



**TÜRKİYE CUMHURİYETİ
ADANA ALPARSLAN TÜRKER SCIENCE AND TECHNOLOGY
UNIVERSITY**

**GRADUATE SCHOOL
MECHANICAL ENGINEERING DEPARTMENT**

**COMBUSTION PERFORMANCE ANALYSIS OF HYDROGEN-
ENRICHED METHANE IN A CUSTOM-DESIGNED BURNER**

ANIL ERKAN

Ph.D.



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**THESIS ADVISOR
PROF. DR. GÖKHAN TÜCCAR**

ADANA, 2025

ÖZET

HİDROJENLE ZENGİNLEŞTİRİLMİŞ METANIN ÖZEL TASARLANMIŞ BİR BRÜLÖRDE YANMA PERFORMANSININ ANALİZİ

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Temmuz 2025, 97 sayfa

Artan küresel enerji talebi ve çevresel kaygılar nedeniyle, saf hidrojenin olumsuz yanma etkileri göz önünde bulundurularak, hidrojen gazının konvansiyonel yakıtlarla farklı oranlarda karıştırılması yoluyla optimum yanma koşullarının sağlanmasına yönelik çeşitli çalışmalar yapılmaktadır. Bu çalışmanın amacı, özel olarak tasarlanmış bir brülör içerisinde metan gazı ile gerçekleştirilen yanma sürecine, ön karıştırma yapılmaksızın farklı konsantrasyonlarda hidrojen ilavesinin alev karakteristikleri üzerindeki etkilerini incelemektir. Analizler, ANSYS Fluent hesaplamalı akışkanlar dinamiği (HAD) simülasyonları ile gerçekleştirilmiş; elde edilen sonuçlar yapay sinir ağı (YSA) yöntemi ile yorumlanarak tahmin edilmiştir. Bu kapsamda, CH₄ gazı ile %0 ila %30 arasında, %2.5'lik artışlarla 13 farklı hidrojen konsantrasyonu kullanılarak yanma reaksiyonları gerçekleştirilmiştir. Simülasyon sonuçlarına göre, karışımdaki hidrojen oranının artmasıyla birlikte alev sıcaklığının yükseldiği ve genel olarak alev yapısının daha kararlı hale geldiği gözlemlenmiştir. Maksimum alev sıcaklığı, %30 hidrojen ilavesinde 2303.82 K olarak elde edilmiştir. Ancak bu konsantrasyonda artış eğiliminin yataylaştığı, karışımın zengin karışım davranışı sergilediği ve sıcaklık artış hızının azaldığı tespit edilmiştir. Ayrıca, brülör merkezindeki eksenel alev profili daha stabil hale gelmiş ve tutarlı dağılımlar gözlemlenmiştir. Elde edilen maksimum sıcaklıklarla doğru orantılı olarak maksimum hız değerlerinde de artış eğilimi gözlenmiştir. YSA ve regresyon denklemleri ile yapılan öngörü analizleri sonucunda, sonuçların doğruluk oranı hesaplanmış ve HAD çalışmalarının güvenilirliği test edilmiştir. HAD analiz sonuçları, literatürdeki çeşitli deneysel çalışmalarla karşılaştırılarak doğrulanmış ve sonuçların uyumlu olduğu belirlenmiştir.

Anahtar Kelimeler: alev sıcaklığı, hidrojen karışım oranı, özel tasarım brülörde metan yanması, yapay sinir ağı, HAD

ABSTRACT

COMBUSTION PERFORMANCE ANALYSIS OF HYDROGEN-ENRICHED METHANE IN A CUSTOM-DESIGNED BURNER

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July 2025, 97 pages

Due to the increasing global energy demand and growing environmental concerns, efforts have been made to achieve optimal combustion conditions by blending hydrogen gas with conventional fuels at various ratios, taking into account the adverse combustion effects of pure hydrogen. The aim of this study is to investigate the effects of hydrogen addition—at varying concentrations and without premixing—on the flame characteristics of methane combustion within a specially designed burner. The analysis was conducted using ANSYS Fluent computational fluid dynamics (CFD) simulations, and the results were further interpreted and predicted through the application of the artificial neural network (ANN) method. In this study, combustion reactions were performed for 13 different hydrogen concentrations ranging from 0% to 30% in increments of 2.5%, blended with CH₄ gas. The simulation results revealed that increasing the hydrogen concentration within the mixture led to higher flame temperatures and generally more stable flame structures. The maximum flame temperature of 2303.82 K was achieved at 30% hydrogen addition. At this concentration, the trend plateaued, indicating rich mixture behavior and a reduced rate of increase. The axial flame profile also became more uniform, with consistent distribution across the burner center. Additionally, maximum velocity values were observed to increase in correlation with rising maximum flame temperatures. As a result of the prediction analyses conducted using ANN and regression equations, the accuracy of the results was calculated, and the reliability of the CFD studies was evaluated. CFD analyses were validated by comparison with various experimental studies, and the results were found to be in agreement.

Keywords: flame temperature, hydrogen blending ratio, methane combustion in a custom-designed burner, artificial neural network, CFD

Dedication

to my precious wife

ACKNOWLEDGEMENTS

I would like to express my endless gratitude to my valuable advisor, Prof. Dr. Gökhan TÜCCAR, who made this doctoral thesis possible, provided me with all kinds of opportunities from the beginning to the end of this process, and never withheld his support.

I would also like to thank my committee members, Prof. Dr. Erine ULUDAMAR, Assoc. Prof. Dr. Tahir DURHASAN, Assoc. Prof. Dr. Tayfun ÖZGÜR and Asst. Prof. Dr. Erdi TOSUN, for sparing their valuable time to attend my thesis defense and for their valuable comments.

I would like to thank, with my most sincere feelings, my beloved wife Gülenay BEKTAŞ ERKAN, who has motivated me with patience and understanding under all circumstances and who has never ceased to support me during this difficult process, as well as my precious family: Zafer ERKAN, Zahide ERKAN, and my siblings.

I would also like to thank Mr. Erkan GÜROCAK and Mr. Halil İbrahim KARAOĞLAN for the technical infrastructure, physical facilities, and other support they provided during the completion of this thesis.

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LIST OF ABBREVIATIONS

AISI	: American Iron and Steel Institute
ANN	: Artificial Neural Network
CAD	: Computer-Aided Design
CFD	: Computational Fluid Dynamics
CH ₄	: Methane
CI	: Compression Ignition
CNG	: Compressed Natural Gas
CO	: Carbon monoxide
CO ₂	: Carbon dioxide
COG	: Coke Oven Gas
DC	: Direct Current
DO	: Discrete Ordinates
DTRM	: Discrete Transfer Radiation Model
EDC	: Eddy Dissipation Concept
GHG	: Greenhouse Gas
GUI	: Graphical User Interface
H ₂	: Hydrogen
H ₂ O	: Water Vapor
HC	: Hydrocarbon
HCNG	: Hydrogen Enriched Compressed Natural Gas
HHO	: Oxyhydrogen
KOH	: Potassium Hydroxide
LFC	: Laminar Flame Concept
LHV	: Lower Heating Value
LNG	: Liquefied Natural Gas
LPG	: Liquefied Petroleum Gas
MATLAB	: Matrix Laboratory
MRE	: Mean Relative Error
MSE	: Mean Squared Error
N ₂	: Nitrogen
NaCl	: Sodium Chloride

NaOH	: Sodium Hydroxide
NO	: Nitric Oxide
NO _x	: Nitrogen Oxides
NTP	: Normal Temperature and Pressure
O ₂	: Oxygen
PDF	: Probability Density Function
P _{max}	: Maximum Pressure
R ²	: Coefficient of Determination
RMSE	: Root Mean Square Error
RNG	: Renormalization Group
RON	: Research Octane Number
RPM	: Revolutions Per Minute
RSM	: Reynolds Stress Model
SCH	: Schedule
SGD	: Stochastic Gradient Descent
SI	: Spark Ignition
SMR	: Steam Methane Reforming
SST	: Shear Stress Transport
TANSIG	: Hyperbolic Tangent Sigmoid Function
TFSC	: Turbulent Flame Speed Closure
T _{max}	: Maximum Temperature
V _{max}	: Maximum Velocity
VOCs	: Volatile Organic Compounds

LIST OF SYMBOLS

x_i, x_j	: Directions
u_i, u_j	: Velocity of i and j
μ	: Viscosity
μ_t	: Eddy viscosity
$\sigma_k, \sigma_\varepsilon$	: Turbulent Prandtl numbers
R_i, R_j	: Net production rates of species i and j by reaction
S_k, S_ε	: User-defined source terms
S	: Modulus of the mean rate-of-strain tensor
S_{ij}	: Mean rate-of-strain tensor
G_k	: Generation of turbulence kinetic energy due to the mean velocity gradients
G_b	: Generation of turbulence kinetic energy due to buoyancy
Y_M	: Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
$C_1, C_2, C_{1\varepsilon}, C_{3\varepsilon}$	: Formula constants
λ	: Excess air ratio
λ_f	: Thermal conductivity
h	: Enthalpy
k	: Turbulence kinetic energy
ε	: Turbulence dispersion ratio
ρ	: Density
v	: Component of the flow velocity
η	: Effectiveness factor
p	: Pressure
t	: Time
φ	: Equivalence ratio
f_{H2}	: The volume fraction of hydrogen
$\dot{m}_{air}$	: Air mass flow rate
τ_{ij}	: Stress tensor
T_f	: Temperature

J_j	: Diffusion flux of species j
K	: Kelvin
Pa	: Pascal
$^{\circ}\text{C}$	: Centigrade
$^{\circ}\text{F}$	: Fahrenheit
m/s	: Meter/second
lb	: Pound
MJ	: Megajoule
ϕ	: Scalar property
Γ	: Diffusion coefficient
$S\phi$	: Source term
a	: Absorption coefficient
σ_s	: Scattering coefficient
G	: Incident radiation (or radiation energy density)
C	: Linear-anisotropic phase function coefficient
σ	: Stefan–Boltzmann constant
n	: Refractive index
q_r	: Heat flux
R	: Reaction rate
n	: Temperature exponent
Ea	: Activation energy
R	: Universal gas constant
k	: Rate constant
b	: Bias term
$\phi(\cdot)$	: Nonlinear activation function
n	: Number of data points in the dataset
t	: Actual (target) output value
o	: Predicted output value
Bm^3	: Billion cubic meters
kW	: Kilowatt
kPa	: Kilopascal
w_k	: Weight vector at iteration k

J_k	: Jacobian matrix
λ	: Levenberg-Marquardt damping parameter
I	: Identity matrix
e_k	: Error vector
k	: Iteration index
mbar	: Milibar
F	: Fuel content
T	: Temperature
P	: Pressure
V	: Velocity



1. INTRODUCTION

The increasing global demand for energy, combined with concerns over environmental sustainability and climate change, has necessitated the development of cleaner, more efficient, and renewable fuel alternatives. Although conventional fossil fuels remain dominant in transportation and energy production, they are increasingly scrutinized due to their substantial carbon footprint and contribution to greenhouse gas (GHG) emissions. This has positioned hydrogen—a sustainable energy carrier—at the center of both scientific and industrial research. In recent years, advancements in hydrogen production, storage, and utilization have established it as a promising alternative to traditional fossil fuels. As the lightest element in nature, hydrogen is colorless, tasteless, and odorless, with its properties summarized in Table 1.1 (LeeS, LeeH, Park, & Cho, 2011; Mazloomi & Gomes, 2012).

1.1. An Overview of Hydrogen

Hydrogen, the lightest element in nature, is a colorless, tasteless, and odorless nonmetal. It does not occur in its free form on Earth but is instead found in compound forms, such as water and fossil fuels. Although it constitutes approximately 90% of the atoms in the universe, hydrogen accounts for about 75% of the mass of Jupiter (Kaya, Öztürk, & Kayfeci, 2017). With a density 14.4 times lower than that of air, hydrogen is significantly lighter (Erdener, Erkan, Eroğlu, Şengül, & Baç, 2010). Furthermore, its energy content per unit mass is notably high, approximately three times greater than that of gasoline and seven times greater than that of coal.

Table 1.1. Properties of hydrogen (LeeS, LeeH, Park, & Cho, 2011; Mazloomi & Gomes, 2012)

Hydrogen Specifications	Unit	Value
Boiling point	°C	-252.87
Melting point	°C	-259.14
Flash point	°C	-253
Density	kg/m ³	Gas: 0.089, Liquid: 70
Ionization energy	eV	13.5989
Lower heating value-LHV	Mj/kg	118.8

Adiabatic flame temperature	°C	2107
Flammability range in air	vol%	4.0-75.0
Laminar flame velocity	m/s	3.06
Auto ignition temperature	°C	585
Research octane number-RON		>130

A comparison of some properties of hydrogen with various conventional fuels is presented in Table 1.2 (Towler, 2014).

Table 1.2. Comparison of properties of hydrogen with other fuels (Towler, 2014)

Parameters	Units	Hydrogen	Methane	Propane	Methanol	Ethanol	Gasoline
Chemical Formula		H ₂	CH ₄	C ₃ H ₈	CH ₃ OH	C ₂ H ₅ OH	C _x H _y (x=4-12)
Molecular Weight		2.02	16.04	44.1	32.04	46.07	100-105
Density (NTP)	kg/m ³	0.0838	0.668	1.87	791	789	751
	lb/ft ³	0.00523	0.0417	0.116	49.4	49.3	46.9
Normal Boiling Point	°C	-253	-162	-42.1	64.5	78.5	27-225
	°F	-423	-259	-43.8	148	173.3	80-437
Vapor Specific Gravity (NTP)	air=1	0.0696	0.555	1.55	N/A	N/A	3.66
Flash Point	°C	<-253	-188	-104	11	13	-43
	°F	<-423	-306	-155	52	55	-45
Flammability Range in Air	vol%	4.0-75.0	5.0-15.0	2.1-10.1	6.7-36.0	4.3-19	1.4-7.6
Auto Ignition Temperature in Air	°C	585	540	490	385	423	230-480
	°F	1085	1003	914	723	793	450-900

1.1.1. Hydrogen Production Methods, Storage, and Applications

Hydrogen is an abundant and versatile energy carrier that can be derived from various organic and inorganic sources, including water, biomass, fossil fuels, and other hydrocarbon-based

materials. At the present time, the main source of hydrogen production is natural gas. Steam methane reformers using natural gas play an important role in the production of special hydrogen in the methanol and ammonia industries (International Energy Agency, 2019). Hydrogen energy, which can be produced by many methods, is one of the most researched energy sources today. It can be produced by heating from natural gas, coal, petrol, methanol, or biomass; by photosynthesis from bacteria and algae; by breaking down water with electricity or sunlight (LeeS, LeeH, Park, & Cho, 2011).

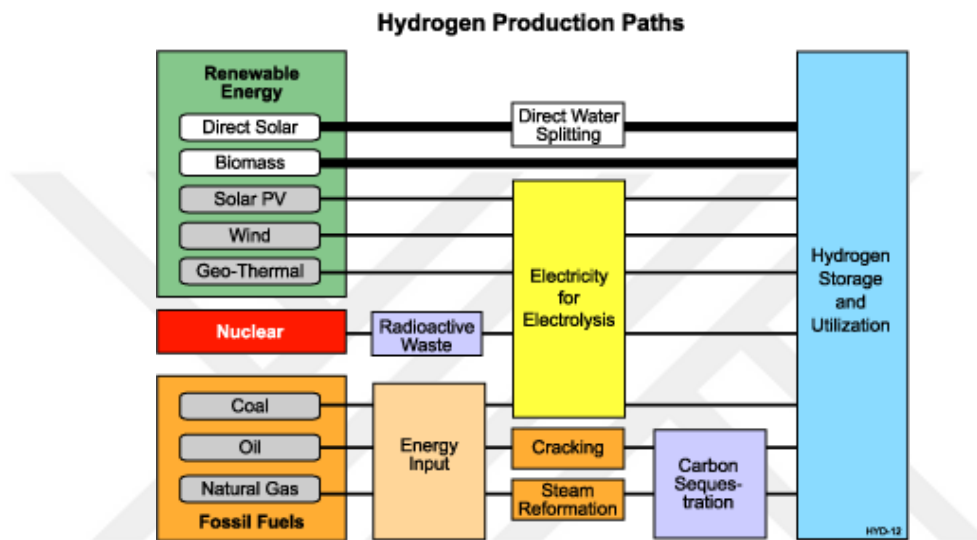


Figure 1.1. Hydrogen production methods (Shyuan, 2014)

A key challenge in utilizing hydrogen as an energy carrier lies in efficiently and economically isolating it from naturally occurring compounds. Several methods have been developed for hydrogen production and extraction, as shown in Figure 1.1 (Shyuan, 2014). Steam methane reforming (SMR) is a well-established industrial process that enables hydrogen generation from hydrocarbons and water, accounting for approximately 95% of the hydrogen produced in the United States. Another widely used method is electrolysis, which involves the application of an electrical current to dissociate water into its constituent hydrogen and oxygen molecules. The electricity required for electrolysis can be derived from various energy sources, including fossil fuels, nuclear power, and renewable energy.

