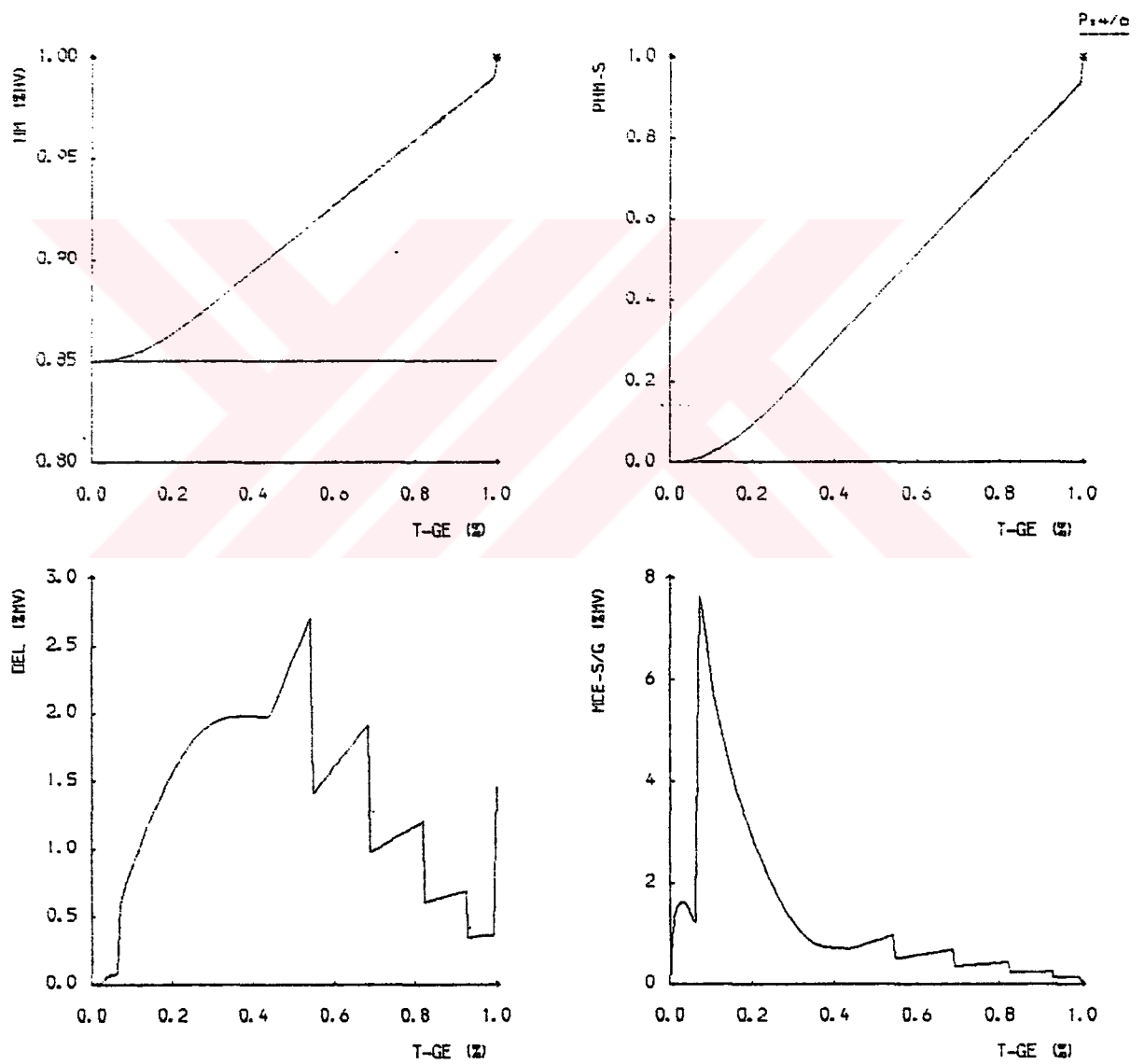


Fig. K.26. Third Detailed Plots Page  
of the Second NFV Case Example.

Sheet 5 / 6 ; Pressure History Plot.

PR - T (Top) - T (%) [Start ; 1.0]  
PR - M (Middle) - T (%) [ " " ; 1.0+ ]  
PR - B (Bottom) - T (%) [ " " ; 1.0++]

P.5/6

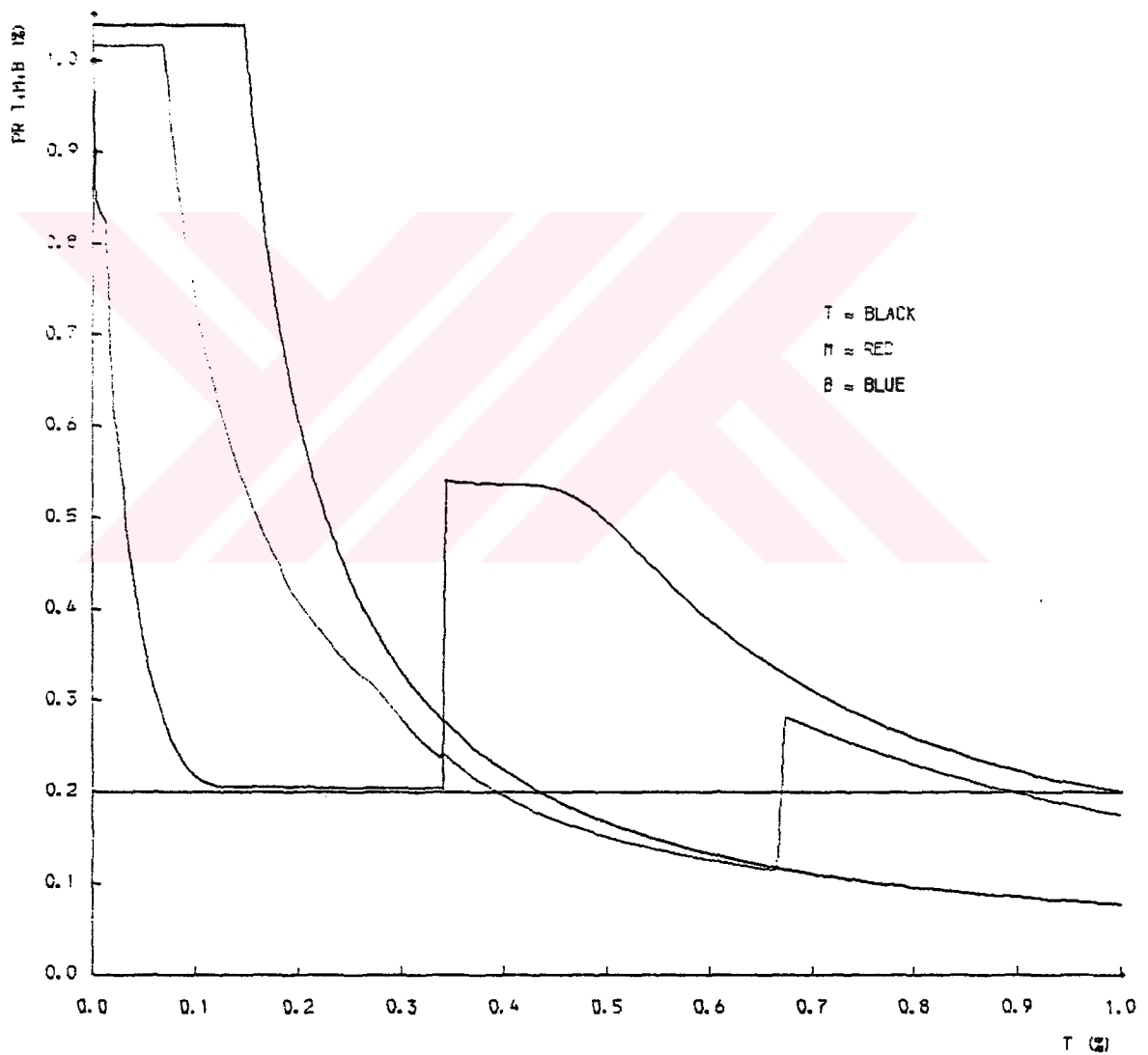


Fig. K.27. Pressure History Plot  
of the Second NFV Case Example.

Sheet 6 / 6 ; Multi Parameter Plot.