One of the main obstacles to the widespread use of hydrogen is its storage. In its gaseous form at room temperature and atmospheric pressure, hydrogen occupies approximately 3,000 times more volume than another gas with the same equivalent energy content. Therefore, for hydrogen to be used in vehicles and mobile applications, it must be compressed, liquefied, or stored using alternative methods. There are four main techniques for hydrogen storage: compressed gas, cryogenic liquid, metal hydrides, and carbon adsorption (Kaya, Öztürk, & Kayfeci, 2017).

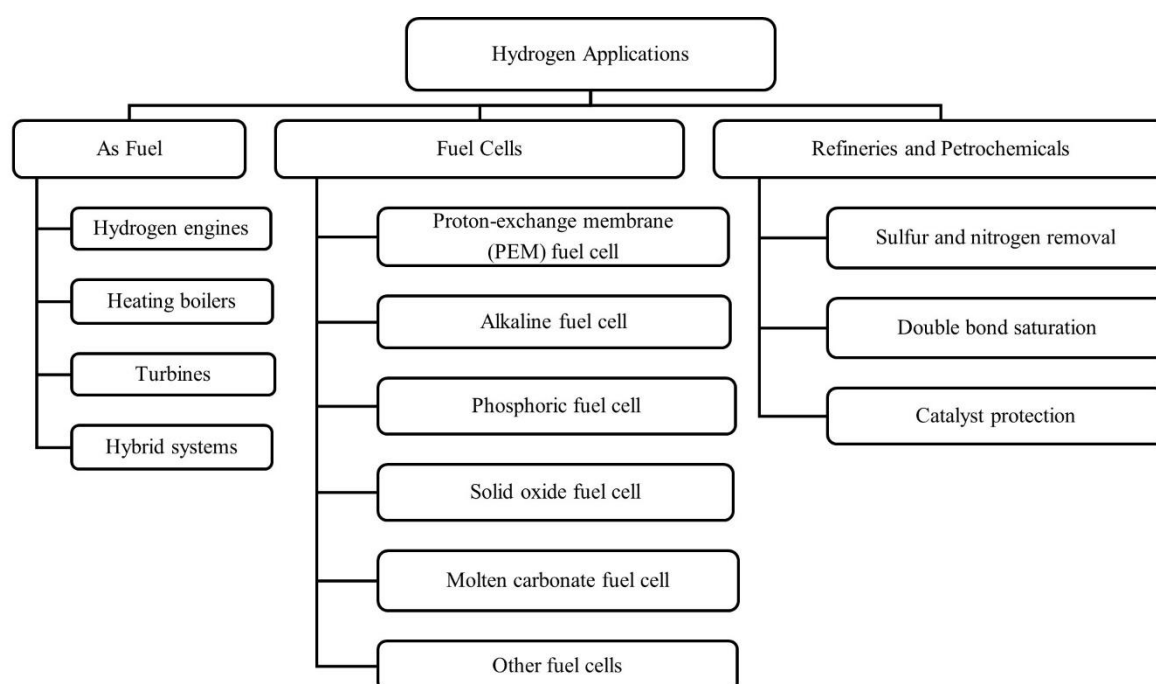


Figure 1.2. The principal areas of hydrogen utilization (Kaya et al., 2017)

As illustrated in Figure 1.2, hydrogen is utilized as a fuel in various combustion systems, as an energy carrier in mobile applications requiring electricity through fuel cells, and in refineries and the petrochemical industry for facilitating a range of processes (Kaya et al., 2017). In this study, the potential of hydrogen to be used as a fuel has also been employed.

1.2. An Overview of Methane as Fuel

Methane (CH_4) is extensively utilized gaseous fuel across domestic, industrial, and power generation sectors, primarily due to its high calorific value and cleaner combustion profile compared to traditional solid and liquid fossil fuels. Methane, which constitutes the major

fraction of natural gas, is a simple hydrocarbon with crucial roles in both energy production and chemical manufacturing. Given their lower carbon intensity and relatively clean combustion profile, methane is increasingly viewed as a transitional fuel that can support global decarbonization efforts and mitigate the environmental impacts associated with conventional fossil fuels.

Methane is a compound with the chemical formula CH₄. Methane, which is gaseous at normal temperatures and pressures, is odorless. It is a component of natural gas and is an important fuel. Combustion of one mole of methane in the presence of oxygen releases one mole of carbon dioxide and two moles of water and 55.5 MJ/kg of heat (Equation 1.1).



As illustrated in Equation 1.2, the complete combustion of methane in air produces nitrogen emissions, unlike combustion in pure oxygen.



Table 1.3. Flame characteristics of methane (Topaloğlu, Özcan, & Sungur, 2020)

Specifications	Unit	Value
Adiabatic flame temperature	K	2227
Laminar flame velocity	m/s	0.37

Methane, which exhibits a laminar burning velocity of 0.37 m/s as shown in Table 1.3, is widely preferred in many combustion systems due to its clean combustion characteristics and safe usage. The adiabatic flame temperature of methane, which represents the temperature at which there is no work, kinetic or potential energy change in the adiabatic combustion process, is 2227 K (Topaloğlu et al., 2020).

Methane reaches its flammability limits in air when present at concentrations between 5% and 15%, potentially leading to explosions known as firedamp. The liquefied form of methane, obtained by cooling it to -161 °C at atmospheric pressure, is referred to as liquefied natural gas

(LNG). As its volume is reduced by approximately 600 times compared to its gaseous state, LNG presents a viable alternative for international natural gas transportation, particularly via maritime shipping. However, due to the requirement for cryogenic storage systems, it involves high capital investment costs. When methane is compressed to high pressures (200–250 bar), it is known as compressed natural gas (CNG). Under these conditions, its volume is reduced to about 1/200 of its original state. Owing to its lower energy density, CNG is primarily used as a fuel for short-distance transportation and urban public transit buses.

The laminar burning velocity refers to the rate at which a one-dimensional, planar flame front moves through a quiescent, premixed, unburned gas mixture, measured in a direction normal to the flame surface, assuming no stretch or external disturbances (Halter et al., 2020). Figure 1.3 presents a comparison of stoichiometric laminar flame speeds for fuels examined in this study—namely hydrogen and methane—against conventional hydrocarbons such as butane, propane, and LPG blends. As illustrated, hydrogen demonstrates a markedly higher laminar flame speed due to its superior diffusivity and reactivity, whereas methane exhibits comparable flame propagation characteristics to those of other hydrocarbon fuels under similar conditions.

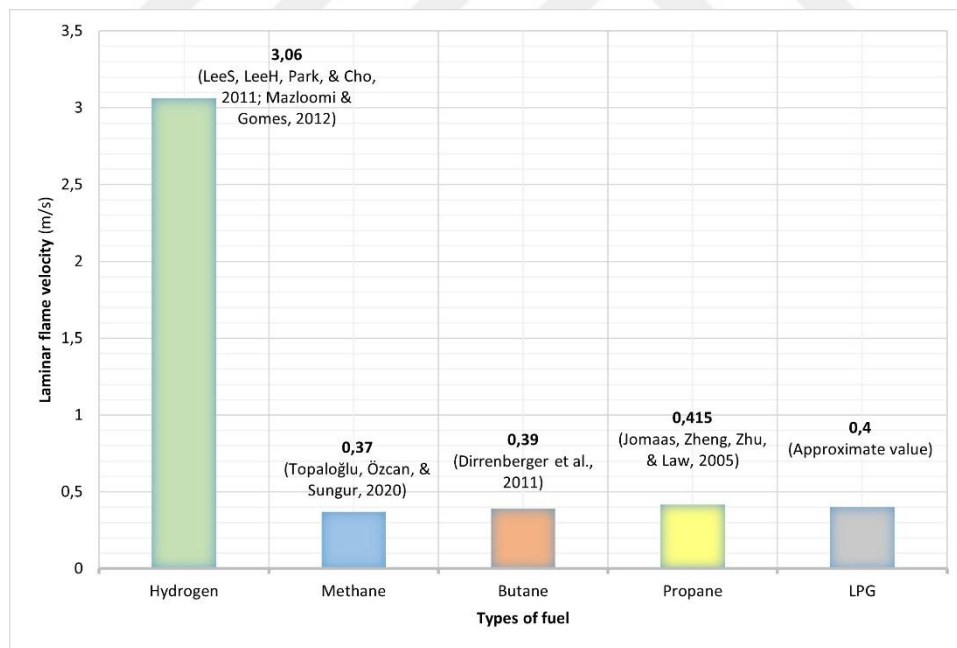


Figure 1.3. Laminar flame velocity of hydrogen, methane, and other fuels

1.3. Design Characteristics and Classification of Burners

A burner is a device designed to facilitate the combustion of fuel by mixing it with air or oxygen in a specific ratio. This apparatus transforms the chemical energy stored in the fuel into thermal energy. By regulating the combustion process, the burner enables a transition from uncontrolled, free combustion to a more stable and efficient controlled combustion regime. Burners are utilized across a broad spectrum of applications, ranging from domestic natural gas boilers to industrial facilities requiring process heat, as well as power plants that generate electricity through coal combustion. Burners are divided into three types according to the operating principle, the type of fuel used, and the atomization of the fuel, as shown in Figure 1.4.

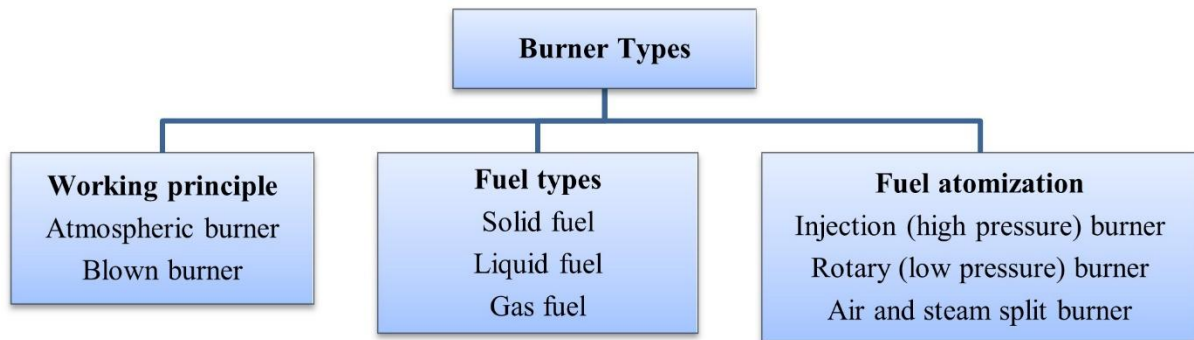


Figure 1.4. Types of burners based on application and fuel type

An atmospheric burner utilizes the natural flow of gas escaping through a nozzle to induce mixing with primary air. In other words, the air required for combustion is drawn directly from the atmosphere without the need for a mechanical blower. In contrast, burners in which the combustion air is pressurized by an auxiliary fan and delivered into the combustion chamber through multiple nozzles are referred to as blown burners. In these systems, air and fuel are mixed at high velocity and imparted with a swirling motion by a turbulator before being introduced into the combustion chamber. Combustion initiates just in front of the turbulator and continues within the combustion chamber. Due to the adjustable air-to-fuel ratio, these burners operate more efficiently than atmospheric burners (Karakoç, 2000).

In contrast to liquid fuels, combustion with gaseous fuels occurs more rapidly, as there is no need for vaporization or gasification. A turbulator may be utilized in burner systems to stabilize the flame during the combustion process, as demonstrated in Figure 1.5 (Mansouri, Aouissi, Abdallah, & Boushaki, 2015). Due to the low density of gaseous fuels, the cross-sectional areas of the fuel supply channels must be larger compared to those used for liquid fuels. Furthermore, to achieve a more homogeneous distribution of gas within the air stream, fuel must be supplied from multiple injection points. In such burners, where the mixing of fuel and air takes place within the combustion zone, diffusion combustion occurs.

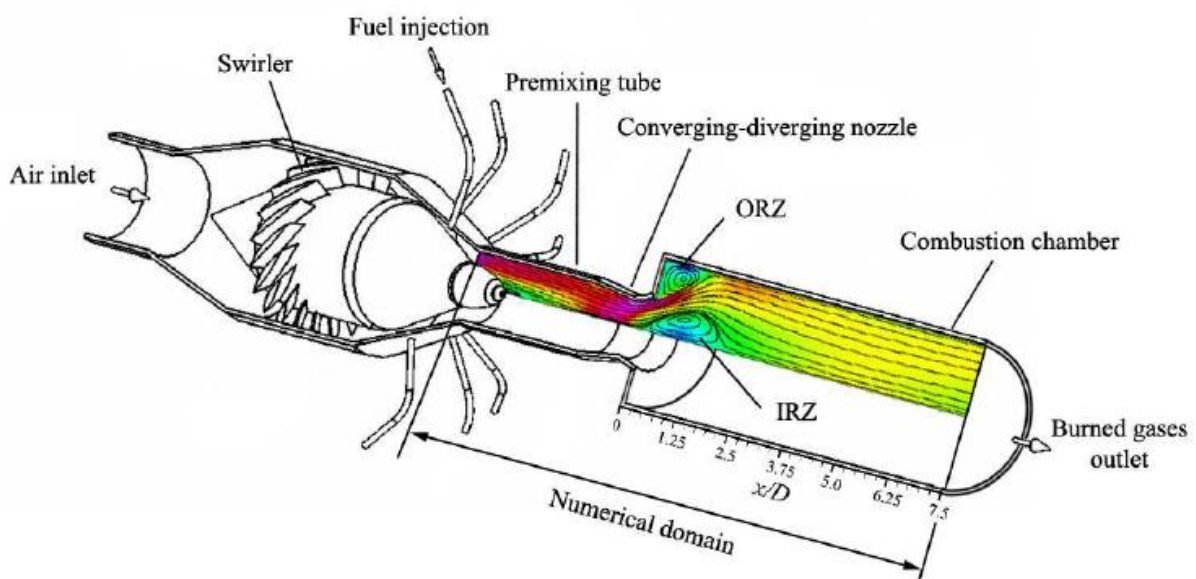


Figure 1.5. Diagrammatic representation of a swirl-stabilized premixed burner (Mansouri et al., 2015)

When selecting a burner, several criteria must be taken into account, including fuel type, boiler capacity, boiler efficiency, combustion chamber dimensions, boiler backpressure, flame length and diameter, and operating altitude. Another critical consideration is whether the fuel undergoes combustion with air or pure oxygen. If the combustion occurs with air, the process is referred to as *air-fuel combustion*, whereas combustion with pure oxygen is known as *oxy-fuel combustion*. The oxy-fuel combustion technique yields significantly higher flame temperatures compared to air-fuel combustion. However, this elevated flame temperature can lead to overheating of the burner and combustion chamber walls. To address this issue, burners

intended for oxy-fuel applications must be constructed from materials capable of withstanding high thermal loads (Markewitz et al., 2012).

Hydrogen burners exhibit a more complex structural design compared to conventional burners due to the distinct combustion characteristics of hydrogen. Several key specifications must be considered in their design to ensure efficient and reliable operation:

- Enhanced flame stability to accommodate the high reactivity of hydrogen.
- High resistance to thermal damage, given the elevated combustion temperature.
- Compatibility with low-calorific secondary gas supplies, ensuring operational flexibility.
- Suitability for industrial applications, providing durability and efficiency in high-demand environments.

A hydrogen burner should be designed individually or in conjunction with whatever fuel it is used for. Its material has to be resistant to high temperatures that will be released during combustion (İlbaş, Bektas, & Karyeyen, 2019).

The German manufacturer Saacke develops hydrogen burners capable of operating with hydrogen mixture ratios ranging from 20% to 100% as shown in Figure 1.6 (SAACKE GmbH, 2020).

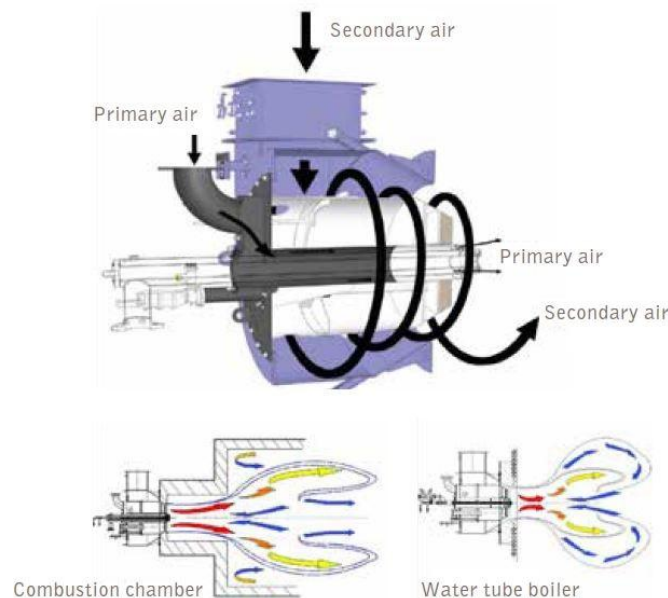


Figure 1.6. Schematic view of Saacke hydrogen burner (SAACKE GmbH, 2020)

Toyota Motor Corporation has developed a versatile hydrogen burner designed for industrial applications (Toyota Motor Corporation [TMC], 2018). In this study, the company successfully reduced the flame temperature by lowering the oxygen concentration to 19% during the primary combustion process, as illustrated in Figure 1.7.

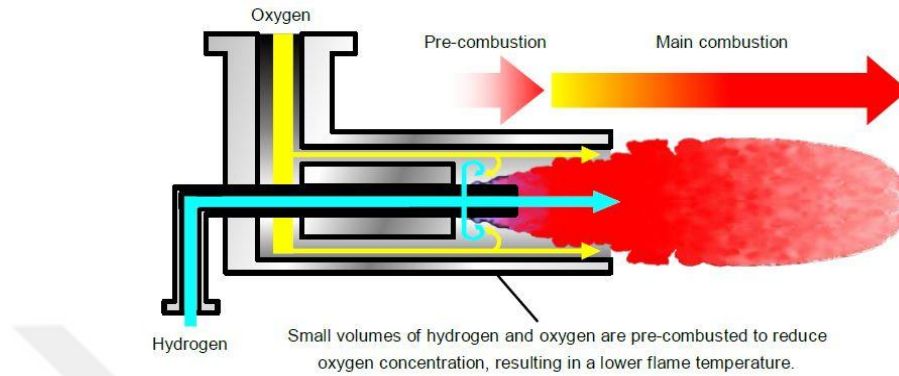


Figure 1.7. Toyota hydrogen burner (TMC, 2018)

To prevent fully mixing, small holes are opened in the pipes that supply hydrogen to the burner. The new burners have greatly reduced NO_x emissions (TMC, 2018) (Figure 1.8).

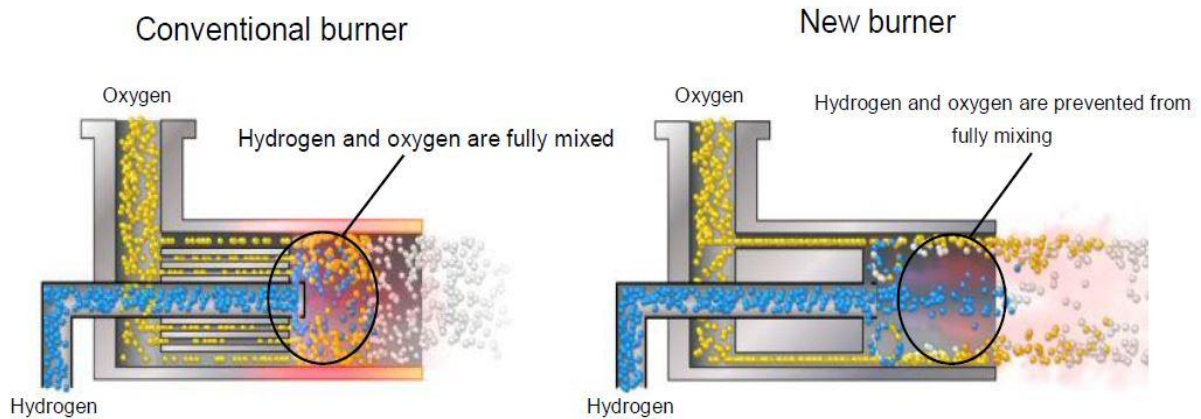


Figure 1.8. Difference between the conventional and new burner (TMC, 2018)

Figure 1.9 illustrates a sample design of a hydrogen-fueled coal gas burner developed and patented by Prof. Dr. Mustafa İlbaşı (İlbaşı, 2015). In this design, the use of a dual-fuel mixture and a turbulator is intended to enhance combustion efficiency.

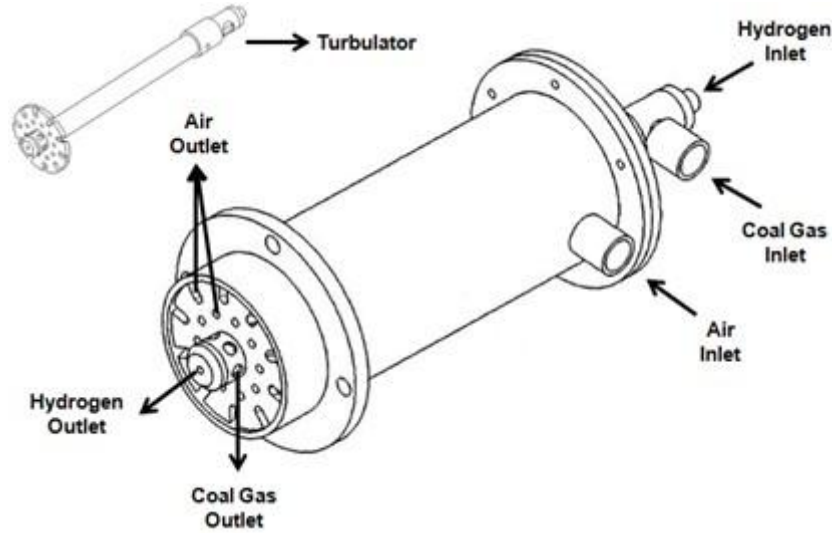


Figure 1.9. A sample design of hydrogen-powered coal gas burner (İlbaş, 2015)

In this thesis, a specially designed burner configured to operate based on non-premixed combustion of a hydrogen–methane fuel mixture was developed using a computer-aided design (CAD) software. The geometric model was created with attention to the specific requirements of turbulent and multi-species reactive flows. Following the design phase, detailed numerical simulations were carried out using ANSYS Fluent CFD software to investigate the combustion characteristics, including temperature distribution, flame structure, and pressure fields within the burner under various hydrogen concentration levels.

To enhance predictive accuracy, an ANN model was employed based on the results obtained from CFD analyses. The ANN model was trained and validated using the simulation outputs, enabling efficient exploration of the parameter space to determine favorable operating conditions. Furthermore, the reliability and accuracy of the numerical results were assessed through a comprehensive validation process involving comparison with relevant experimental studies available in the literature. This ensured that the proposed simulation and modeling approach was in agreement with physical phenomena observed under similar conditions, thereby reinforcing the credibility of the findings.

1.4. Combustion Reactions of Hydrogen and Methane

Hydrogen combustion is a critical focus within sustainable energy research due to its superior energy density and fast reaction rates, which facilitate highly efficient energy release. Unlike traditional fossil fuels, its oxidation results primarily in water vapor, making it an environmentally favorable option for reducing carbon emissions and advancing clean combustion technologies. When hydrogen (H_2) undergoes combustion in the presence of oxygen (O_2), it releases energy and forms water (H_2O) as the only by-product (Equation 1.3). Due to the absence of carbon-based emissions, the energy produced from hydrogen combustion is often referred to as "clean energy".

Air, containing approximately 21% oxygen by volume, is commonly employed as the oxidizer in hydrogen combustion processes. Combustion of hydrogen with pure oxygen results in elevated flame temperatures and increased nitrogen oxides (NO_x) emissions, which can lead to material overheating and operational challenges. In contrast, when hydrogen combusts in air, both the flame temperature and NO_x formation rates are significantly reduced due to the diluting effect of nitrogen. This reduction facilitates improved thermal management and simplifies burner design considerations. The combustion reaction of hydrogen with air is given in Equation 1.4.



As shown in Figure 1.10, hydrogen combustion can be categorized into two primary modes: deflagration and detonation (Debnath & Pandey, 2017). In deflagration, the flame propagates through the hydrogen-air mixture at subsonic velocities. This phenomenon typically occurs when an unconfined hydrogen-air cloud is ignited by a localized ignition source (Das, 1996). Conversely, detonation is characterized by the simultaneous propagation of a flame front and shock wave at supersonic speeds. Detonation frequently develops from an initial deflagration event within a confined or partially confined hydrogen-air mixture (Das, 1996).

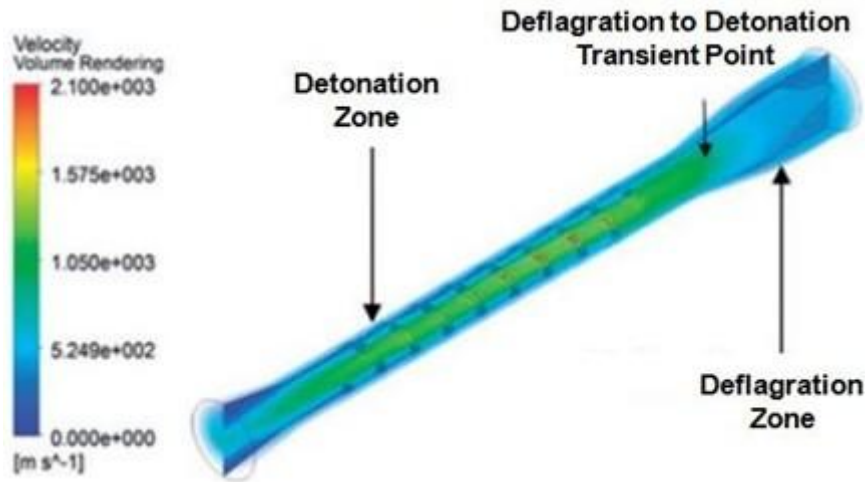
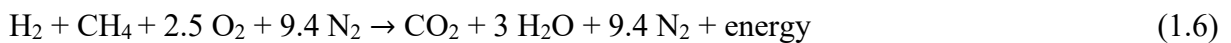


Figure 1.10. Deflagration and detonation zones of hydrogen combustion (Debnath & Pandey, 2017)

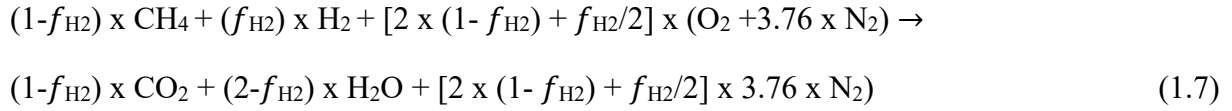
During the complete combustion of hydrogen with methane in the presence of pure oxygen, carbon dioxide (CO₂) and water vapor (H₂O) are formed as the primary products. However, if the combustion process occurs under incomplete conditions, various harmful emissions such as carbon monoxide (CO), volatile organic compounds (VOCs), soot (particulate matter), and nitrogen oxides (NO_x) may be produced. The occurrence and extent of these emissions are strongly influenced by several factors, including combustion temperature, air-to-fuel ratio, turbulence intensity, and the homogeneity of the fuel–oxidizer mixture. The complete combustion reaction of hydrogen with methane is presented in Equation 1.5.



Equation 1.6 presents the complete combustion reaction of hydrogen with methane in the presence of air as the oxidizer.



The combustion reaction of a hydrogen-methane mixture can be expressed as shown in Equation 1.7, assuming that air consists of 20.9% oxygen and 79.1% nitrogen (Dincer, Javani, Sorgulu, & Öztürk, 2021).



1.5. Comparative Analysis of Emission Characteristics for Hydrogen and Methane Fuels

The combustion of conventional fossil fuels results in the emission of various pollutants such as CO₂, CO, unburned hydrocarbons (HC), and NO_x into the atmosphere. In contrast, hydrogen combustion primarily generates water vapor and a limited amount of NO_x, with no carbon-based emissions. The accumulation of CO₂ and other greenhouse gases contributes significantly to the greenhouse effect, which drives global climate change. Among these pollutants, NO_x emissions are of particular concern due to their role in the formation of acid rain through reactions with atmospheric water vapor. Furthermore, the formation of NO_x is highly sensitive to combustion temperature, exhibiting a direct correlation wherein higher flame temperatures lead to increased NO_x production.

Van der Drift et al. developed a novel burner design and tested it using a hydrogen-rich fuel mixture. Their experimental results demonstrated that low NO_x emissions, below 5 ppm, could be achieved (Drift, Tjeng, Beckers, & Beesteheerde, 1996). However, with the tightening of NO_x emission limits under the European Emission Standards, there is an increasing demand for more advanced and efficient burner technologies. In this context, Chiong et al. highlighted the significance of spray atomization in reducing NO_x emissions, as illustrated in Figure 1.11 (Chiong et al., 2019). Similarly, Hashimoto et al. employed a gas turbine swirl flame burner and observed that high atomization pressures led to the formation of finer fuel droplets, which in turn contributed to a significant reduction in NO_x emissions (Hashimoto et al., 2008).

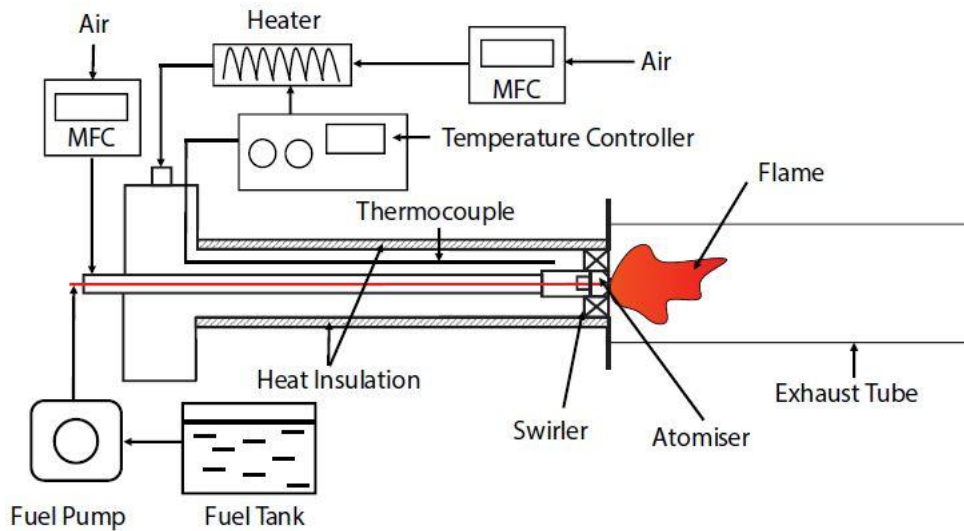


Figure 1.11. The schematic diagram for reacting spray rig (Chiong et al., 2019)

In the summer of 2020, the German Federal Government implemented the “National Hydrogen Strategy”, aligning with the European Commission’s objectives outlined in the Green Deal. The Green Deal seeks to achieve a fundamental transformation of the energy system, with the goal of reducing CO₂ emissions by 40% by 2030 and establishing Europe as a climate-neutral continent by 2050. As part of this initiative, the production of clean hydrogen is projected to reach one million tons by 2024. Hydrogen is thus envisioned not only as a critical component in mitigating climate change and facilitating the energy transition but also as a catalyst for technological innovation and economic growth (SAACKE GmbH, 2020).