PR - T & M & B - T (%) [Not Signed]  
PCEP & CEC & PCAL & DTRT - T (%) [Not Scaled]

Pr. 0.0

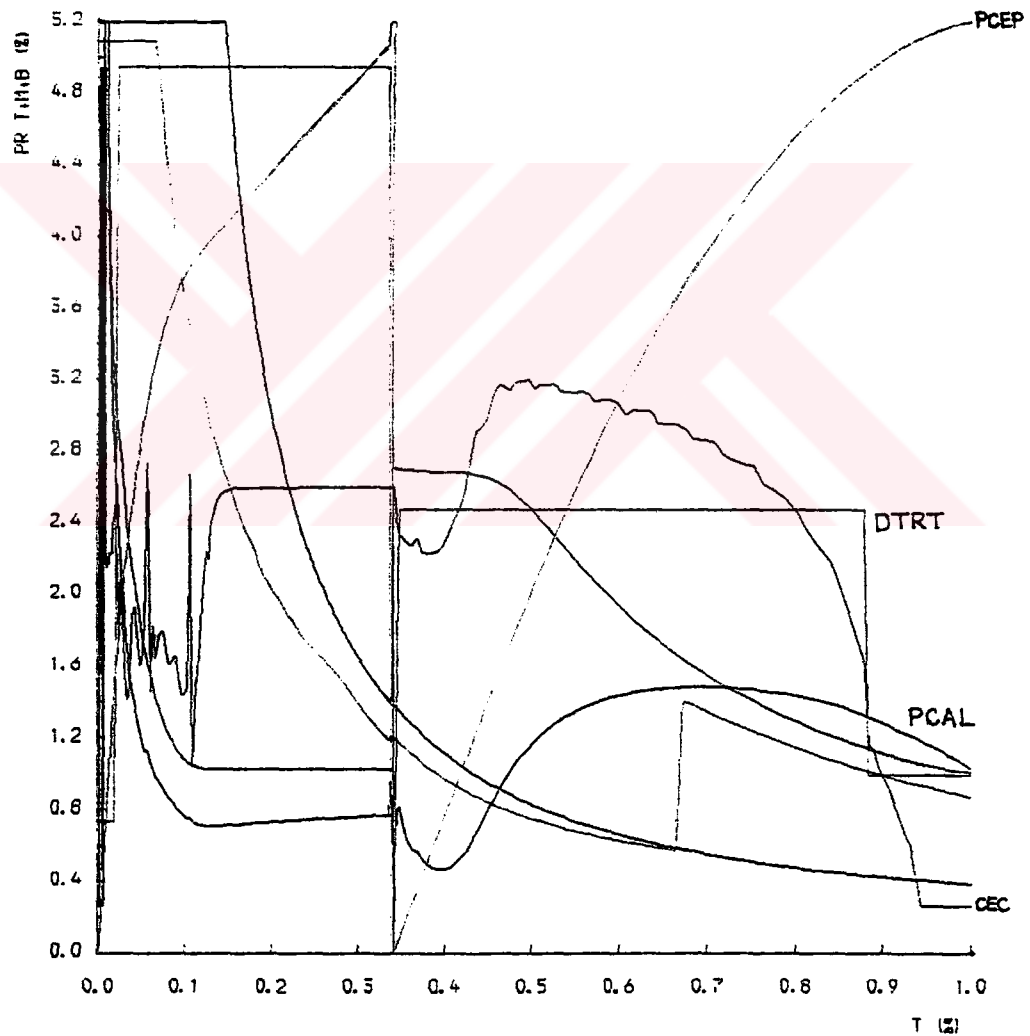


Fig. K.28. Multi Parameter Plot  
of the Second NFV Case Example.

END OF THE NFV CASE PLOTS

K.3. THE PRESSURIZED GAS BOTTLE CASE EXAMPLE.

Sheet 1 / 5 : Main Data And Results.

| PRESSURIZED GAS BOTTLE |                            |                        |                      |
|------------------------|----------------------------|------------------------|----------------------|
| CL... = 1.000 (M)      | CV... = 0.200 (M)          | TETA. = 90.0 (DEG)     | NCV... = 0           |
| PRD... = 5.00          | PHIF. = 0.100              | TCO... = 1.000E-03 (S) | IVFC. = 1            |
| MF... = 20             | CTOF. = 10.0               | CTMF. = 3.0            | IFC... = 0           |
| RGS... = 1.205 (KG/M3) | VCG... = 0.18E-04 (KG/M*S) | GN... = 1.40           | GGC... = 286.9 (MKS) |
| LCS... = 0             | KMCCE = 0                  | KMCDE = 0              | CRCBC = 1.00         |
| LMCU. = 2              | LMCP. = 1                  | ILMCU = 0              | ILMCP = 0            |
| IECG. = 1              | PRLG. = 1.0100             | ULMG = 5.000 (M/S)     | ICRG. = 1            |

| MAIN RESULTS      |                     |                    |                |
|-------------------|---------------------|--------------------|----------------|
| DE... = 0.096 (S) | PCALF = 1.0044      | PMGZF = 1.5973     | IJE... = 0     |
| JEND. = 1140      | RJME. = 57.00       | PMGEF = 0.684      | DMGF. = 1.0094 |
| JGLE. = 571       | MGF... = 0.056 (KG) | MGEF. = 0.121 (KG) | PHIF. = 0.100  |

Fig. K.29. List of Main Data and Results  
of the Gas Bottle Case Example.

Sheet 2 / 5 ; Four Plots.

PCAL - T (%)  
CEC - T (%)  
DT (%MV) - T (%)  
DTRT - T (%)

P.2/5

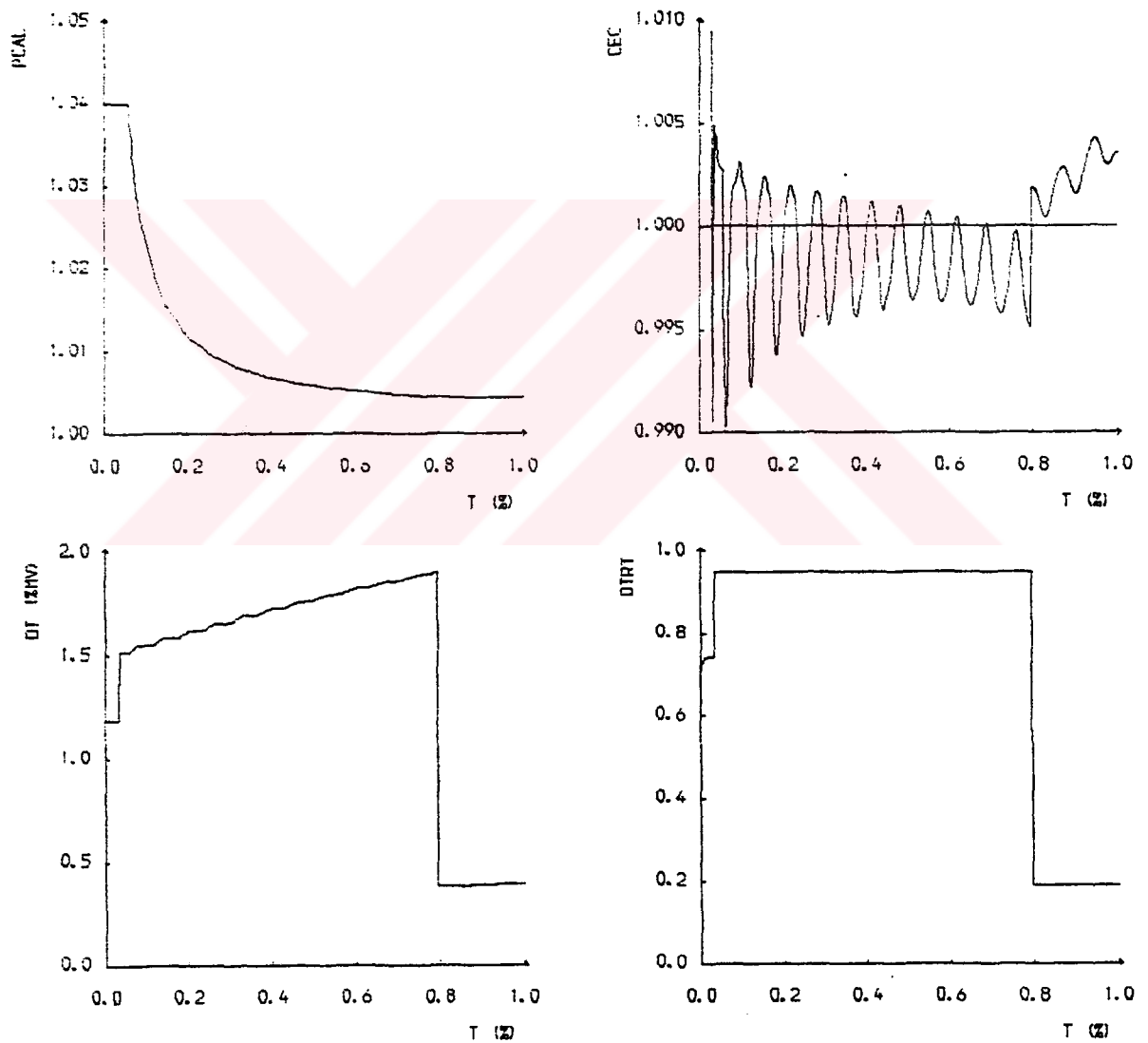


Fig. K.30. First Detailed Plots Page  
of the GB Case Example.

Sheet 3 / 5 ; Four Plots.