Due to its lower carbon content, methane is more efficient than other fossil fuels in terms of CO₂ emissions. However, in the case of incomplete combustion, even small leaks of CH₄ can lead to a significant greenhouse effect due to its high global warming potential. Methane is both a hydrocarbon fuel and a greenhouse gas (GHG), serving as the primary constituent of natural gas. Due to its significant global warming potential, methane plays a critical role in influencing the Earth's temperature and climate system. It is emitted into the atmosphere from a variety of anthropogenic and natural sources (Global Methane Initiative, 2023). Although methane produces fewer emissions compared to other fossil fuels, its widespread use and high consumption volume contribute significantly to global warming. According to the Global Methane Assessment Report published by the United Nations Environment Programme (UNEP) in 2021, methane is responsible for approximately 25% of global warming (United

Nations Environment Programme, 2022). In response, the Global Methane Pledge (GMP) was established, bringing together 159 participating countries and the European Commission, with the goal of reducing methane emissions by at least 30% below 2020 levels.

In this context, reducing the usage rate of methane can lead to a decrease in total emission levels. One effective approach is the addition of environmentally friendly hydrogen gas to methane combustion. This not only lowers the amount of methane required but also does not contribute to additional emissions due to hydrogen's clean energy nature. In Turkey, an integrated system has been designed to blend hydrogen into the natural gas reserves of the Black Sea region. The study concluded that adding up to 20% hydrogen can reduce annual natural gas consumption, thereby extending the usable life of the country's potential gas resources (Ozturk & Dincer, 2022).

One of the objectives of this study is to optimize the maximum flame temperature values resulting from the blending of methane fuel with hydrogen—classified as a green energy source—in order to reduce temperature-dependent emission levels. Furthermore, the addition of hydrogen will play a crucial role in reducing the consumption of methane fuel, thereby contributing to the reduction of dependency on conventional fossil fuels. While addressing these objectives, the potential increase in NO_x emissions due to higher hydrogen concentrations can be mitigated by optimizing burner design and ensuring that the fuel-air mixture is properly controlled under suitable operating conditions.

1.6. An Overview of Computational Fluid Dynamics Modeling

Experimental studies are generally labor-intensive and require significant financial investment. With the rapid advancement of technology and the increasing capabilities of computational tools in recent years, numerical methods have become widely adopted in solving complex engineering problems. In particular, for systems where fluid motion and behavior play a critical role, Computational Fluid Dynamics (CFD) has emerged as a powerful tool. CFD involves the application of numerical algorithms and computational techniques to analyze and solve fluid flow phenomena within a virtual environment, thus reducing the need for costly and time-consuming experimental setups (Topaloğlu, Özcan, & Sungur, 2020). The foundation of CFD lies in the governing equations of fluid dynamics, which mathematically represent the

conservation laws of physics (Tu, Yeoh, & Liu, 2013). The generic form of the governing equations for CFD is shown in Equation 1.8 (conservative incompressible form) and 1.9 (conservative compressible form) (Tu et al., 2013). These equations, known as transport equations for the scalar property ϕ , describe various physical transport processes within a fluid flow. The terms on the left-hand side represent local acceleration and advection, while the right-hand side includes the diffusion term (Γ , the diffusion coefficient) and the source term (S_ϕ), accounting for diffusive transport and generation or consumption of the property, respectively.

$$\frac{\partial \phi}{\partial t} + \frac{\partial(u\phi)}{\partial x} + \frac{\partial(v\phi)}{\partial y} + \frac{\partial(w\phi)}{\partial z} = \frac{\partial}{\partial x} \left[\Gamma \frac{\partial \phi}{\partial x} \right] + \frac{\partial}{\partial y} \left[\Gamma \frac{\partial \phi}{\partial y} \right] + \frac{\partial}{\partial z} \left[\Gamma \frac{\partial \phi}{\partial z} \right] + S_\phi \quad 1.8$$

$$\frac{\partial(\rho\phi)}{\partial t} + \frac{\partial(\rho u\phi)}{\partial x} + \frac{\partial(\rho v\phi)}{\partial y} + \frac{\partial(\rho w\phi)}{\partial z} = \frac{\partial}{\partial x} \left[\Gamma \frac{\partial \phi}{\partial x} \right] + \frac{\partial}{\partial y} \left[\Gamma \frac{\partial \phi}{\partial y} \right] + \frac{\partial}{\partial z} \left[\Gamma \frac{\partial \phi}{\partial z} \right] + S_\phi \quad 1.9$$

Due to the interrelated nature of flow turbulence, chemical kinetics, and thermal transport, combustion reactions are often too complex to be fully explained by experimental methods alone. Therefore, CFD is frequently preferred in combustion analyses. It enables the evaluation of different fuels, modifications to burner geometry, and assessment of varying operating conditions without the need for costly prototypes or trial-and-error testing (Peters, 2000). In this way, a significant challenge in developing low-emission, environmentally friendly, sustainable, and high-efficiency technologies for both conventional and renewable energy applications can be overcome (Turns, 2013).

1.6.1. Application of ANSYS Fluent in CFD Modeling

All numerical calculations for this specially designed burner have been conducted using the Ansys Fluent CFD software. CFD software, based on the Navier-Stokes equations, is a computational modeling and simulation approach used to analyze fluid flow and heat transfer phenomena. Its applications include assessing combustion stability, regulating combustion rates, and characterizing flame dynamics (Ilbas, Crayford, Yilmaz, Bowen, & Syred, 2006).

In combustion studies, turbulence models are applied to better represent real-world conditions, as most natural flows are turbulent in nature. Common turbulence models used in such simulations include Spalart-Allmaras, Standard k- ϵ , RNG k- ϵ , Realizable k- ϵ , Standard k- ω ,

SST k- ω , and the Reynolds Stress Model (RSM) (Topaloğlu, Özcan, & Sungur, 2020). In this thesis, the Realizable k- ε turbulence model was selected for the combustion analyses, with the rationale for its use explained in the Materials and Methods section. As a result of the combustion process, flame temperatures can reach significantly high levels, depending on the type of fuel used and the stoichiometric mixture ratios.

Therefore, if the analysis is not conducted under adiabatic conditions, radiation modeling must also be incorporated to obtain a more accurate prediction of the temperature distribution within the combustion chamber. ANSYS Fluent offers several radiation models, including Rosseland, P-1 Approximation, Discrete Transfer, Surface-to-Surface, and Discrete Ordinates (DO). The choice of model may vary depending on the purpose and application of the study. In this study, the P-1 approximation model was employed to account for radiative heat transfer, and the rationale for its selection is detailed under the Materials and Methods section. The P-1 radiation model represents the simplest form of the P-N approximation. When four terms are used when modeling gray radiation, Equation 1.10 for the radiation flux q_r is obtained (Ansys, 2021).

$$q_r = -\frac{1}{3(a+\sigma_s)-C\sigma_s}\nabla G \quad 1.10$$

Here, a denotes the absorption coefficient, σ_s represents the scattering coefficient, G is the incident radiation (or radiation energy density), and C stands for the linear-anisotropic phase function coefficient.

$$-\nabla \cdot q_r = aG - 4an^2\sigma T^4 \quad 1.11$$

The $-\nabla \cdot q_r$ term presented in Equation 1.11 may be directly integrated into the energy equation, thereby accounting for thermal energy contributions resulting from radiative heat transfer (Ansys, 2021).

Various approaches are available in ANSYS Fluent for modeling combustion, including non-premixed, premixed, partially premixed, species transport, and composition PDF models, which are selected based on the specific requirements of the study (Topaloğlu, Özcan, & Sungur, 2020). In this thesis, hydrogen/methane mixture was analyzed using the non-premixed

combustion model. This model involves solving transport equations for one or two conserved scalars. It accounts for the interaction between turbulence and chemical reactions through a probability density function (PDF), and it is specifically developed for the simulation of diffusion flames and fast chemistry phenomena. Compared to the species transport model, the non-premixed model offers greater computational efficiency and provides advantages in predicting intermediate species, capturing strain effects, and modeling intense turbulence-chemistry interactions (Topaloglu et. al, 2020).

Arrhenius equations are commonly used in CFD software such as ANSYS Fluent to model chemical reaction rates, particularly in combustion analyses. As shown in Equation 1.12, the Arrhenius-type reaction rate expression defines R as the reaction rate, T as the temperature, n as the temperature exponent, E_a as the activation energy, and R as the universal gas constant.

$$R = A.T^n.e^{-\frac{E_a}{RT}} \quad 1.12$$

In the standard Arrhenius equation, the temperature exponent n is taken as 0, simplifying the expression to the form shown in Equation 1.13. Here, k represents the rate constant (Yildiz Technical University, 2020).

$$E_a = -R \frac{d(\ln k)}{d\left(\frac{1}{T}\right)} \rightarrow k = Ae^{-\frac{E_a}{RT}} \quad 1.13$$

As illustrated in Figure 1.12, under practical conditions, the reaction rate constant k increases with temperature T , primarily because the activation energy E_a is significantly greater than the product RT . In its simplest interpretation, k represents the number of successful collisions per second that lead to a chemical reaction. The pre-exponential factor A denotes the total number of molecular collisions per second with appropriate orientation, irrespective of whether they lead to a reaction (Silberberg, 2006), while the exponential term $e^{-\frac{E_a}{RT}}$ quantifies the probability that a given collision possesses sufficient energy to overcome the activation barrier.

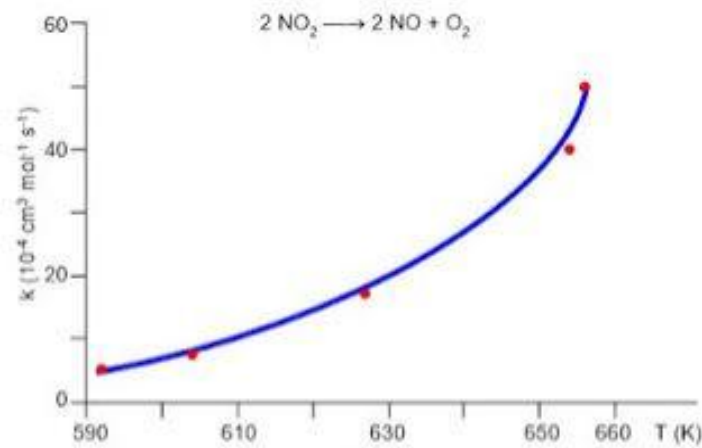


Figure 1.12. Relationship between temperature and rate constant (Besergil, 2019)

The Arrhenius equation is widely regarded as one of the most effective empirical models for describing temperature-dependent chemical behavior (Connors, 1990). It has been successfully applied to predict temperature variations in diffusion coefficients, vacancy concentrations in crystals, creep phenomena, and various thermally activated processes and reactions (Besergil, 2019). Consequently, it serves as a fundamental expression within CFD applications involving chemical kinetics.

Chemical kinetics is a branch of science that investigates the temporal evolution of chemical reactions and the factors influencing their rates. It encompasses the analysis of all processes occurring from the initiation of a reaction to the attainment of chemical equilibrium. This field primarily focuses on the experimental determination of reaction rates to elucidate the underlying kinetic mechanisms governing the transformation of reactants into products (Havyali, 2017; Harris & Kesvani, 2009). The change in concentration of a reactant or product with time (m/s) is called the reaction rate. (California State University Sacramento, 2006). The definitions of reactants and products are provided in Equations 1.14 and 1.15.

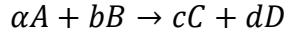
Reactants → Products

A → B

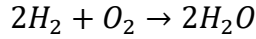
$$\text{Average Rate} = \frac{\text{change in number of moles of B}}{\text{change in time}} = \frac{\Delta(\text{moles of B})}{\Delta t} = \frac{\Delta[B]}{\Delta t} \quad 1.14$$

$$\text{Since reactants go away with time Rate} = -\frac{\Delta[A]}{\Delta t} \quad 1.15$$

The general form of the reaction rate and the specific expression for hydrogen combustion are presented in Equations 1.16 and 1.17, respectively.



$$Rate = -\frac{1}{\alpha} \frac{\Delta[A]}{\Delta t} = -\frac{1}{b} \frac{\Delta[B]}{\Delta t} = \frac{1}{c} \frac{\Delta[C]}{\Delta t} = \frac{1}{d} \frac{\Delta[D]}{\Delta t} \quad 1.16$$



$$Rate = -\frac{1}{2} \frac{d[H_2]}{dt} = -\frac{d[O_2]}{dt} = \frac{1}{2} \frac{d[H_2O]}{dt} \quad 1.17$$

The parameters influencing the reaction rate are outlined below (Aguilar, 2016).

Concentrations of reactants: Reaction rates generally increase as the concentrations of the reactants are increased.

Temperature: Reaction rates generally increase rapidly as the temperature is increased.

Surface area: For reactions that occur on a surface rather than in solution, the rate increases as the surface area is increased.

Catalysts: Catalysts speed up reactions, and inhibitors slow them down.

A mesh is divided into smaller cells with this property to accurately represent the geometry of the object being simulated in the CFD program. Higher-quality mesh enables more precise and realistic results. The selection of mesh type and refinement level must be carefully considered based on the nature of the study and the geometry used. A poorly refined or improperly generated mesh can lead to numerical diffusion, convergence issues, and unreliable results. Therefore, to ensure the mesh is appropriately refined, a grid independence test must be conducted. In this thesis, the mesh structure and the grid independence test are explained in detail in the Materials and Methods section.

1.7. Artificial Neural Network (ANN)

Artificial neural networks (ANNs) are parametric learning systems composed of multilayer artificial neurons capable of modeling nonlinear convolutional functions. Fundamentally, an ANN can be defined as a mapping function that transforms an input vector into an output vector

through a series of weighted summations and activation functions. In an artificial neuron within the network, each input $x_1, x_2, \dots, x_n$ is multiplied by its corresponding weight $w_1, w_2, \dots, w_n$ and these products are aggregated to generate a net input signal. This signal is typically combined with a bias term b , and subsequently passed through a nonlinear activation function $\phi(\cdot)$ to produce the neuron's output, as expressed in Equations 1.18 and 1.19.

$$z = \sum_{i=1}^n w_i x_i + b \quad 1.18$$

$$Y = \phi(z) \quad 1.19$$

ANNs typically consist of three fundamental layers: an input layer, one or more hidden layers, and an output layer (Figure 1.13). Each artificial neuron in a given layer processes signals received from the preceding layer by applying weighted summations followed by an activation function to generate an output. The weights are parameters that are adjusted during the learning process and have a direct impact on the network's performance. This learning process is most commonly carried out using the backpropagation algorithm in conjunction with the gradient descent optimization method.

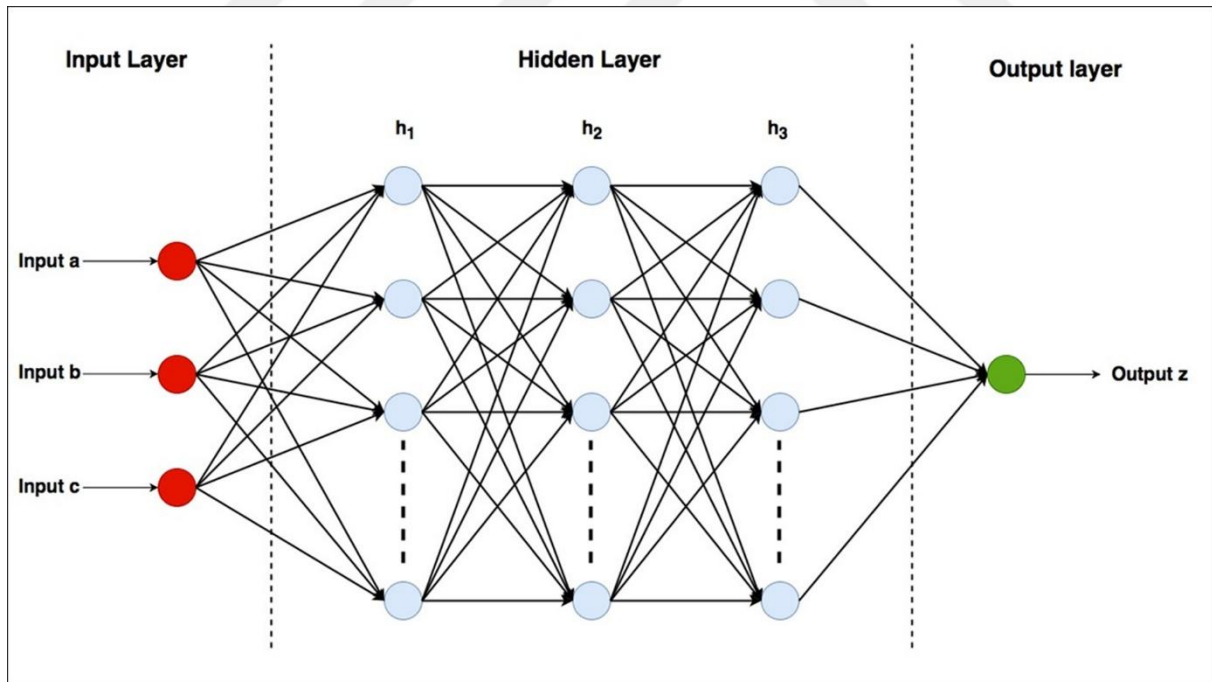


Figure 1.13. The general structure of ANN

The overall output of the network is computed through the sequential application of these operations across the layers. This layered structure enables the network to learn high-dimensional and nonlinear decision boundaries. The learning process typically involves the backpropagation algorithm, which calculates the partial derivatives of the loss function with respect to the weights and biases, followed by minimization using stochastic gradient descent (SGD) or one of its variants. The performance of an ANN depends not only on the size and quality of the dataset used but also on the model's capacity, the strategies employed to mitigate overfitting (e.g., L2/L1 regularization, dropout, batch normalization), and the optimization of hyperparameters.

ANNs are composed of simple processing elements that operate in parallel with one another (Toghyani, Kasaeian, Ahmadi, & Mohammadi, 2016). As illustrated in Figure 1.13, these processing elements play a critical role in the transmission of signals between neurons. As a result of these transmissions, the ANN module produces an output. If the resulting output exhibits a low level of accuracy, it becomes necessary to improve the applied model. To enhance the accuracy of ANN models, various learning strategies must be employed. Among these strategies are several well-known learning algorithms, such as supervised learning, unsupervised learning, and hybrid learning methods (Jain, Mao, & Mohiuddin, 1996). The error formulations used in ANN computations are presented in Equations 1.20, 1.21, and 1.22.

$$R^2 = 1 - \left(\frac{\sum_{i=1}^n (t_i - o_i)^2}{\sum_{i=1}^n (o_i)^2} \right) \quad 1.20$$

$$MRE (\%) = \frac{1}{n} \sum_{i=1}^n \left| 100 \frac{t_i - o_i}{t_i} \right| \quad 1.21$$

$$RMSE (\%) = \sqrt{\frac{1}{n} \sum_{i=1}^n (t_i - o_i)^2} \quad 1.22$$

In these formulations, “ n ” denotes the number of data points in the dataset, “ t ” represents the actual (target) output value, while “ o ” denotes the predicted output value (Uslu & Celik, 2018).

In this thesis, the numerical analyses and simulations conducted using computational fluid dynamics (CFD) were interpreted and further developed within the MATLAB environment. The capabilities of this software were utilized for the visual presentation of the results across various modules. In this way, the accuracy and validity of the findings obtained through both theoretical and applied approaches were ensured by means of a reliable computational platform.

In various subfields of engineering, natural sciences, and social sciences, numerical computing tools hold a significant position in both academic and industrial studies. In this context, the importance of high-level software platforms used for technical calculations, data analysis, modeling, simulation, and visualization continues to increase. MATLAB (Matrix Laboratory) stands out as a powerful and versatile programming environment that meets these demands.

MATLAB is fundamentally based on a matrix-oriented computational structure, which provides users with great flexibility in areas such as linear algebra operations, solving differential equations, optimization algorithms, and system modeling (Gilat, 2011). With its rich library of built-in functions, graphical user interface (GUI) support, and a wide range of toolboxes, MATLAB offers a comprehensive working environment for researchers from various disciplines. Particularly in the solution of engineering problems, the Simulink add-on allows for system modeling and dynamic simulation through block diagram representations.

One of the primary reasons for MATLAB's widespread adoption is its ability to simplify algorithm development and facilitate the implementation of complex mathematical models. Additionally, its user-friendly interface and extensive documentation enable researchers to concentrate more effectively on the development process. In recent years, with the advancement of computing power and parallel programming capabilities, MATLAB has become an effective tool not only for theoretical studies but also for advanced applications such as big data analysis, artificial intelligence, and real-time system control.

1.8. The Aim and Outline of the Thesis

Due to its high energy content and the almost negligible emission values it produces, hydrogen has emerged as one of the most promising alternative fuels to conventional fossil fuels for the future. However, to enable its optimal use across various applications, further research is

required. Owing to the challenges associated with using hydrogen in its pure form, it is commonly blended as a secondary fuel with methane, currently the primary fuel for industrial and domestic applications worldwide. This study investigates the flame characteristics resulting from blending hydrogen with methane at varying concentrations. The core focus of the research is on flame temperatures and characteristics, which have been identified as a gap in the existing literature. Most prior studies have primarily concentrated on emission values and various combustion properties. Approaches that aim to enhance the accuracy of CFD-based methane–hydrogen combustion analyses through the integration of ANN-assisted predictive models have been addressed in a limited number of studies and have been relatively less adopted in the literature. This gap in the literature provided strong motivation for the present study. Numerical simulations were conducted using ANSYS Fluent, with the hydrogen concentration increased from 0% to 30% in 2.5% increments. Such a fine increment step is not commonly found in existing studies, thus offering further motivation and novelty to the research. Another innovative aspect of the study is the design of a burner specifically intended for potential future industrial applications, which was used in the simulations. In contrast, previous studies have typically focused on conventional combustion systems such as household boilers and internal combustion engines. In the numerical modeling of the study, the realizable $k-\epsilon$ turbulence model was employed, and the non-premixed addition of hydrogen to the methane provides a further contribution to the literature in this field. Additionally, to enhance the realism of the simulations, the P-1 radiation model was also incorporated.

The study has been structured in detail to enhance clarity and comprehension. From a general perspective, the first chapter serves as the *Introduction*, providing an overview of the background and foundation of the study, outlining key concepts, and presenting the relevant formulations. This is followed by the literature review chapter, which offers a comprehensive analysis of previous studies on hydrogen-methane mixture and ANN, highlighting their findings and contributions. The subsequent chapter, titled *Materials and Methods*, explains the combustion and radiation models used within the CFD framework, along with justifications for their selection. It also discusses the mesh structure, governing equations, and relevant chemical reactions employed in the simulations. The structure of the ANN model, along with the relevant parameters and associated formulations, is presented in this section. Under the same heading, detailed descriptions of all materials and equipment used in the experimental setup are provided,

accompanied by the relevant schematic diagrams. The *Results and Discussion* chapter is a critical part of the thesis, presenting and analyzing the outcomes of the CFD simulations and ANN predictions. In this section, the results obtained from various hydrogen-methane mixture ratios are interpreted and evaluated for their consistency with existing literature. This section also emphasizes the validation of the numerical results obtained with experimental data reported in the literature. The final chapter, *Conclusion*, summarizes the main outcomes of the study, evaluates their applicability, and provides recommendations for further improvements. Overall, the aim of the study is to conduct a detailed analysis and evaluation of the subject matter, thereby contributing to the literature in this emerging and innovation-driven field and serving as a valuable resource for researchers interested in the topic.



2. LITERATURE REVIEW

In recent years, environmental conditions, sustainability concerns, and the limited availability of fossil fuel reserves have driven researchers toward alternative and clean energy sources. In this context, hydrogen has emerged as a promising fuel due to its environmentally friendly characteristics and high energy content. The question of how hydrogen can be utilized in the most efficient and effective manner has become a common research concern, leading to a significant increase in studies in this field. Hydrogen has the ability to be used as a secondary fuel in combination with various fossil fuels. In this thesis, the flame characteristics that emerge when hydrogen is added as a secondary fuel to methane will be examined in detail. Previous numerical and experimental studies in the literature involving methane-hydrogen mixtures as fuel have been comprehensively reviewed and are presented below. Furthermore, scientific studies conducted on ANN within this context are also discussed under this section.

Ortiz-Imedio et al. (2020) conducted thermal efficiency and emission analyses by comparing coke oven gas (COG), which contains high percentages of H_2 and CH_4 , with pure hydrogen and methane in a spark-ignition port fuel injection engine. The results indicated that COG exhibited superior performance and lower emission levels compared to pure H_2 and CH_4 . In case the air-fuel ratio value is equal to 1.5, the thermal efficiency of COG increased by 7% compared to H_2 and by 10.3% compared to CH_4 . In engines operating with high-hydrogen-content fuels, retarded spark timing can reduce NO_x emissions due to lower combustion temperatures. However, in mixtures with a high air-fuel ratio, flammability decreases. Increasing the hydrogen ratio in the mixture raises the combustion temperature, thereby reducing HC emissions.

Amez et al. (2021) conducted a study aimed at enabling the use of biogas in conventional natural gas equipment. In this study, biogas was blended with hydrogen to enhance its calorific value and tested in a conventional natural gas burner capable of operating up to 100 kW. The results indicated that the biogas-hydrogen mixture improved flame stability and combustion behavior. To improve flame stability, hydrogen was added to the biogas in proportions ranging from 5% to 25%. Furthermore, it was noted that when the hydrogen content exceeded 20%, the combustion characteristics exhibited only minor changes, but these changes do not necessarily

mean an improvement. The optimum operating conditions for biogas were achieved with hydrogen concentrations between 5% and 10%, particularly when the CO₂ content in the biogas exceeded 60%.

Öztürk and Dinçer (2022) designed an integrated system for the production of green hydrogen and its blending with the potential natural gas reserves located in the Black Sea region of Turkey. In this system, the effects of the hydrogen addition on natural gas consumption and selected emission parameters were investigated. The study observed that increasing the hydrogen ratio in the natural gas–hydrogen mixture to 20% resulted in a reduction in annual natural gas consumption from 46.55 Bm³ to 43.29 Bm³. Consequently, the projected lifespan of the existing natural gas reserves was extended from 11.6 years to 12.5 years. Moreover, while increasing the hydrogen share in the blend from 5% to 20% led to reductions in CO and CO₂ emissions, an increase in NO_x emissions was also identified.

Ökten, Variyenli, Karyeyen, and Göktekin (2025) investigated the potential physical and performance changes resulting from the combustion of a methane–hydrogen fuel mixture in a domestic boiler burner. The study was based on both experimental investigations and numerical modeling. CFD analyses were employed, utilizing the realizable k- ϵ turbulence model and the eddy-dissipation combustion model. It was observed that increasing the hydrogen content from 0% to 30% resulted in a rise in the combustion chamber temperature. Additionally, the thermal power output of the boiler increased from 13 kW to 14.7 kW. Emission measurements indicated an increase in CO₂ and NO_x levels, while a reduction in CO emissions was observed.

İlbaş et al. (2006) conducted analyses using hydrogen–air and hydrogen–methane–air mixtures with varying density levels in a test setup inspired by the cloud chamber design developed at Cardiff University. Quartz windows were used to observe flame propagation, and flame speeds were precisely measured using the schlieren photography technique. The results demonstrated that increasing the hydrogen fraction in the hydrogen–methane mixture led to higher combustion speeds and an expansion of the flammability limits. This study also demonstrated that a 30% hydrogen and 70% methane gas mixture could serve as an alternative fuel for existing combustion systems.

Nieto-Londoño, Silva-López, and Gómez-Velásquez (2025) conducted a numerical study on combustion dynamics and flame stabilization in a millimeter-scale reactor they designed, focusing on varying mixture ratios of methane, hydrogen, and air. The study employed a laminar flow model and examined the effects of increasing hydrogen concentration in the fuel mixture. According to the results, higher hydrogen content led to increased flame temperatures, with the maximum heat release rate observed at 40% hydrogen. Increasing the hydrogen concentration from 0% to 90% raised flame temperatures by approximately 300 K, and elevating the outlet pressure resulted in a 15% increase in flame temperature. When the methane–air mixture was enriched with 50% hydrogen and operated at an outlet pressure of 100 kPa, the maximum flame temperature was measured at 2232 K; this value increased to 2350 K when the outlet pressure was raised to 1000 kPa under the same mixture conditions. The study also found that increasing the hydrogen content improved complete oxidation, which may offer advantages in high-altitude regions where oxidant levels are naturally lower. Additionally, higher hydrogen concentrations in the fuel led to greater CO₂ formation but reduced CO emissions. The simulations revealed that decreasing the microreactor diameter resulted in incomplete combustion and elevated CO emissions, while larger reactor diameters reduced heat losses and improved combustion efficiency by approximately 20%.

Mihăescu et al. (2021) conducted a comparative analysis of hydrogen and methane in diffusion mode with respect to combustion and ignition characteristics in a hydrogen burner. Numerical simulations were performed using ANSYS Fluent to carry out these comparisons. The study analyzed flame temperature maps of hydrogen–air and methane–air mixtures, revealing that hydrogen flames exhibited higher burning velocities and that the flame length was approximately 10% shorter compared to methane–air flames. The core temperature of the hydrogen flame was measured to be around 2160 K, indicating a higher temperature than that of the methane flame core. The researchers noted that, overall, there were similarities between hydrogen and methane combustion in terms of flame length and recorded flame temperatures. The study is intended to serve as a foundation for the development of efficient and applicable hydrogen burner designs.

Taştan, Mutlu, and Çetintaş (2023) conducted an experimental study on the combustion characteristics of a propane–methane mixture with hydrogen addition under external acoustic

excitation. Two different fuel mixtures were utilized in the study: 67% methane – 33% propane and 63.5% methane – 31.5% propane – 5% hydrogen. Among these, the mixture with 5% hydrogen addition, which possesses a higher calorific value, exhibited a tendency toward higher flame temperatures in the burner. This increase in temperature was attributed to the hydrogen component participating more rapidly in combustion reactions with carbon and oxygen. It was observed that the addition of 5% hydrogen enhanced flame stability and light intensity, while the dynamic instability demonstrated non-monotonic behavior in relation to flame temperature and luminous intensity. Moreover, under high acoustic excitation, the hydrogen-enriched mixture yielded negative emission outcomes, whereas the mixture without hydrogen showed the opposite trend.

Aravindan et al. (2024) conducted a study investigating the effects of hydrogen addition on LPG–air and methane–air mixtures. In the study, a 50% hydrogen blend was used in both fuel mixtures. The methane–hydrogen mixture yielded a 20.97% higher laminar flame speed, while the LPG–hydrogen mixture resulted in 42.89% more H radicals, 50.24% fewer O radicals, and 24.01% more OH radicals. The findings emphasize that the addition of hydrogen to both LPG and methane mixtures improves combustion characteristics.