PCE (%FV) - T (%)

MG (%IV) - T (%)

MCE-S (%MV) - T (%)

PR-T - CSN

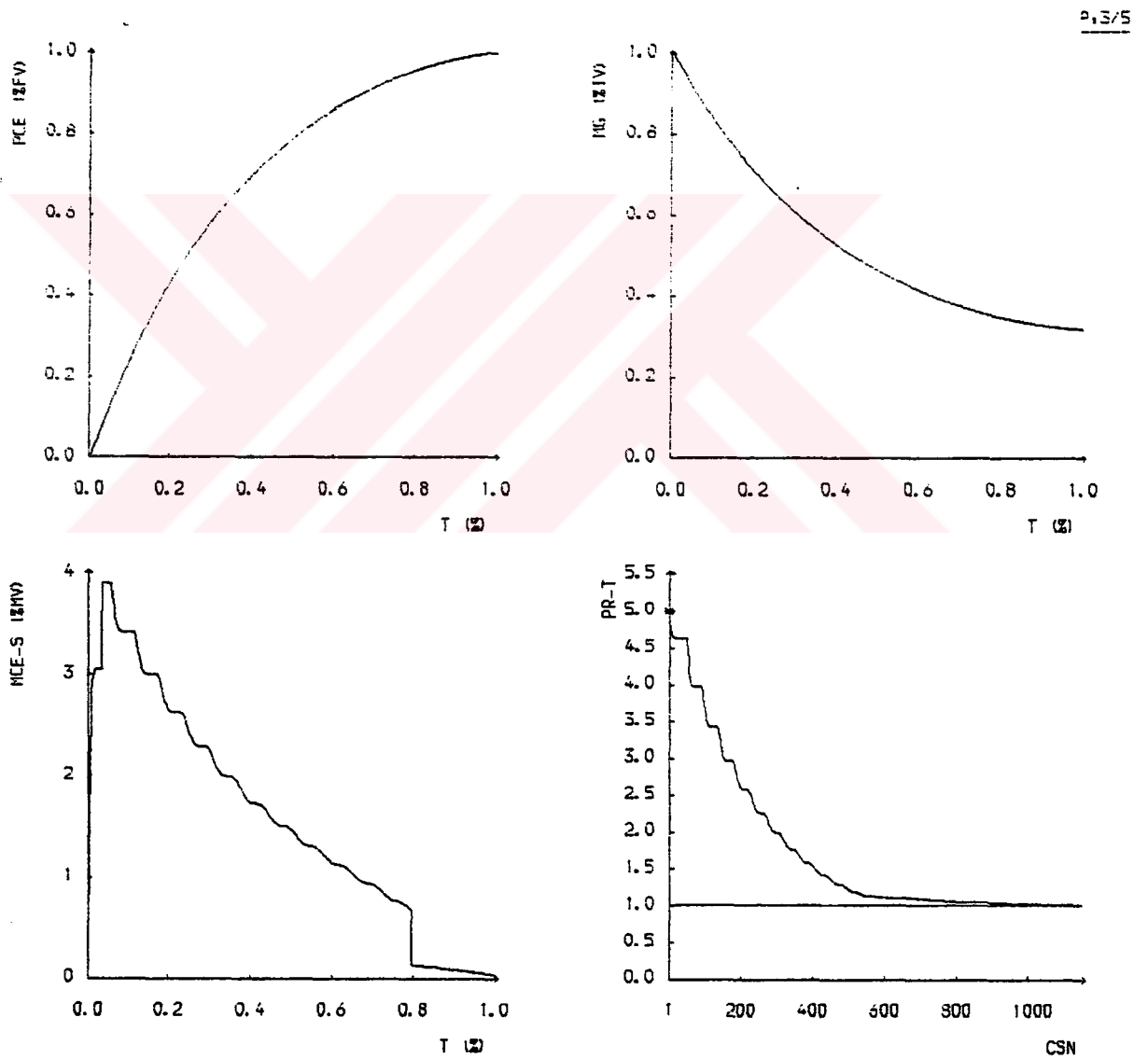


Fig. K.31. Second Detailed Plots Page  
of the GB Case Example.

Sheet 4 / 5 ; Pressure History Plot.

PR - T (Top) - T (%)

PR - M (Middle) - T (%)

PR - B (Bottom) - T (%)

P<sub>4</sub>/5

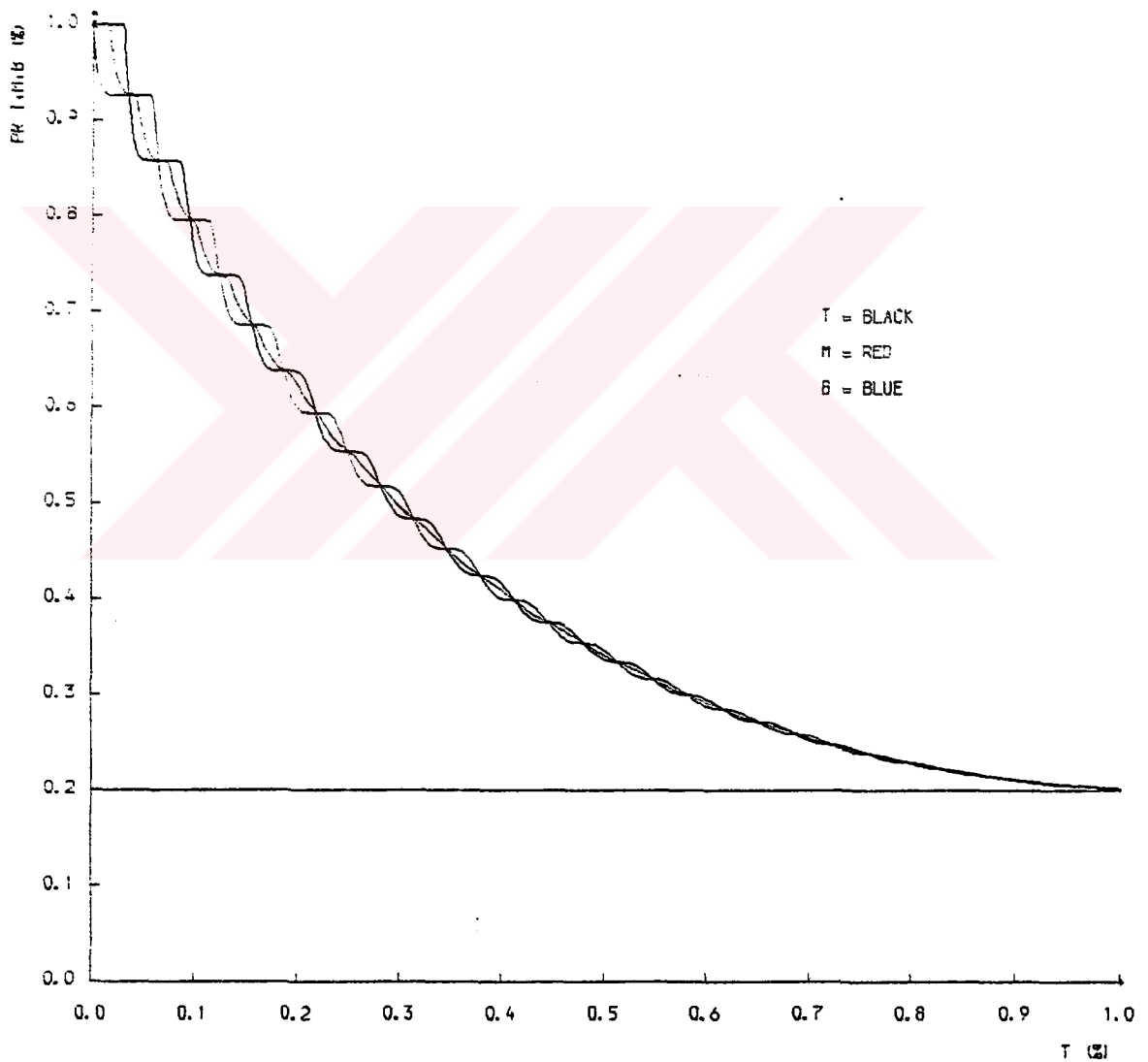


Fig. K.32. Principal Pressure History Plot  
of the Gas Bottle Case Example.

Sheet 5 / 5 ; Multi Parameter Plot.

PR - T & M & B - T (%) [Unsigned]  
PCEP & CEC & PCAL & DTRT - T (%) [Not Scaled]