In their study, Öztuna and Büyükkakın (2020) enriched methane gas with hydrogen and presented various experimental and numerical results. A non-premixed combustion chamber was employed to investigate the effects of hydrogen addition on diffusion flame structure and emissions. According to the findings, enriching methane with hydrogen resulted in a broader and shorter diffusion flame structure compared to the use of pure methane. The addition of hydrogen to methane reduced flame intensity and increased flow velocity, thereby broadening the diffusion flame. The maximum flame temperature was measured as 2030 K for a 15% hydrogen addition, whereas it was 2050 K for pure methane. The researchers observed that in methane-hydrogen mixtures with 15% hydrogen content, the maximum flame temperatures and NO emission levels were lower than those in pure methane combustion. This behavior was attributed to the expansion of the flame structure due to hydrogen addition, which increased the mixing ratio of combustion products and reactants in the back-pressure burner. As a result, the flame temperature and concentration of free radicals decreased, leading to a reduction in NO

formation. However, for hydrogen concentrations above 15%, both flame temperature and NO emissions tended to increase due to the higher heating value of hydrogen compared to methane.

Bayramoğlu, Bahlekeh, and Masera (2023) conducted a numerical study on a diesel engine to investigate the combustion performance and emission characteristics of hydrogen–methane and hydrogen–methane–ammonia blends at varying concentrations. In the hydrogen–methane mixture, hydrogen was incrementally increased at 5%, 10%, and 15% by volume. The results indicated that the addition of 15% hydrogen to methane fuel led to an increase of approximately 100 K in the peak in-cylinder temperature. Furthermore, a 10% increase in hydrogen concentration within the methane–hydrogen blend resulted in a 28% rise in NO_x emissions. Additionally, enriching methane with 15% hydrogen was found to reduce CO₂ emissions by 37.7% compared to pure methane combustion.

Madia, Cicalese, and Dalseno (2023) conducted a comparative analysis of CFD and experimental results for hydrogen, methane, and blended fuels in an internal combustion engine. In the experimental study, the maximum temperature obtained during pure methane combustion was measured at 1920 K. When using the Laminar Flame Concept (LFC) model, this value was calculated as 2160 K, while the Eddy Dissipation Concept (EDC) model yielded a value of 2030 K. In tests conducted with a fuel blend consisting of 33.2% hydrogen, 22.1% methane, and 44.7% nitrogen, the experimental temperature was measured at 1850 K. In the numerical simulations, the EDC model predicted a maximum temperature of 2028 K, while the LFC model produced a value of 2088 K. Overall, the EDC model was found to yield results closer to the experimental data. In engine simulations, the Turbulent Flame Speed Closure (TFSC) model most accurately represented the combustion development, particularly when both laminar and turbulent flame speeds were defined. The study generally highlights that selecting an appropriate model specific to the application is critical for accurate combustion prediction.

In their study, Xiao et al. (2024) conducted prediction and optimization analyses on combustion parameters and emission outcomes of lean methane–hydrogen mixtures. An experimental setup employing a non-premixed burner was used. The results revealed that the hydrogen blending ratio had the most significant effect on NO emissions at 64.6% and on CO₂ emissions at 83.5%. The study also indicated that the equivalence ratio was not a significant parameter in

determining NO and CO₂ emissions. The adjusted coefficients of determination for the reduced predictive model were found to be 0.9707 and 0.9360, respectively, demonstrating a high degree of model fit and strong explanatory power. Furthermore, the peak temperature at the center of the combustion chamber was observed to increase within the range of 1.02% to 3.61%. Overall, the study provides researchers with detailed insights into prediction and optimization approaches for non-premixed methane–hydrogen combustion.

Mehra et al. (2018) investigated the performance and emission characteristics of an internal combustion engine fueled with hydrogen-enriched compressed natural gas (HCNG) through both experimental methods and artificial neural network (ANN)-based analyses. The experimental tests were conducted under varying ignition timings and excess air ratios. The results demonstrated that hydrogen enrichment had a favorable impact, particularly in reducing fuel consumption and extending lean burn limits. However, at higher hydrogen concentrations, an increase in in-cylinder temperatures was observed, which led to a corresponding rise in NO_x emissions. The ANN model was developed using four input and six output parameters. The model's performance was found to be satisfactory, as indicated by low mean squared error (MSE) values and high correlation coefficients. Overall, the study concluded that ANN provides a reliable and efficient alternative model for predicting the performance and emissions of HCNG-fueled engines.

Molina, Novella, Gomez-Soriano, and Olcina-Girona (2021) developed a novel combustion modeling approach for a spark-ignition internal combustion engine fueled with a methane–hydrogen blend. The model, trained under a wide range of operating conditions, was integrated with an artificial neural network (ANN) designed to predict laminar flame speeds and applied to a virtual light-duty engine. The study concluded that hydrogen addition to the blend positively influenced combustion, particularly under lean conditions, by increasing the burn rate. It was also observed that maximum pressure values exhibited an increasing trend with higher hydrogen concentrations in the mixture. However, the study also acknowledged the presence of certain thermodynamic losses associated with the physical properties of hydrogen and highlighted some limitations that affect the accuracy of the model.

Table 2.1. Overview of key studies on methane, propane, and hydrogen combustion

Reference	Primary Fuel	Secondary Fuel	Burner Type	Method(s)
Ortiz-Imedio et al. (2020)	COG (Coke Oven Gas)	Methane /Hydrogen	Spark ignition engine	Experimental
Amez et al. (2021)	Biogas	Hydrogen	Conventional natural gas systems	Numerical, Experimental
Öztürk and Dinçer (2022)	Natural Gas	Hydrogen	An integrated system	Numerical
Ökten et al. (2025)	Methane	Hydrogen	Combined type gas burner (combi boiler)	Numerical, Experimental
İlbaş et al. (2006)	Methane	Hydrogen	A modified test setup inspired by the cloud chamber of Cardiff University	Experimental
Nieto-Londoño et al. (2025)	Methane	Hydrogen	Millimeter-scale reactors	Numerical
Mihăescu et al. (2021)	Methane	Hydrogen	Hydrogen burner	Numerical
Taştan et al. (2023)	Propane/Methane	Hydrogen	A premixed and vortex-supported system	Experimental
Aravindan et al. (2024)	LPG/Methane	Hydrogen	Combustion chamber	Numerical
Öztuna and Büyükakın (2020)	Methane	Hydrogen	Back-pressure combustion chamber	Numerical, Experimental
Bayramoğlu et al. (2023)	Methane	Hydrogen/Ammonia	Compression ignition engine	Numerical

Madia et al. (2023)	Methane	Hydrogen	Spark ignition engine	Numerical, Experimental
Xiao et al. (2024)	Methane	Hydrogen	Combustion chamber	ANN, Experimental
Mehra et al. (2024)	CNG (Compressed Natural Gas)	Hydrogen	Combustion chamber	ANN, Experimental
Molina et al. (2021)	Methane	Hydrogen	Spark ignition engine	ANN

A comprehensive review of the literature, as shown in Table 2.1, reveals that the majority of studies have primarily focused on investigating emission characteristics, while specific evaluations of flame characteristics, as addressed in this thesis, have been largely overlooked. Furthermore, many of the existing studies have concentrated on widely recognized technologies such as internal combustion engines, whereas investigations conducted on specially designed, innovation-oriented burners remain limited. Although various turbulence models have been employed in the CFD analyses found in the literature, the use of one of the most recent approaches, the realizable $k-\varepsilon$ turbulence model, has been relatively scarce. Additionally, although a wide range of hydrogen concentration levels has been examined in previous studies, there appears to be a lack of experiments conducted using more precise incremental increases in hydrogen concentration by volume. Moreover, the literature predominantly focuses on premixed mixtures, indicating a noticeable gap in research related to non-premixed combustion systems. In addition, it has been concluded that studies involving ANN-based prediction models for hydrogen-methane blended fuels remain limited in the current literature.

3. MATERIALS AND METHODS

This thesis is based on the investigation of flame characteristics resulting from the reaction of methane, a conventional fuel enriched with various proportions of hydrogen, an environmentally friendly energy source. Within the scope of the study, numerical analyses and artificial neural network (ANN) prediction models were conducted for the methane–hydrogen mixture, while experimental investigations were carried out using a hydrocarbon-based gas and oxyhydrogen (HHO). This chapter provides a detailed description of the specially designed burner used in the numerical studies, along with the turbulence, radiation, and mesh models employed in the CFD analyses. The methodologies applied in the ANN modeling, as well as the specific ANN structure determined for this study, are also explained in this section. In addition, the fundamental formulations utilized throughout the research are presented here. The chapter concludes with a comprehensive description of the experimental setup, including the equipment and measurement devices used in the experiments.

3.1. Burner Selection and Modeling

The selection of burners necessitates the consideration of various criteria, including fuel type, burner capacity, burner efficiency, combustion chamber dimensions, burner counter pressure, flame length and diameter, and altitude. Additionally, the mode of fuel combustion—whether with air or pure oxygen—plays a critical role in burner performance. When fuel combusts in the presence of air, the process is referred to as air-fuel combustion, whereas combustion with pure oxygen is termed oxy-fuel combustion. The oxy-fuel combustion technique results in a significantly higher flame temperature compared to air-fuel combustion. However, this elevated temperature may lead to excessive heating of the burner and combustor walls, potentially causing structural degradation. To mitigate this issue, burners should be constructed using materials capable of withstanding high temperatures associated with oxy-fuel combustion (Markewitz et al., 2012).

In the numerical studies conducted within the scope of this thesis, a specially designed open-ended burner suitable for methane–hydrogen combustion reactions was employed. This burner has dimensions of 100 × 500 mm and is equipped with one methane, two hydrogen, and two air inlet ports. As schematically illustrated in Figure 3.1, the methane inlet (V_1) has a width of

3.6 mm, the hydrogen inlets (V_2) are 0.2 mm wide, and the air inlets (V_3) have a width of 48 mm. Additionally, the burner was designed to withstand the high temperatures that may arise during hydrogen combustion reactions.

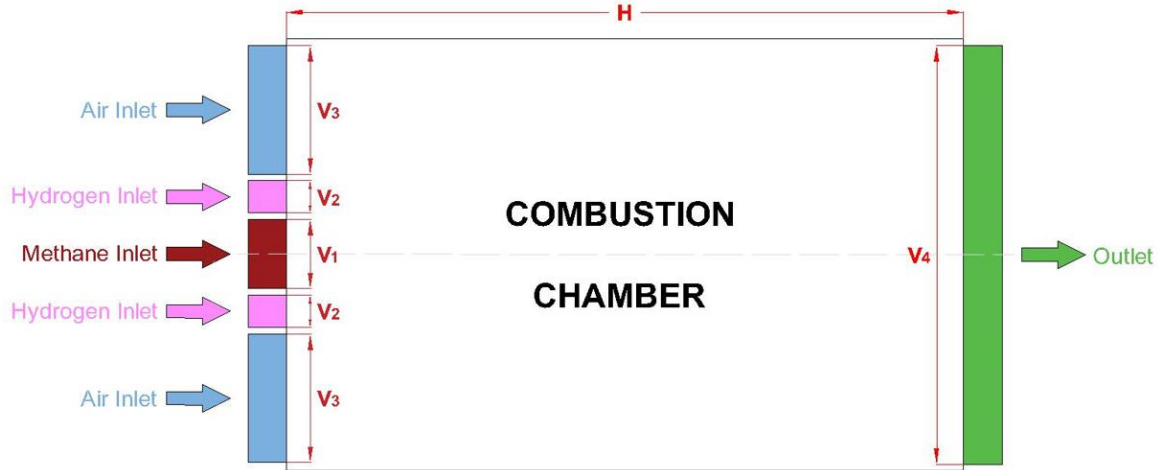


Figure 3.1. Schematic model of the burner for non-premixed combustion

Investigations were conducted on the flame temperatures resulting from the addition of hydrogen at thirteen different concentrations (0%, 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5%, 20%, 22.5%, 25%, 27.5%, 30%) to the methane combustion reaction. Additionally, ten equidistant points along the burner axis, as schematically illustrated in Figure 3.2, were identified. Temperature, pressure, and velocity variations at these points were observed, and relevant interpretations were made based on the obtained results.

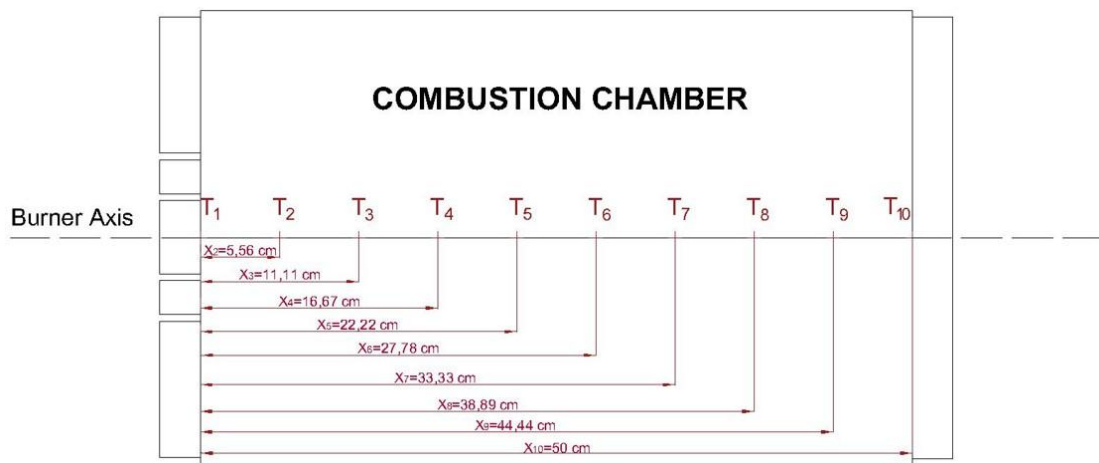


Figure 3.2. Schematic model of distance on the burner axis

3.2. Numerical Solution in ANSYS Fluent

All numerical calculations for this specially designed burner have been conducted using the Ansys Fluent CFD (Computational Fluid Dynamics) software. CFD software, based on the Navier-Stokes equations, is a computational modeling and simulation approach used to analyze fluid flow and heat transfer phenomena. Its applications include assessing combustion stability, regulating combustion rates, and characterizing flame dynamics (Öztürk, 2013).

3.2.1. Turbulence Modeling

In the numerical analysis, the realizable k- ϵ turbulence model (Equations 3.1 and 3.2) was used, as it more accurately predicts the spreading rate of jets with different structures (planar and circular). The term "realizable" indicates that the model satisfies specific mathematical constraints on the Reynolds stresses, ensuring consistency with the physics of turbulent flows. In contrast, neither the standard k- ϵ model nor the RNG k- ϵ model is realizable (Ansys, 2021).

The realizable k- ϵ model is considered more practical for industrial applications due to its improved accuracy and closer alignment with physical reality compared to other turbulence models (Shih, Liou, Shabbir, Yang, & Zhu, 1995). It is frequently preferred in high-temperature combustion flows such as burner design, combustion chambers, and gas turbines. Studies have shown that the realizable model delivers the best performance among the k- ϵ model variants in validating separated flows and flows with complex secondary flow features (Ansys, 2021). However, it falls short in scenarios involving near-wall flow details and laminar-to-turbulent transition, where other models may perform better (Pope, 2000). Two-equation turbulence models are also limited in their ability to capture the subtle relationships between turbulent energy production and turbulent stresses caused by anisotropy in normal stresses (Versteeg & Malalasekera, 2007). Another limitation of the realizable k- ϵ model arises in domains involving both rotating and stationary fluid regions, where it may produce non-physical turbulent viscosities (Ansys, 2021).

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad 3.1$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \quad \text{where}$$

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right], \eta = S \frac{k}{\varepsilon}, S = \sqrt{2 S_{ij} S_{ij}} \quad 3.2$$

3.2.2. Radiation Modeling

In combustion studies involving very high temperatures, it is necessary to incorporate radiation modeling in addition to combustion modeling. Unless an adiabatic environment—which is physically difficult to achieve—is used in the study, the high temperatures within the burner will inevitably lead to heat transfer through radiation. In this numerical study, the P-1 radiation model was employed to enhance computational efficiency and numerical stability. The P-1 radiation model calculates the radiative heat flux using a derived equation, as presented in Equation 3.3.

$$\nabla \cdot \left(\frac{1}{3(a + \sigma_s)} \nabla G \right) - (a + \sigma_s) G = -4a\sigma T^4 \quad 3.3$$

In this equation, G represents the incident radiation, a denotes the absorption coefficient, σ_s is the scattering coefficient, T is the temperature, and σ refers to the Stefan–Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$). In the P-1 model, Equation 1.10 is used to calculate the radiative heat flux, while Equation 1.11 is employed to account for heat sources (or sinks) resulting from radiation.

The P-1 radiation model is employed as part of CFD analyses to develop solutions for industrial problems. As a derived form of the radiative transfer equation, this model offers the significant advantage of fast computation time and a relatively simple structure, enabling efficient calculations. For this reason, it is commonly preferred as a reliable model in terms of the speed–accuracy balance, particularly for geometries that are not highly complex. The suitability of the burner geometry used in this study for such a modeling approach was one of the reasons for its selection.

It has been determined that the P-1 radiation model is beneficial when applied over a general curvilinear coordinate system in environments where thermal radiation may occur. Radiation originating from particles must be incorporated into thermal calculations in a simplified

manner. One of the advantages of this model is its ability to compute radiative exchange between gases and particles. Moreover, in a study conducted on an industrial coal furnace, the results obtained from the P-1 radiation model showed very good agreement with experimental temperature distribution measurements (Sazhin, Sazhina, Faltsi-Saravelou, & Wild, 1996).

If radiation is not accurately modeled within CFD analyses, flame temperatures may be overestimated. In this model, direct in-flame radiation calculations, volumetric radiation in the gas phase, and combustion reactions not limited to solid surfaces converge more rapidly, allowing radiation losses to be predicted more accurately and resulting in more precise flame temperature values. However, in cases where directionality—i.e., anisotropic radiation—is significant, the model may not provide reliable radiation predictions. Additionally, the P-1 model is limited in analyzing radiation effects originating from heat sources in optically thin media (Sazhin et al., 1996). It accounts only for diffuse reflections and is incapable of calculating specular reflections. Therefore, in such cases, the desired level of radiation prediction cannot be achieved. In this thesis, the burner used has a diffuse reflective surface and is characterized as isotropic, making the P-1 model a suitable choice due to its rapid convergence properties and reliable radiation calculations.

In the study conducted by Yılmaz, Taştan, İlbaş, and Tarhan (2013), the effects of turbulence and radiation models on flame characteristics were investigated using various mixtures of hydrogen and propane gases. In the comparison of radiation models with respect to temperature gradients, the results obtained from the Discrete Transfer Radiation Model (DTRM) did not align with values reported in the literature. In contrast, the P-1 radiation model demonstrated a general agreement between simulation results, experimental data, and literature values. Due to its lower computational requirements and fast convergence capability, the P-1 model was utilized for the propane–hydrogen mixture in the study.

3.2.3. Mesh Modeling

A mesh is divided into smaller cells with this property to accurately represent the geometry of the object being simulated in the CFD program. Higher-quality mesh enables more precise and realistic results. The mesh structure of the combustion chamber, as illustrated in Figure 3.3, was

determined based on the grid independence test presented in Figure 3.4. For the case with 18 divisions at the methane inlet, the mesh consists of 162162 nodes and 161000 elements.

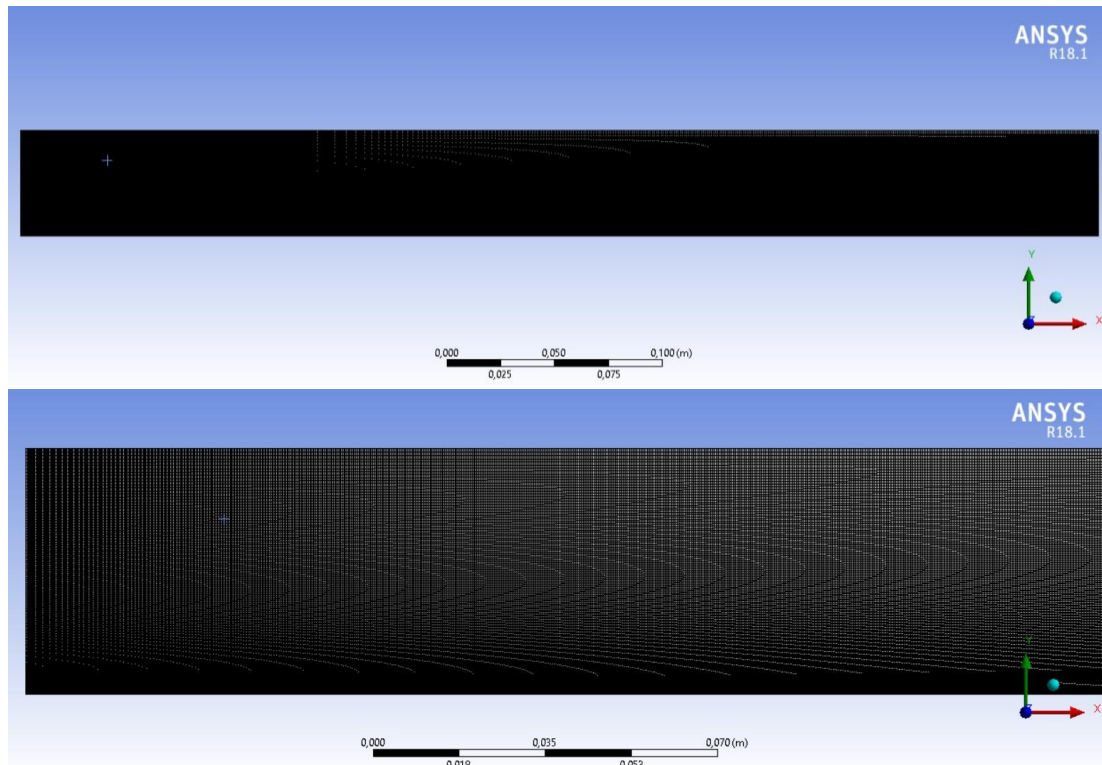


Figure 3.3. Mesh structure overview

In the grid independence test conducted by varying the number of divisions at the methane inlet, it was observed that increasing the number of divisions led to convergence toward the temperature value obtained with 18 divisions. Therefore, the number of nodes and elements was determined based on this selected division count.

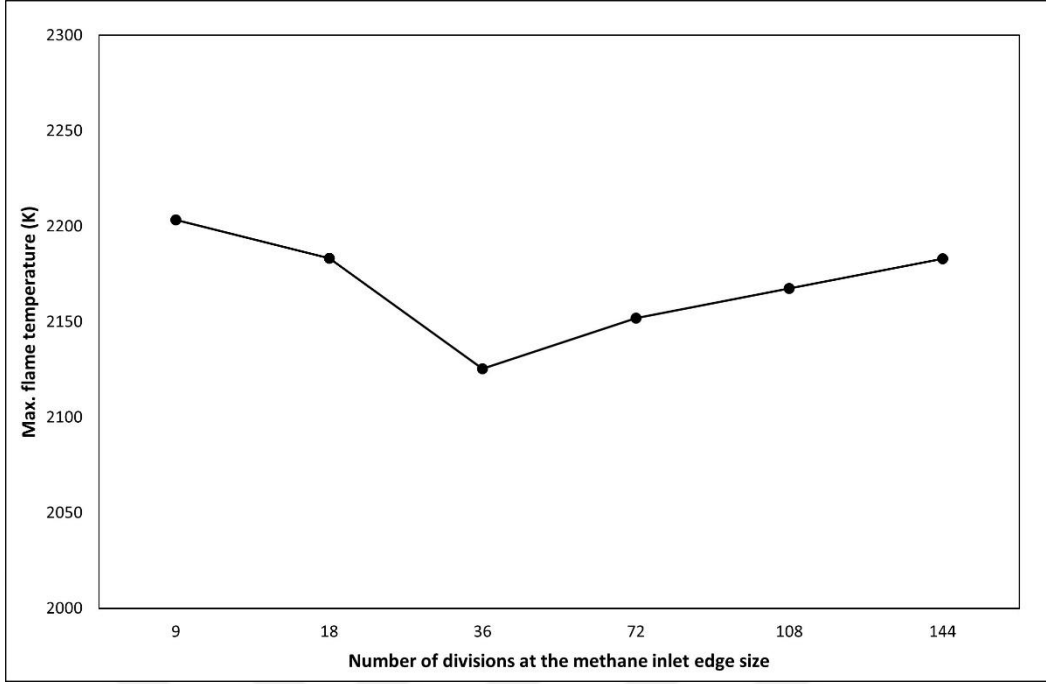


Figure 3.4. Grid independence test

3.2.4. Formulation

The simulation was conducted under steady-state conditions. The fundamental governing equations are provided as follows: the conservation of mass (continuity) in Equation 3.4, the conservation of momentum in Equation 3.5, the conservation of energy in Equation 3.6, and the conservation of species in Equation 3.7 (Yilmaz, Karyeyen, Tepe, & Brüggemann, 2023).

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial t} = 0 \quad (3.4)$$

$$\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j - \tau_{ij}) = \frac{\partial p}{\partial x_j} \quad (3.5)$$

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho u_i h)}{\partial x_i} = \frac{\partial(\lambda_f \rho T_f)}{\partial x_i} - \sum_j \frac{\partial(h_j J_j)}{\partial x_i} + \sum_j h_j R_j \quad (3.6)$$

$$\frac{\partial(\rho Y_i)}{\partial t} + \frac{\partial(\rho u_i Y_i)}{\partial x_i} = \frac{\partial J_j}{\partial x_i} + R_i \quad (3.7)$$

When fuels reach their ignition temperature and oxygen is present in the environment, they undergo a chemical reaction, releasing heat along with certain byproducts. This process is referred to as combustion. One of the most critical parameters in a combustion process is the air-fuel mixture ratio. The minimum amount of air required to achieve complete combustion is

defined as stoichiometric air. The excess air ratio (λ) is determined by dividing the actual air-fuel ratio by the stoichiometric air-fuel ratio (Equation 3.8). Under stoichiometric combustion conditions, the excess air ratio is equal to 1. The equivalence ratio (φ) is obtained by dividing the stoichiometric air-fuel ratio by the actual air-fuel ratio, serving as an indicator of the fuel content in the mixture. When $\varphi > 1$, the mixture is fuel-rich, whereas when $\varphi < 1$, the mixture is fuel-lean. In the case of $\varphi = 1$, a stoichiometric mixture is achieved (Ökten, Variyenli, Karyeyen, & Goktekin, 2025). In this thesis, analyses were conducted under lean combustion conditions.

$$\lambda = \frac{\dot{m}_{air}}{\dot{m}_{air,stockiometric}} \times 10 \quad (3.8)$$

3.3. Artificial Neural Network Modeling

In this section of the study, an artificial neural network (ANN) structure was developed to evaluate the accuracy of the maximum flame temperatures obtained from the CFD analyses. According to the fundamental principle of ANN operation, the more input information is provided, the better the model learns and the more accurate the predictions become. To clearly demonstrate this behavior, the ANN architectures used within the scope of this thesis are presented in Figures 3.5 and 3.6.

In Figure 3.5, the input parameters consist solely of temperature values (K) measured at 10 axial locations for 13 different hydrogen and methane concentration cases, with the target parameter defined as the maximum flame temperature (K). In contrast, Figure 3.6 utilizes temperature (K), pressure (Pa), and velocity (m/s) values at the same 10 axial locations for the same 13 hydrogen and methane concentration cases as input parameters, with the target again being the maximum flame temperature (K). In other words, the ANN model in Figure 3.6 was constructed using four categories of input variables to predict a single output parameter. The detailed input, test, and target parameters of the two ANN models used in this study are presented in Table 3.1.

Table 3.1. Input, test, and target parameters utilized in the ANN model configuration

ANN Model-1	Input Parameters				
	Fuel Rate (%)		T (K)		
	Hydrogen	Methane			
	0	100	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	2.5	97.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	5	95	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	7.5	92.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	10	90	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	12.5	87.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	15	85	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	17.5	82.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	20	80	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	22.5	77.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	25	75	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	27.5	72.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
	30	70	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀		
Test Parameters					
T _{max} CFD (0/100), T _{max} CFD (2.5/97.5), T _{max} CFD (5/95), T _{max} CFD (7.5/92.5), T _{max} CFD (10/90), T _{max} CFD (12.5/87.5), T _{max} CFD (15/85), T _{max} CFD (17.5/82.5), T _{max} CFD (20/80), T _{max} CFD (22.5/77.5), T _{max} CFD (25/75), T _{max} CFD (27.5/72.5), T _{max} CFD (30/70)					
Target Parameters					
T _{max} (0/100), T _{max} (2.5/97.5), T _{max} (5/95), T _{max} (7.5/92.5), T _{max} (10/90), T _{max} (12.5/87.5), T _{max} (15/85), T _{max} (17.5/82.5), T _{max} (20/80), T _{max} (22.5/77.5), T _{max} (25/75), T _{max} (27.5/72.5), T _{max} (30/70)					
ANN Model-2	Input Parameters				
	Fuel Rate (%)		T (K)	P (Pa)	V (m/s)
	Hydrogen	Methane			
	0	100	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	2.5	97.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	5	95	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	7.5	92.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	10	90	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	12.5	87.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	15	85	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	17.5	82.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	20	80	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	22.5	77.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	25	75	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	27.5	72.5	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
	30	70	T ₁ , T ₂ , T ₃ , T ₄ , T ₅ , T ₆ , T ₇ , T ₈ , T ₉ , T ₁₀	P ₁ , P ₂ , P ₃ , P ₄ , P ₅ , P ₆ , P ₇ , P ₈ , P ₉ , P ₁₀	V ₁ , V ₂ , V ₃ , V ₄ , V ₅ , V ₆ , V ₇ , V ₈ , V ₉ , V ₁₀
Test Parameters					
T _{max} CFD (0/100), T _{max} CFD (2.5/97.5), T _{max} CFD (5/95), T _{max} CFD (7.5/92.5), T _{max} CFD (10/90), T _{max} CFD (12.5/87.5), T _{max} CFD (15/85), T _{max} CFD (17.5/82.5), T _{max} CFD (20/80), T _{max} CFD (22.5/77.5), T _{max} CFD (25/75), T _{max} CFD (27.5/72.5), T _{max} CFD (30/70)					
Target Parameters					
T _{max} (0/100), T _{max} (2.5/97.5), T _{max} (5/95), T _{max} (7.5/92.5), T _{max} (10/90), T _{max} (12.5/87.5), T _{max} (15/85), T _{max} (17.5/82.5), T _{max} (20/80), T _{max} (22.5/77.5), T _{max} (25/75), T _{max} (27.5/72.5), T _{max} (30/70)					

The neurons in the hidden layer, located between the input and output layers, operate with nonlinear activation functions to perform the necessary computations and learning process. As a result, a comparison between these two ANN configurations was conducted to assess their prediction performance.