P.5/5

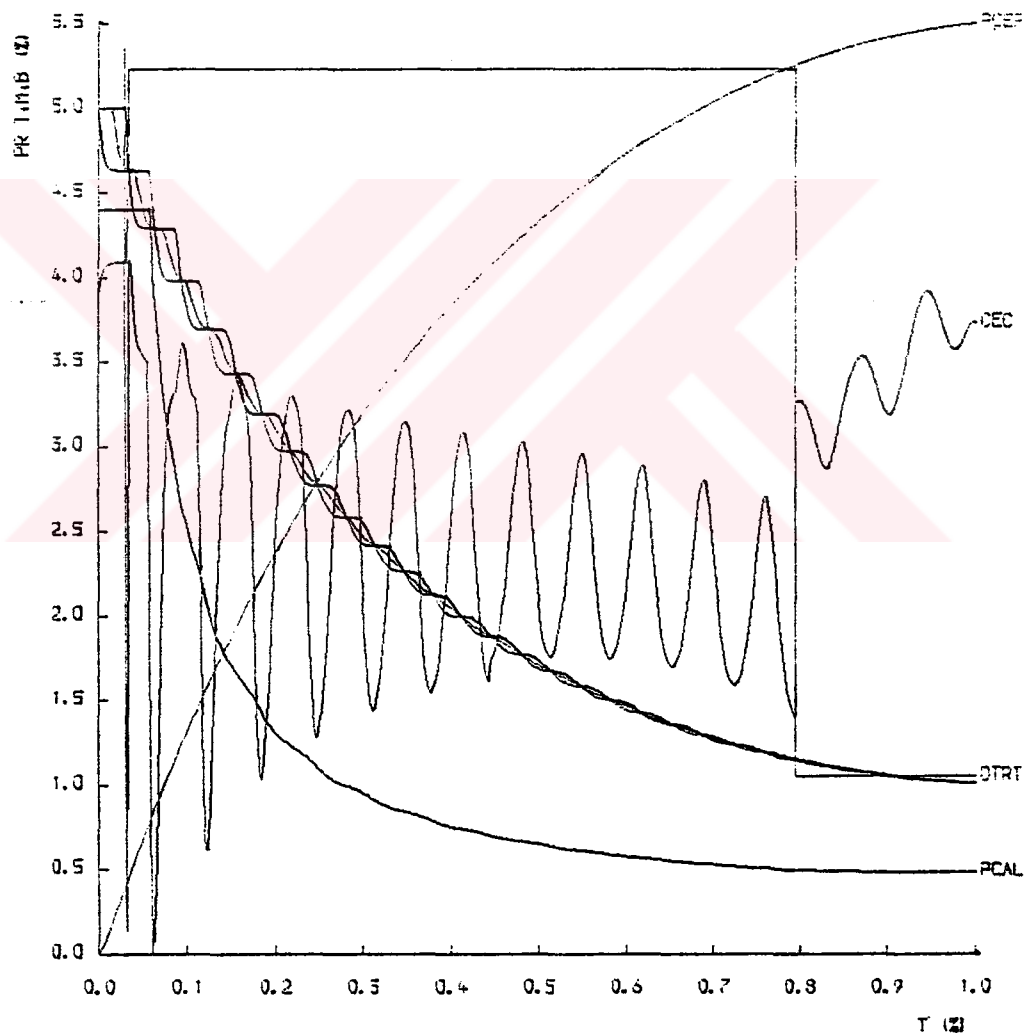


Fig. K.33. Multi Parameter Plot  
of the Gas Bottle Case Example.

END OF APPENDIX K

## A P P E N D I X - L

### I N P U T / O U T P U T E X A M P L E S

The six data files of the program [Chap.1.4] has the same format and the corresponding parts of them has exactly the same character, and they are grouped and placed at the same order. All of the data files are stored in the programme -at the end of the main part- for safe keeping and here only the most complete one of them all ; the data file of the Non-Full Vessel Case is listed as an example. In addition, examples for the data lists of the multi data cases are given.

The order of appearance of the groups of data in the data files - when exist - may be listed as given in Table L-1 ;

Table L-1 Order of the Data in the Data Files.

Heading, Site and Type of the Job Oriented Data.  
Dimensions of the Cylindrical Vessel.  
Quality of the Mixture. (Cond. of the Bubbles.)  
Opening Dimension and Conditions.  
Initial MC Calculation Adjustments.  
Definition of the MC Mesh.  
Characteristics of the Output File.  
Economic Run Measures.  
Geometry of Non-Cylindrical Vessel.  
Physical Conditions of the Fluids.  
Discharge Calculations.  
Common MC Calculations.  
Ways of Ending the Calculations.  
NFV to FV Transformation.  
Speed of Sound and the CPR Calculations.  
Shock Front Calculations.  
    Principal Definitions of the SF calculations.  
    Precision and SF Point Calculations.  
    SF-MC Calculations and Library Use Parameters.  
Graphics Drawing.  
Single / Multi Data Cases Definition.  
The MC Calculation Loops.  
The Discontinuity Surfaces.  
The Open and Closed End Points.  
Ordinary Points.  
Debugging and the Batch Jobs.  
Informativeness and Size of the Output File.  
Environmental Conditions.  
Input Lists of the Multi Data Cases.

L.1. DATA FILE OF THE NON-FULL VESSEL CASE. (Six Pages)

P:1/6

```

I=====I
1.=NDF I*** KDF= 1. : (DNF) = NON - FULL VESSEL *****I KNC=3. LGL=1.
I-----I
1. - 1. & 1. = LLQ - LBG & LRG WATER - NITROGENE & AIR
I-----I
CASE: NFV *** TRIAL RUN *** DATE: 24.10.1984
I-----I
I***** H *****I***** DV *****I***** TETA *****I***** HMI *****I***** PHMI *****I
(M) (M) (DEG) (M) (%)
1.500 0.300 90.0 0.0 0.850
I-----I
I***** PTI *****I***** PRTI *****I***** (TCO)*****I***** AOF *****I***** PHIF *****I
(N/M2) (0) (SEC) (M2) (%)
0.0 15.0 -2.10 0.0 0.200
I-----I
I*** (BBI)***I*** (BTI)***I***** CBI *****I
(%) (%) (BI FUNC PAR)
0.030 0.040 1.0
I-----I
I*** (BRBI)***I*** (BRTI)***I***** CBRI *****I
(M) (M) (BRI FUNC PAR)
-3.10 -3.50 1.0
I-----I
I*** CTDNF *****I***** CTMNF *****I***** CTDF *****I***** CTMF *****I
(.GE.5.) (.GE.1.5) (.GE.5.) (.GE.5.)
15.0 3.0 20.0 10.0
I-----I
I*** (TCOX)***I***** CTDX *****I***** CTMX *****I
(SEC) (.GE.5.) (.GE.5.)
-2.10 5.0 5.0
I-----I
I*** RICL *****I***** RJCF *****I***** RIFG *****I***** RIFM *****I
(M=NF(MAX)) (>0:SP MC CE) (1:FG INCL) (1:FM INCL)
800. 0. 1. 1.
I-----I
I*** RMNF *****I***** RJGS *****I***** RJMS *****I***** RJZNF *****I***** ENF *****I
(30/40/50) (MNF/...:INT) (MNF/...:INT) (.GE.20) (.LE..95)
40. 5. 5. 50. 0.95
I-----I
I*** RMF *****I***** RJFS *****I***** RJZF *****I***** EF *****I
(20/30/40/50) (MF/...:INT) (.GE.25) (.LE..95)
20. 5. 50. 0.95
I-----I
I*** RIDIMF **I*** RIMIVF **I*** XMIVF *****I***** RIDWF *****I***** XIDWF *****I
(0:M(FV-IN)=MF) (M=IMIV*MF) (JZ (M=MF)) (1:M=MF - WF) (M=MF:...% WF)
0. 2. 5.0 1. 0.50
I-----I
I*** RIJTS *****I RMJTS (2**I)I RLJTSB (=>5)I RLJTST (=>5)I
(1:JT-SAVE C) (M.GE.MJTS*MNF) (LJTSB.GT."I".LT.(LO-LJTST))
0. 2. 5. 5.

```

Data File of the Non-Full Vessel Case. (Cont.)

P:2/6

```

I-----I
I*** RJGRC ***I*** RIOAL ***I*** RJSGL ***I*** RJALO ***I*** RNODPR ***I
 (1:GR PROD) (O/P AR LIST) (GL INF STEP) (GL ARY LIM.) (0:DATE PR)
 1. 1. 1. 0. 0.
I-----I
I*** RIUOA ***I*** RLSGL ***I*** RLGRO ***I*** RLOLO ***I*** RNGDRP ***I
 (OP LI LEVEL) (GR USE LIST) (1:GR ONLY) (1:OL ONLY) (0:G D+R INF)
 2. 0. 0. 0. 0.
I-----I
I*** RISVC ***I*** RICOH ***I*** RLGDP ***I*** RIBRCL ***I*** RLEGRI ***I
 (SINGLE V.C.) (0/1:CURV/PTP)(0/1:CVO/NSC) (BR/CL/BOTH) (1:EX GR INF)
 1. 0. 1. 2. 0.
I-----I
I*** RNCV ***I*** RICDA ***I*** CDAC ***I*** (ZK) ***I*** RLPVC ***I
 (0.: CYL VES) (DA CAL. M) (DA CAL. C) (M) (VES C INF)
 0. 1. 0.0 -4.50 0.
I-----I
I*** XVRL ***I*** XVRU ***I*** XVRT ***I*** TDI ***I
 (%H LOWER S) (%H UPPER S) (%H TOP S) (% DV)
 0.10 0.65 0.85 0.00
I-----I
I*** DBLS ***I*** DBCS ***I*** DBUS ***I*** DBTS ***I
 (%DV BOT.L.S) (%DV BOT.C.S) (%DV BOT.U.S) (%DV BOT.T.S)
 0.90 1.20 1.05 0.90
I-----I
I*** CSSPL ***I*** CSSPD ***I*** TSIAB ***I*** TSIAT ***I
 (%HC CSSPL) (%DV CSSPD) (T.S.BOT DEG) (T.S.TOP DEG)
 0.70 0.95 5.00 1.00
I-----I
I*** RINSF ***I*** RMSFM ***I*** RLSFIC ***I*** RJSFUP ***I*** ESF ***I
 (0:NO SF) (SF CAL WAY) (IN U/PU CAL) (DW CW U/P) (.LE. 0.97)
 1. 0. 1. 0. 0.95
I-----I
I*** DSFXL ***I*** (UWSFL) ***I*** (PWSFL) ***I*** RNRPSF ***I*** RKRPSF ***I
 (DSFX LIM) (M/S) (N/M2) (RPSF CALC) (RPSF CALC)
 0.97 -5.10 -2.50 0. 1.
I-----I
I*** (DWSFL) ***I*** (DWRCL) ***I*** (RPDLI) ***I*** (DWISF) ***I*** (DUSFL) ***I
 (DWSF LIM.) (DWSF RC LIM) (RPDEL LIM.) (MSSFM-DW L) (SFE ER LI)
 -10.10 -10.10 -12.10 -1.10 -5.10
I-----I
I*** RIPRSF ***I*** APISF ***I*** BPISF ***I*** PRISF ***I*** DSFRP ***I
 (RPSF ST C W) (RPSF START CALC. COEFF.) (RPSF START) (START RP C.)
 1. 1.10 0.40 1.10 0.1
I-----I
I*** (RPISF) ***I*** (RPSFI) ***I*** (RPSRI) ***I*** (RUSFI) ***I*** RLMCSF ***I
 (RP21 IN INC) (RP21 INC) (RPSR INC) (SFE C INC) (SF-MC C RPT)
 0.050 -4.10 0.010 0.001 1.

```

Data File of the Non-Full Vessel Case. (Cont.)

P:3/6

```

I-----I
I*** RJSFBM **I*** CSFP1 ***I*** CSFP2 ***I*** CSFP3 ***I
(INI VAL CAL) (PARAMETERS OF THE INITIAL RPSF21)
 1. 0.99 0.50 0.0
I-----I
I*** RJSFBR **I*** CSFD1 ***I*** CSFD2 ***I*** CSFD3 ***I
(R IN VAL C.) (PARAMETERS OF THE INITIAL RPSFIX)
 1. 0.20 0.0 0.0
I-----I
I*** RNDWSF **I*** RJRPSF **I*** RJLISF **I*** CJRSF ***I*** DILSF ***I
(DWSF C. WAY) (XYZ LI=3/4) (XYZ LI=1/2) (SPECIAL XYZ) (RPSF XYZ C.)
 1. 1. 0. 5.0 0.10
I-----I
I** RJSFCE ***I** RJSFEP ***I*** RPSFE ***I** (DSFNE)***I*** CPCSF ***I
(SF C-E WAY) (PR CAL MET.)(RP21<.:SF-END) (DSF CE LIM) (CR SF RP CO)
 1. 0. 1.035 0.050 0.70
I-----I
I** RKSFC ***I*** CSFPC ***I*** RJLLSF **I** RJLUSF ***I
(SF P CORR.) (<-C:0.26-0.32) (SRPSF INF LOW / UP LIM.)
 0. 0.30 0. 0.
I-----I
I** RLRPEW ***I*** RPNSF ***I*** PRMPS ***I*** PRPSL ***I*** PRMPL ***I
(LOW RP E W) (RPNEW LIM) (PR(MP) LIM.) (PR ST PR LI) (PR(MP)E LIM)
 1. 1.003 1.03 1.10 1.015
I-----I
I** RNLSFC ***I** RNLSFT ***I** RNSFNC ***I** RNSFNT ***I** RNLSFI ***I
(1: NAG CALC) (1: NAG TIDY) (CALC - NAG ROU NUM - TIDY) (1: NAG-INF)
 0. 0. 1. 1. 0.
I-----I
I** RNRSFB ***I*** RNRSFR **I** (DWNCL)***I*** RNRSCE **I** RNRSOE ***I
(NAG USE BEG) (NAG IN RC) (DW NAG C L) (CE - NAG CAL REG DIS - OE)
 0. 0. -3.50 1. 1.
I-----I
I** RKMCSF ***I*** RKESFC **I** (DSFCL)***I*** RLPSFC **I
(SF P MC CAL) (1:MC D/U C.) (MC D/U LIM) (SF INF OP)
 0. 0. -2.10 2.
I-----I
I** RJMCSF ***I** RJDSFP ***I** RKDSFP ***I** RKSFOP ***I
(SFMC INF) (C-I: JDSF/) (C-I: >JDSF) (SF FIELD OP)
 0. 1. 1. 1.
I-----I
I*** RNSF ****I*** RNSFMC ***I*** RKSFWI ***I*** RKSFWL ***I*** RNSFCI ***I
(2..5) (2..5) (2..5) (2..5) (2..5)
 4. 3. 5. 5. 5.
I-----I
I**** RL *****I*** (VCL)***I*** (BML)***I*** (STCL)***I
(KG/M3) (KG/M*S) (N/M2) (N/M)
 998.2 -2.100 10.180 -3.730

```

Data File of the Non-Full Vessel Case. (Cont.)

P:4/6

```

I-----I
I*** RKVPQL **I*** TLKO *****I*** CPLQ *****I*** CVLQ *****I
(PQ-L CAL LVL) (K) (KJ/KG*KEL) (KJ/KG*KEL)
1. 293.0 4.182 4.158
I-----I
I***** RBS *****I*** (VCB)***I***** CPBG ***I*** CVBG *****I
(KG/M3) (KG/M*S) (KJ/KG*KEL) (KJ/KG*KEL)
1.293 -4.181 1.012 0.718
I-----I
I*** RKVPQB **I***** BN *****I***** BGC *****I*** TBKO *****I*** RICBN ***I
(PQ-BG C LVL) (CPBG/CVBG) (MKS) (K) (BG TERM BHV)
1. 1.00 286.9 293.0 0.
I-----I
I***** RGS *****I*** (VCG)***I***** CPG *****I*** CVG *****I
(KG/M3) (KG/M*S) (KJ/KG*KEL) (KJ/KG*KEL)
1.293 -4.181 1.012 0.718
I-----I
I*** RKVPQG **I***** GN *****I***** GGC *****I*** TGKO *****I
(PQ-G CAL LVL) (CPG/CVG) (MKS) (K)
1. 1.401 286.9 293.0
I-----I
I*** RJRENC **I***** CRRL ***I*** CRRB *****I*** CRVL ***I*** CRVB *****I
(REN-M COE U) (RREN-MIX. C.: RL & RB) (VREN-MIX. C.: VCL & VCB)
0. 1.00 0.0 1.00 0.0
I-----I
I*** RLDON ***I*** RLPHI ***I*** RLXERC **I*** RLXEMC ***I
(-1:-/0:D/1:N)(PHI IN QC C) (QC: REY EFF) (QC: MINOR C)
0. 1. 1. 1.
I-----I
I** RLCBCM ***I***** CLCAD **I*** CLCBD *****I***** CLCAN **I*** CLCBN *****I
(1:QC MIX COR) (QC COR COE - MIX : A + B * VOID FR. ; EE TYPE D & N)
0. 0.90 0.0 0.90 0.0
I-----I
I*** CBIMD ***I*** CBIMN ***I*** TFOEM ***I*** TFOIM ***I
(COR COE B-F MIX : DI & NO) (FULL O MIX EXP & B-F FL C)
0.90 0.70 0.98 0.90
I-----I
I***** COFM ***I***** TOFM ***I***** CBFM ***I*** TBFM *****I
(NON STRD EE : QC - MIX) (NON STRD EE : QC BF MIX)
0.60 0.95 0.50 0.90
I-----I
I*** XBFG ***I*** CBIGD ***I*** CBIGN ***I*** TFOEG ***I*** TFOIG ***I
(% EG IN B-F) (COR COE B-F GAS : DI & NO) (FULL O GAS EXP & B-F FL C)
0.70 0.90 0.80 0.99 0.95
I-----I
I***** COFG ***I***** TOFG ***I***** CBFM ***I*** TBFM *****I
(NON STRD EE : QC - GAS) (NON STRD EE : QC BF GAS)
0.60 0.95 0.50 0.90

```

Data File of the Non-Full Vessel Case. (Cont.)

P:5/6

```

I-----I
I**** RIOMC ***I*** DELXL ***I***** RJKC ***I*** RJJS *****I
(1:OPT M C.) (.LE..95) (L+KC+JKC=MP) (NFV TO FV T)
 1. 0.95 1. 0.
I-----I
I**** RLFVT ***I*** RIDTRC ***I*** RINFEC ***I*** RINFFX ***I*** RJCSMB ***I
(NFV-FV T W) (0:NO RES DT) (NF-F B COR) (0:PRS MET) (CS B CALC)
 0. 1. 1. 0. 1.
I-----I
I***** RIOE ***I*** RIOEQ ***I***** EXYK ***I*** RIJOEM ***I***** RJCMB ***I
(IOEM/IOEBN) (OE QO CALC.) (IOE>5 COEF.) (NOEM ADJ.) (OP B CALC)
 11. 0. 1.0 1. 1.
I-----I
I***** RKCM ***I*** (EMVM)**I***** VWT *****I***** OEA *****I***** OEB *****I
(SWP 0:ORD.WAY) (N/M2) (M) (UG / UL) (D(UG)/D(UL)
 7100. 11.120 0.0030 1.00 1.00
I-----I
I**** RICWN ***I*** PDPL *****I*** (DYL)***I*** (FFL)***I*** RNPRC ***I
(CPR CAL WAY) (CAL NEADED!) (DY ERR. LIM) (FF ERR. LIM) (LOOP LIM)
 0. 0.20 -5.10 -5.10 0.
I-----I
I**** RINAG ***I*** CNRL *****I*** CNRU *****I*** (EPSN)***I*** (ETAN)***I
(NAG NUM.) (LOWER LIM C) (UPPER LIM C) (NAG EPS) (NAG ETA)
 1. 0.90 1.10 -5.10 -5.10
I-----I
I***** RLCS ***I*** RLMCU ***I*** RLMCP ***I*** RILMCU **I*** RILMCP ***I
("S" CAL WAY) (MC U CAL W.) (MC P CAL W.) (MC U CALC.) (MC P CALC.)
 0. 2. 1. 0. 4.
I-----I
I**** CRCBC ***I*** RLMCCE **I*** RLMCOE **I*** RLMCL ***I*** RKBRMC ***I
(MC XB/C CAL) (MC C RPT CE) (MC C RPT OE) (MC C RPT OP) (MC CE B/R)
 1.00 1. 1. 1. 0.
I-----I
I**** RIPD *****I*** RLAL ***I*** RKMCE **I*** RKMCOE **I*** PRDOE ***I
(STEP IN LEV) (L&K/A LIM) (CE MC CAL W) (OE MC CAL W) (DOE PR LIM)
 2. 5. 0. 0. 1.30
I-----I
I**** RIWFC ***I*** RIULC ***I***** RDT *****I***** PRDT ***I***** DTPR ***I
(IWF CALC.) (I U-LIM USE) (DT=RDT*DT) (PR<PRDT : DT=DTPR*DT)
 1. 0. 0.50 1.15 0.20
I-----I
I**** RIECM ***I*** PRLM *****I*** ULIMM ***I*** UVLM *****I*** RICRM ***I
(CAL END WAY M) (PR<.: "END") (U(M/S)<:END) (M/S) (CR-F M)
 1. 1.010 0.05 1.0 1.
I-----I
I**** RIECG ***I*** PRLG *****I*** ULIMG ***I*** UVLG *****I*** RICRG ***I
(CAL END WAY G) (PR<.: "END") (U(M/S)<:END) (M/S) (CR-F G)
 1. 1.008 5.0 1.0 1.

```

Data File of the Non-Full Vessel Case. (Cont. - Last Page) P:6/6

|                                                                               |                                         |                            |               |               |
|-------------------------------------------------------------------------------|-----------------------------------------|----------------------------|---------------|---------------|
| I***** RNWF ***I**** RKWF ***I****( DWFL )**I**** RNDWF ***I**** RLPWFC **I   | (WFC MC LOOP) (1:D/U CHECK)             | (D/U LIM.)                 | (IO WF DO LI) | (WF INF OP)   |
| 3.                                                                            | 0.                                      | -2.10                      | 10.           | 1.            |
| I-----I                                                                       |                                         |                            |               |               |
| I**** RNOEM ***I**** RKEOEM **I** ( DOEML )**I**** UDCLM ***I**** RLPOEM **I  | (OEM MC LOOP) (1:D/U CHECK)             | (D/U LIM.)                 | (FO (U/C)LIM) | (OEM INF OP)  |
| 3.                                                                            | 0.                                      | -2.10                      | 1.020         | 1.            |
| I-----I                                                                       |                                         |                            |               |               |
| I**** RNOEG ***I**** RKEOEG **I** ( DOEGL )**I**** UDCLG ***I**** RLPOEG **I  | (OEG MC LOOP) (1:D/U CHECK)             | (D/U LIM.)                 | (FO (U/C)LIM) | (OEG INF OP)  |
| 3.                                                                            | 0.                                      | -2.10                      | 1.030         | 1.            |
| I-----I                                                                       |                                         |                            |               |               |
| I***** RNM *****I**** RKEMCM **I** ( DMCML )**I**** RLPFM ***I**** RLPMCM **I | (MIX MC LOOP) (1:D/U CHECK)             | (D/U LIM.)                 | (FM INF OP)   | (MIX INF OP)  |
| 3.                                                                            | 0.                                      | -2.10                      | 1.            | 1.            |
| I-----I                                                                       |                                         |                            |               |               |
| I***** RNG *****I**** RKEMCG **I** ( DMCGL )**I**** RLPFG ***I**** RLPMCG **I | (GAS MC LOOP) (1:D/U CHECK)             | (D/U LIM.)                 | (FG INF OP)   | (GAS INF OP)  |
| 3.                                                                            | 0.                                      | -2.10                      | 1.            | 1.            |
| I-----I                                                                       |                                         |                            |               |               |
| I**** RNCS *****I**** RKECS ***I**** ( DCSL )**I**** RLPCSC **I** RNCSIP ***I | (CS MC LOOP) (1:D/U CHECK)              | (D/U LIM.)                 | (CS MC IN OP) | (NCS INF O/P) |
| 3.                                                                            | 0.                                      | -2.10                      | 1.            | 32.           |
| I-----I                                                                       |                                         |                            |               |               |
| I***** RNCE ***I**** RKECE ***I**** ( DCEL )**I**** CUCE ***I**** RLPCEC **I  | (CE MC LOOP) (1:D/U CHECK)              | (D/U LIM.)                 | (U(MC)=C.*UC) | (CE INF OP)   |
| 3.                                                                            | 0.                                      | -2.10                      | 0.0           | 1.            |
| I-----I                                                                       |                                         |                            |               |               |
| I***** RJJZ ***I**** RJSTOP **I**** RNOFII **I**** RJJ *****I**** RISRUN **I  | (JL.GE.*:JZ=JJ) (JL=.:STOP)             | (1:NO FIELDS)              | (JJZ:JZ=JJ)   | (0.:NORM OF)  |
| 0.                                                                            | 0.                                      | 0.                         | 1.            | 0.            |
| I-----I                                                                       |                                         |                            |               |               |
| I**** RIJK *****I**** RJLL ***I**** RJLU *****I**** RILL ***I**** RILU *****I | (1:CAL. INF.) (JLL =< STEP - JL =< JLU) | (ILL =< POINT - IL =< ILU) |               |               |
| 0.                                                                            | 0.                                      | 0.                         | 0.            | 0.            |
| I-----I                                                                       |                                         |                            |               |               |
| I* TMILL (S) *I** TMSL(S) **I**** RJMTP ***I**** RLIJK ***I* TMSFL (S) *I     | (JOB MT LIM.) (STEP MT LIM)             | (OP MT INF)                | (MT-END IJK)  | (SF ST MT LI) |
| 3000.0                                                                        | 50.0                                    | 1.                         | 0.            | 30.0          |
| I-----I                                                                       |                                         |                            |               |               |
| I**** RKESR ***I* TMTOS (S) *I* OFDT (MS) *I**** RIMST ***I**** RIOLC ***I    | (J=? INF.) (0.:NO MTPOS)                | (OF TIME STEP)             | (1:OFDT USED) | (1:CP START)  |
| 0.                                                                            | 2.0                                     | 0.0                        | 0.            | 0.            |
| I-----I                                                                       |                                         |                            |               |               |
| I**** RIPOH ***I**** RIFDL ***I**** RITDL ***I**** RITMFO **I** RIPCAL ***I   | (O/P HEADING) (FULL DATA L)             | (EX TIDY DFL)              | (TIDY O/P LI) | (1:NO PCAL)   |
| 0.                                                                            | 0.                                      | 0.                         | 0.            | 0.            |
| I-----I                                                                       |                                         |                            |               |               |
| I***** PE *****I**** TEK *****I**** G *****I**** RTLIM ***I** RKSRLT ***I     | (P EN (N/M2)) (T EN (K))                | (M/S2)                     | (MIN)         | (1:RT LI USE) |
| 101325.0                                                                      | 293.0                                   | 9.807                      | 1000.0        | 0.            |
| XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  |                                         |                            |               |               |

| I NO = I | PRO | I- PHIF | I-( BV ) | I(BRV M) | I(TCO S) | I- RM | I- CTD | I CTM |
|----------|-----|---------|----------|----------|----------|-------|--------|-------|
| 1        | 1.5 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 2        | 2.0 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 3        | 2.5 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 4        | 3.0 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 5        | 3.5 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 6        | 4.0 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 7        | 4.5 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 8        | 5.0 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 9        | 5.5 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 0        | 6.0 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 11       | 6.5 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |
| 12       | 7.0 | 0.250   | 0.050    | -3.50    | -2.10    | 30.   | 20.0   | 5.0   |

### L.3. EXAMPLES ON THE CHARACTER OF THE OUTPUT FILES.

The two examples below of the printout for non-special calculation steps , are given with the aim of showing the highly informative and orderly character of the output files.

Ordinary step with the Contact Surface example ;

|       |                     |                     |                     |                      |               |
|-------|---------------------|---------------------|---------------------|----------------------|---------------|
| J= 28 | T...= 0.0019 (S)    | DT...= 0.067E-3 (S) | PR...= 4.062        | CPRG= 1.895          | IS...= 1      |
|       | AO...= 0.01227 (M2) | PHI...= 0.250       | UG...= 504.50 (M/S) | QG...= 11.297 (KG/S) | JL...= 1      |
|       | LC5...= 43          | DSX...= 0.5134      | DELY= 0.0020        | KC...= 4             | IC...= 1      |
|       | HM...= 2.126 (M)    | PHM...= 0.850       | VM...= 0.1043 (M3)  | PVM...= 0.850        | EVH...= 1.000 |
|       | PMG...= 0.824       | PMGE= 0.178         | DTRT= 0.141         | IDTL= 0              |               |
|       | BV...= 0.0503       | PBV...= 1.006       | RVGR= 0.998         |                      | RVL...= 1.024 |
|       | LWF2= 41            | SVFM= 103.48 (M/S)  | DVFX= 0.9818        | DVDX=-0.1380         |               |
|       | DEGM= 0.984         | DMGE= 1.073         | DMG...= 1.014       | CEC...= 0.984        | PCAL= 1.073   |

|      |                |                 |                      |                      |                |                  |
|------|----------------|-----------------|----------------------|----------------------|----------------|------------------|
| I= 1 | U= 0.000 (M/S) | C= 105.40 (M/S) | P=0.52639E+06 (N/M2) | R=0.9486E+03 (KG/M3) | B=0.0500       | BR=0.100E-03 (M) |
| 2    | 0.000          | 105.36          | 0.52593E+06          | 0.9486E+03           | 0.0500         | 0.109E-03        |
| 5    | 0.000          | 105.22          | 0.52453E+06          | 0.9486E+03           | 0.0500         | 0.118E-03        |
| 10   | 0.000          | 104.99          | 0.52221E+06          | 0.9486E+03           | 0.0500         | 0.185E-03        |
| 15   | 0.000          | 104.75          | 0.51988E+06          | 0.9486E+03           | 0.0500         | 0.232E-03        |
| 20   | 0.000          | 104.52          | 0.51756E+06          | 0.9486E+03           | 0.0500         | 0.279E-03        |
| 25   | 0.000          | 104.29          | 0.51523E+06          | 0.9486E+03           | 0.0500         | 0.326E-03        |
| 30   | 0.000          | 104.05          | 0.51290E+06          | 0.9486E+03           | 0.0500         | 0.373E-03        |
| 35   | 0.000          | 103.82          | 0.51058E+06          | 0.9486E+03           | 0.0500         | 0.420E-03        |
| 40   | 0.000          | 103.58          | 0.50825E+06          | 0.9486E+03           | 0.0500         | 0.467E-03        |
| 41   | 0.000          | 103.53          | 0.50779E+06          | 0.9486E+03           | 0.0500         | 0.476E-03        |
| 42   | 0.018          | 103.13          | 0.50543E+06          | 0.9486E+03           | 0.0502         | 0.489E-03        |
| 43   | 1.084          | 85.42           | 0.41331E+06          | 0.9380E+03           | 0.0606         | 0.530E-03        |
|      |                | 78.61           |                      | 0.9328E+03           | 0.0658         | 0.551E-03        |
|      | 1.542          |                 | 0.37789E+06          |                      |                |                  |
| 44   | 5.137          | 341.11          |                      | 0.4559E+01           | TEN=288.94 (K) |                  |
| 45   | 13.167         | 341.16          | 0.37832E+06          | 0.4562E+01           | 289.04         |                  |
| 50   | 43.829         | 341.53          | 0.38114E+06          | 0.4586E+01           | 289.66         |                  |
| 51   | 47.507         | 345.21          | 0.41045E+06          | 0.4837E+01           | 295.93         |                  |
|      |                | 345.32          | 0.41155E+06          | 0.4844E+01           | 296.12         |                  |

TMS = 0.063 (S)                      TM = 1.235 (S)

Ordinary step with a Shock Front example ;

|        |                     |                      |                        |                      |              |
|--------|---------------------|----------------------|------------------------|----------------------|--------------|
| J= 250 | T...= 0.0809 (S)    | DT...= 1.146E-3 (S)  | PR...= 2.206           | CPRM= 3.110          | IS...= 0     |
|        | AO...= 0.01227 (M2) | PHI...= 0.250        | UM...= 17.676 (M/S)    | QM...=101.933 (KG/S) | JE...= 1     |
|        | VL...= 0.0964 (M3)  | VLE...= 0.00351 (M3) | ELV...= 0.117E-03 (M3) | PPRM= 2.206          | IDTL= 0      |
|        | PL...= 0.965        | PLE...= 0.035        | BV...= 0.2143          | PBV...= 1.154        | DTRT= 0.475  |
|        | DELV= 1.020         | DVLE= 1.0070         | DVL...= 1.0003         | CEC...= 1.020        | PCAL= 1.007  |
|        | LSF...= 13          | USF...= -25.81 (M/S) | RP21= 2.59074          | DSFX= 0.2400         | D9DX= 0.471  |
|        | DWSF= 0.903E-06     | RPLI= 0.160E-06      | UPMS= 0.68E-06 (MKS)   | J.N.= 40 / 31        | M1...= 1.608 |
|        | RCSF= 1.000000      | RMSF= 1.000000       | RESF= 1.017069         | RUSF= 1.002350       | M2...= 0.623 |

|      |                |                |                      |                      |          |                  |
|------|----------------|----------------|----------------------|----------------------|----------|------------------|
| I= 1 | U= 0.000 (M/S) | C= 19.62 (M/S) | P=0.74857E+05 (N/M2) | R=0.7312E+03 (KG/M3) | B=0.2677 | BR=0.191E-03 (M) |
| 2    | 0.521          | 19.47          | 0.74012E+05          | 0.7296E+03           | 0.2693   | 0.255E-03        |
| 5    | 2.119          | 19.00          | 0.71439E+05          | 0.7237E+03           | 0.2752   | 0.365E-03        |
| 10   | 4.667          | 18.57          | 0.69068E+05          | 0.7185E+03           | 0.2805   | 0.536E-03        |
| 12   | 5.432          | 19.02          | 0.71347E+05          | 0.7255E+03           | 0.2734   | 0.601E-03        |
| 13   | 5.734          | 19.46          | 0.73569E+05          | 0.7318E+03           | 0.2672   | 0.628E-03        |
| 9F-1 | 9.862          | 19.70          | 0.74823E+05          | 0.7351E+03           | 0.2630   | 0.641E-03        |
|      |                |                |                      |                      |          |                  |
| 9F-2 | 0.750          | 42.67          | 0.19385E+06          | 0.8765E+03           | 0.1222   | 0.468E-03        |
| 14   | 0.852          | 43.24          | 0.19675E+06          | 0.8782E+03           | 0.1205   | 0.481E-03        |
| 15   | 1.006          | 44.28          | 0.20208E+06          | 0.8811E+03           | 0.1176   | 0.504E-03        |
| 20   | 2.110          | 48.12          | 0.22168E+06          | 0.8906E+03           | 0.1081   | 0.619E-03        |
| 21   | 2.328          | 48.59          | 0.22351E+06          | 0.8920E+03           | 0.1067   | 0.639E-03        |

TMS = 0.337 (S)                      TM = 151.859 (S)

# L.4. FULL DISK LIST OF THE PROGRAMME.

Lists all files used for the job in different capacities.

Order : F-Name / F-Type / Disk / Rec.-F / Rec.-L / Length /B-Size.

|        |         |    |   |     |       |     |         |       |    |   |     |     |   |
|--------|---------|----|---|-----|-------|-----|---------|-------|----|---|-----|-----|---|
| DNF    | DATA    | A1 | F | 80  | 295   | 6   | INFE    | EXEC  | A1 | V | 78  | 106 | 2 |
| DFV    | DATA    | A1 | F | 80  | 175   | 4   | J       | EXEC  | A1 | V | 73  | 615 | 5 |
| DFM    | DATA    | A1 | F | 80  | 219   | 5   | JA      | EXEC  | A1 | V | 69  | 140 | 2 |
| DFS    | DATA    | A1 | F | 80  | 247   | 5   | JAF     | EXEC  | A1 | V | 70  | 186 | 2 |
| DGB    | DATA    | A1 | F | 80  | 143   | 3   | JB      | EXEC  | A1 | V | 80  | 621 | 7 |
| DMS    | DATA    | A1 | F | 80  | 178   | 4   | JBAF    | EXEC  | A1 | V | 78  | 388 | 4 |
| MSYFNF | DATA    | A1 | F | 72  | 29    | 1   | JF      | EXEC  | A1 | V | 80  | 601 | 7 |
| MSYFFV | DATA    | A1 | F | 72  | 29    | 1   | JO      | EXEC  | A1 | V | 62  | 38  | 1 |
| MSYFGB | DATA    | A1 | F | 72  | 29    | 1   | JOB     | EXEC  | A1 | V | 62  | 40  | 1 |
| PFS    | FORTRAN | A1 | F | 80  | 8461  | 166 | JW      | EXEC  | A1 | V | 59  | 66  | 1 |
| NAF    | FORTRAN | A1 | F | 80  | 7717  | 151 | L       | EXEC  | A1 | V | 54  | 53  | 1 |
| MAR    | FORTRAN | A1 | F | 80  | 7938  | 156 | LD      | EXEC  | A1 | V | 70  | 133 | 1 |
| SMC    | FORTRAN | A1 | F | 80  | 5735  | 113 | LGF     | EXEC  | A1 | V | 78  | 112 | 1 |
| SSF    | FORTRAN | A1 | F | 80  | 6437  | 126 | LNF     | EXEC  | A1 | V | 71  | 163 | 2 |
| SGR    | FORTRAN | A1 | F | 80  | 9324  | 183 | LOG     | EXEC  | A1 | V | 70  | 46  | 1 |
| MSYF   | FORTRAN | A1 | F | 80  | 2318  | 46  | ME      | EXEC  | A1 | V | 57  | 43  | 1 |
| ACPR   | FORTRAN | A1 | F | 80  | 207   | 5   | P       | EXEC  | A1 | V | 50  | 62  | 1 |
| CFWN   | FORTRAN | A1 | F | 80  | 112   | 3   | PF      | EXEC  | A1 | V | 72  | 238 | 2 |
| FAC    | FORTRAN | A1 | F | 80  | 153   | 3   | PL      | EXEC  | A1 | V | 71  | 107 | 1 |
| GDP    | FORTRAN | A1 | F | 80  | 92    | 2   | PLS     | EXEC  | A1 | V | 81  | 214 | 3 |
| MC     | FORTRAN | A1 | F | 80  | 50    | 1   | PLTM    | EXEC  | A1 | V | 73  | 169 | 2 |
| ABC    | FORTRAN | A1 | F | 80  | 40    | 1   | PO      | EXEC  | A1 | V | 62  | 38  | 1 |
| CL     | FORTRAN | A1 | F | 80  | 10    | 1   | PR      | EXEC  | A1 | V | 72  | 326 | 3 |
| ERRSET | FORTRAN | A1 | F | 80  | 13    | 1   | PRL     | EXEC  | A1 | V | 80  | 388 | 4 |
| JTIME  | TXTLIB  | A1 | F | 80  | 240   | 5   | PROFILE | EXEC  | A1 | V | 73  | 80  | 1 |
| GRAPH  | TXTLIB  | A1 | F | 80  | 8664  | 170 | PS      | EXEC  | A1 | V | 72  | 225 | 2 |
| GDRW   | TXTLIB  | A1 | F | 80  | 16378 | 320 | Q       | EXEC  | A1 | V | 47  | 282 | 2 |
| CURVD  | TXTLIB  | A1 | F | 80  | 678   | 14  | QP      | EXEC  | A1 | V | 81  | 677 | 8 |
| PFS    | TEXT    | A1 | F | 80  | 2690  | 53  | R       | EXEC  | A1 | V | 70  | 191 | 2 |
| NAF    | TEXT    | A1 | F | 80  | 2740  | 54  | RCB     | EXEC  | A1 | V | 66  | 99  | 1 |
| MAR    | TEXT    | A1 | F | 80  | 2817  | 56  | RDF     | EXEC  | A1 | V | 72  | 67  | 1 |
| SMC    | TEXT    | A1 | F | 80  | 2592  | 51  | RL      | EXEC  | A1 | V | 106 | 108 | 2 |
| SSF    | TEXT    | A1 | F | 80  | 2361  | 47  | RN      | EXEC  | A1 | V | 59  | 47  | 1 |
| SGR    | TEXT    | A1 | F | 80  | 4340  | 85  | S       | EXEC  | A1 | V | 68  | 90  | 1 |
| A      | EXEC    | A1 | V | 72  | 308   | 3   | SF      | EXEC  | A1 | V | 70  | 44  | 1 |
| B      | EXEC    | A1 | V | 64  | 78    | 1   | SR      | EXEC  | A1 | V | 73  | 109 | 1 |
| CAF    | EXEC    | A1 | V | 73  | 105   | 1   | SU      | EXEC  | A1 | V | 70  | 54  | 1 |
| CAL    | EXEC    | A1 | V | 75  | 138   | 2   | T       | EXEC  | A1 | V | 64  | 29  | 1 |
| CATE   | EXEC    | A1 | V | 69  | 75    | 1   | TD      | EXEC  | A1 | V | 73  | 180 | 2 |
| CJE    | EXEC    | A1 | V | 69  | 198   | 2   | TL      | EXEC  | A1 | V | 68  | 84  | 1 |
| CN     | EXEC    | A1 | V | 79  | 115   | 1   | TR      | EXEC  | A1 | V | 70  | 93  | 1 |
| COM    | EXEC    | A1 | V | 59  | 28    | 1   | TW      | EXEC  | A1 | V | 70  | 83  | 1 |
| CPE    | EXEC    | A1 | V | 71  | 136   | 1   | X       | EXEC  | A1 | V | 72  | 149 | 1 |
| CYS    | EXEC    | A1 | V | 81  | 289   | 4   | XD      | EXEC  | A1 | V | 60  | 74  | 1 |
| CY     | EXEC    | A1 | V | 69  | 131   | 1   | XE      | EXEC  | A1 | V | 58  | 44  | 1 |
| CYD    | EXEC    | A1 | V | 72  | 43    | 1   | XG      | EXEC  | A1 | V | 72  | 155 | 2 |
| CYS    | EXEC    | A1 | V | 72  | 128   | 1   | Z       | EXEC  | A1 | V | 28  | 17  | 1 |
| CYU    | EXEC    | A1 | V | 73  | 108   | 1   | G       | XEDIT | A1 | V | 72  | 131 | 1 |
| DF     | EXEC    | A1 | V | 63  | 101   | 1   | PROFILE | XEDIT | A1 | V | 67  | 172 | 2 |
| DOCE   | EXEC    | A1 | V | 67  | 65    | 1   | TCL     | XEDIT | A1 | V | 67  | 124 | 1 |
| DUL    | EXEC    | A1 | V | 69  | 221   | 2   | TNF     | XEDIT | A1 | V | 61  | 41  | 1 |
| E      | EXEC    | A1 | V | 62  | 65    | 1   |         |       |    |   |     |     |   |
| ER     | EXEC    | A1 | V | 70  | 103   | 1   |         |       |    |   |     |     |   |
| EXI    | EXEC    | A1 | V | 67  | 73    | 1   | DFI     | LIST  | A1 | F | 80  | 390 | 8 |
| FBE    | EXEC    | A1 | V | 67  | 72    | 1   | DISK    | LIST  | A1 | V | 66  | 613 | 9 |
| FF     | EXEC    | A1 | V | 67  | 53    | 1   | LOADMAP | LIST  | A1 | V | 38  | 566 | 4 |
| FL     | EXEC    | A1 | V | 106 | 157   | 2   |         |       |    |   |     |     |   |
| FP     | EXEC    | A1 | V | 63  | 45    | 1   |         |       |    |   |     |     |   |
| FV     | EXEC    | A1 | V | 66  | 55    | 1   |         |       |    |   |     |     |   |
| FVS    | EXEC    | A1 | V | 73  | 564   | 5   |         |       |    |   |     |     |   |

F-Name : File Name      Rec.-F : Record Format      Length : [Lines]  
F-Type : File Type      Rec.-L : Record Length      B-Size : [4k Blocks]

END OF APPENDIX L

## CURRICULUM VITAE

Şukru BALTA

Born in İstanbul at 24.X.1947. Graduate of the Kabataş Lyceum. Entered to the Fac. of Mech. Engng. of the İ.T.Ü. in 1965. After graduation with the degree of M.Sc. in 1970 , started to work in the Chair of Hydraulic Machinery of the same faculty. Sent to Britain for Ph.D. study in 1978 by the Ministry of Education. After his return , in December 86 started to work as research assistant at the same place named Energy Division and since May 1992 working as specialist at the same place , now named Division of Hydraulic Machinery.

# INDEX of the LIST of REFERENCES

| <u>RN : PN</u>          | <u>RN : PN</u> | <u>RN : PN</u> |
|-------------------------|----------------|----------------|
| 1 : 44                  | 21 : 43        | 41 : 110       |
| 2 : 26                  | 22 : 115       | 42 : 26        |
| 3 : 54 , 113            | 23 : 54        | 43 : 59        |
| 4 : 45                  | 24 : 19        | 44 : 18        |
| 5 : 1 , 3               | 25 : 114       | 45 : 19        |
| 6 : 44                  | 26 : 29        | 46 : 44        |
| 7 : 42                  | 27 : 45        | 47 : 29 , 46   |
| 8 : 29                  | 28 : 45        | 48 : 13        |
| 9 : 29                  | 29 : 43        | 49 : 43        |
| 10 : 29                 | 30 : 26        | 50 : 43        |
| 11 : 29                 | 31 : 19        | 51 : 54        |
| 12 : 43 , 44 , 58 , 112 | 32 : 25        | 52 : 56        |
| 13 : 45                 | 33 : 54        | _____          |
| 14 : 18 , 93            | 34 : 54 , 59   | 53 : 91        |
| 15 : 18 , 43            | 35 : 54 , 60   | 54 : 91        |
| 16 : 114                | 36 : 111       | 55 : 91        |
| 17 : 43                 | 37 : 44        | 56 : 91        |
| 18 : 59                 | 38 : 43        | 57 : 91 , 92   |
| 19 : 116                | 39 : 110       | _____          |
| 20 : 116                | 40 : 110       |                |

[ RN : Reference Number.  
PN : Page Number.  
]