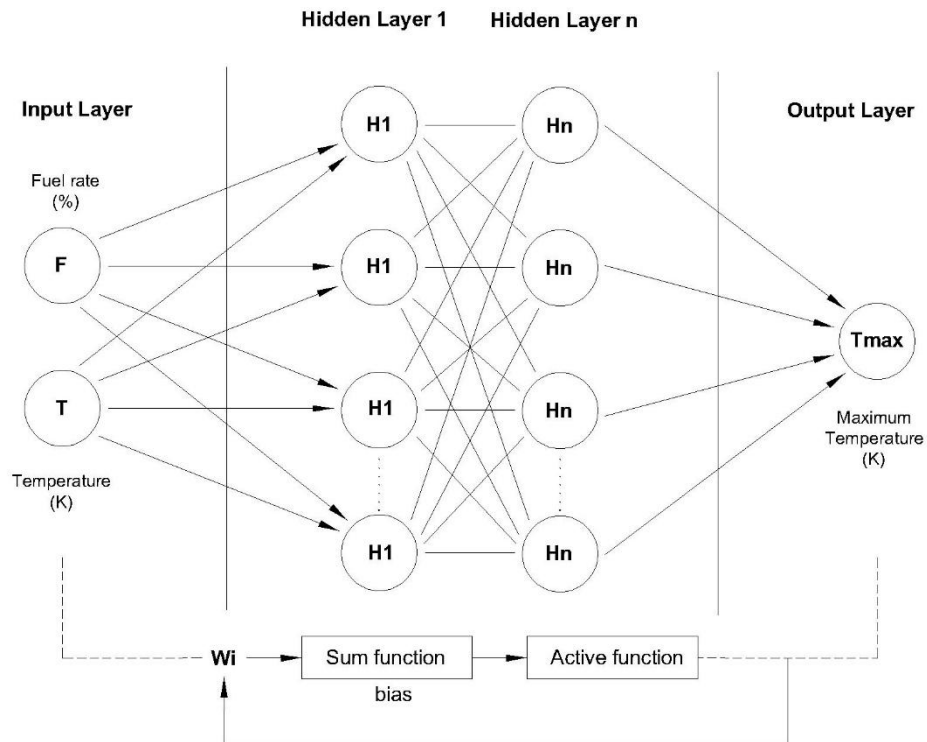


Figure 3.5. Schematic diagram of ANN architecture with two inputs

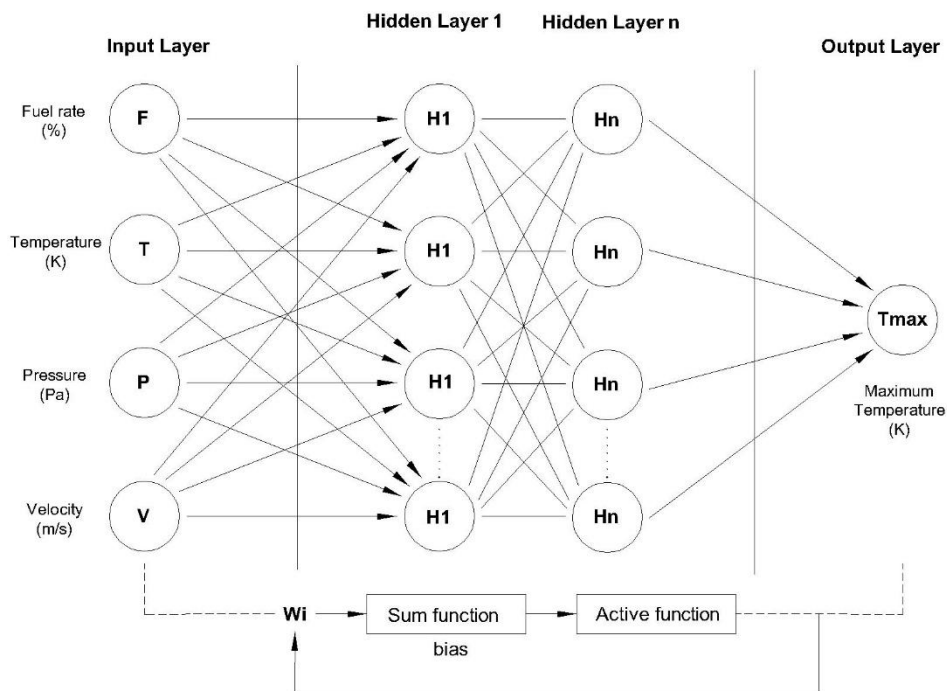


Figure 3.6. Schematic diagram of ANN architecture with four inputs

One of the primary objectives of employing an ANN model is to achieve time efficiency and to reduce the potential costs associated with experimental or numerical analyses. In the constructed ANN model, the error metrics were calculated using the formulations provided in Equations 1.20, 1.21, and 1.22. Among these, the most critical metric is the coefficient of determination, presented in Equation 1.20. This coefficient takes a value between 0 and 1 ($0 \leq R^2 \leq 1$). The closer this value is to 1, the more accurate the predictions made by the ANN are considered to be. In other words, as the R^2 value increases, the accuracy of the ANN model improves, whereas a decrease in this coefficient indicates a decline in model performance. The parameters related to the developed ANN architecture are presented in Table 3.2.

Table 3.2. Artificial Neural Network configuration parameters

Configuration	Parameters
Training algorithm	Levenberg-Marquardt
Adaptive learning function	LEARNGDM
Performance function	Mean squared error
Layer size	10
Transfer function	TANSIG
Network type	Feed-forward backprop

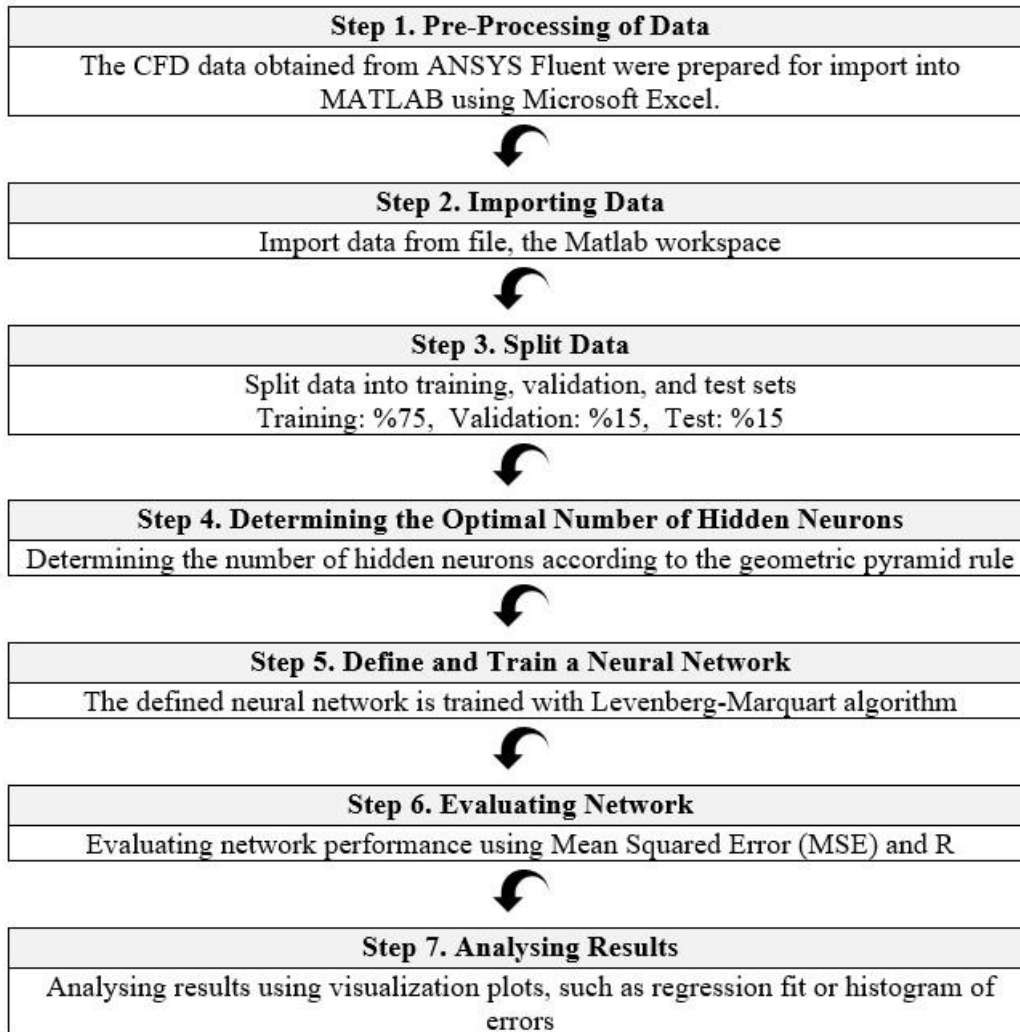


Figure 3.7. Overview of the ANN methodology employed in the study

Figure 3.7 provides an ANN methodology employed, including a detailed description of the model architecture, training algorithm, and performance evaluation metrics. In this study, the Levenberg-Marquardt algorithm was employed to develop the ANN model. The Levenberg-Marquardt algorithm is a widely used optimization technique for solving nonlinear least squares problems. Due to its high efficiency in minimizing the error between predicted and actual outputs, it is frequently applied in the training of artificial neural networks. The algorithm integrates the strengths of both the Gauss-Newton method and the steepest descent approach. The operational procedure of the algorithm can be summarized as follows: Initially, the weights of the network are assigned. Subsequently, the difference between the predicted output and the actual value is computed. Based on this error, the weights are updated using a combination of

the Gauss-Newton and steepest descent methods. This process continues iteratively until the convergence criteria are met or the maximum number of iterations is reached (Levenberg, 1944). The mathematical formulation of the algorithm can be expressed in Equation 3.9 (Yıldırım, 2024).

$$w_{k+1} = w_k - (J_k^T J_k + \lambda I)^{-1} J_k^T e_k \quad (3.9)$$

In the presented equation, w_k denotes the weight vector at iteration k ; J_k corresponds to the Jacobian matrix; λ represents the Levenberg-Marquardt damping parameter; I is the identity matrix; and e_k signifies the error vector. Here, k refers to the iteration index.

3.4. Experimental Setup Equipment

The primary components of the flame specification evaluation setup are the hydrocarbon-based gas and hydrogen supply lines. In this section, hydrogen used in the experiment refers to HHO (hydrogen-hydrogen-oxygen) gas, which is produced through the process of electrolysis. HHO is also commonly known as oxyhydrogen or hydroxy gas. In the experimental setup schematically illustrated in Figure 3.8, the burner features two separate inlets. One of these lines delivers hydrocarbon-based gas, while the other supplies hydrogen gas produced from a hydrogen generation unit.

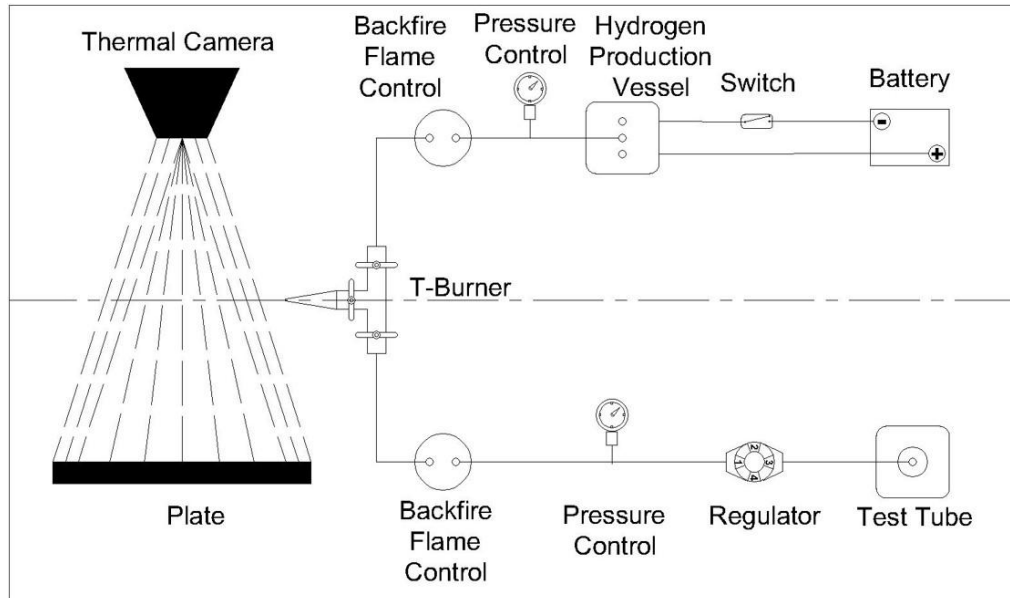


Figure 3.8. Schematic view of the experimental setup

Figure 3.9 presents the general view of the experimental setup established in the laboratory environment. The specifications of all equipment used in this setup are described in detail under the following headings.



Figure 3.9. Overall view of the experimental setup

3.4.1. Test tube

The hydrocarbon-based gas test tube shown in Figure 3.10 is a specially designed, high-safety test vessel with a length of 500 mm, a diameter of 110 mm, and a total volume of 3 liters, manufactured in accordance with SCH 80 standards. A gate valve is installed at the upper part of the test tube to control the initial flow.



Figure 3.10. Test tube

3.4.2. Pressure Control Regulator

Since the test tube operates at an approximate pressure of 5 bar, direct transfer to the system is not considered safe. Therefore, a pressure regulator with an operating range of 0–10 bar, as shown in Figure 3.11, was integrated into the system for safety purposes. The regulator is mounted at the outlet of the gate valve located at the upper part of the test tube, allowing the flow to be brought under control.



Figure 3.11. Pressure control regulator

3.4.3. Manometer

To monitor the pressure within the system, manometers operating in the range of 0–400 mbar, whose specifications are provided in Table 3.3, were used. As shown in Figure 3.12, two manometers were installed in the experimental setup, one on the hydrocarbon-based gas line and the other on the hydrogen line.

Table 3.3. Technical specifications of the manometer

Manufacturer	Pakkens
Operating pressure	0 - 400 mbar
Operating temperature	Min. -20 °C / Max. +60 °C
IP (Ingress Protection) rating	IP 41
Maximum mechanical shock test load	15 kg
Nominal diameter of the pressure gauge	Ø 63 mm
Standard connection threads	G 1/4" B
Manufacturing standard	TSE EN 837-3
Calibration accuracy	CL 1,6 (Precision Types)



Figure 3.12. 0 - 400 mbar manometer

3.4.4. Backfire Flame Control Equipment

Direct use of gas discharged from the cylinder may pose serious safety risks within the system. If hydrocarbon-based gas is ignited in the burner without the use of proper safety equipment, the flame may propagate back through the hose and into the cylinder, potentially causing an explosion. To prevent such incidents, a backfire flame control device, also known as a flame arrester, was employed in the experiment. This equipment, illustrated in Figure 3.13, is a specially designed unit with a water capacity of 500 ml and features two 8 mm pneumatic connectors—one for the gas inlet and one for the outlet. In this setup, the gas enters at the bottom of the water-filled chamber, rises to the surface as bubbles, and proceeds to the burner through the outlet port. In the event of a potential flashback, the water in the chamber acts as a safety barrier, extinguishing the flame before it can reach the test tube.



Figure 3.13. Backfire flame control equipment

3.4.5. T-Burner

To ensure controlled combustion of the hydrocarbon-based gas/hydrogen mixture, a burner equipped with flow control valves and constructed from an anti-spark brass alloy and AISI 420 stainless steel was used. As illustrated in Figure 3.14, this burner is designed in a “T” configuration and is therefore referred to as a T-burner. One inlet of the burner is connected to the hydrocarbon-based gas line, while the other is connected to the hydrogen line, with flame formation occurring at the burner tip section. The inlet ports of the T-burner are fitted with stainless steel pneumatic components. Gas is delivered to these ports using transparent pneumatic hoses measuring 8×5.5 mm, rated for pressures up to 8 bar, which are securely connected to the pneumatic fittings on the burner. The burner is equipped with a total of three red-capped mini valves, consisting of two inlets and one outlet. The primary function of these valves is to regulate the flow rate and pressure of both gas streams.



Figure 3.14. Special design T-burner with needle tip on the platform

3.4.6. Battery and On-Off Switch

The other fuel line in the experimental setup is the hydrogen line, whose most critical component is the hydrogen (HHO) generation unit. For hydrogen production, a battery with a rating of 12 volts and 9 amperes, as shown in Figure 3.15, is used. In order to safely transmit the current from the battery without overheating, it is essential to use cables that are resistant to the applied voltage and current levels. Otherwise, the cable ends may overheat and burn, leading to potential safety hazards. For these reasons, the experiment utilized insulated, 6 mm² single-core copper electrical cables of the Prysmian brand, which comply with fire reaction performance standards.

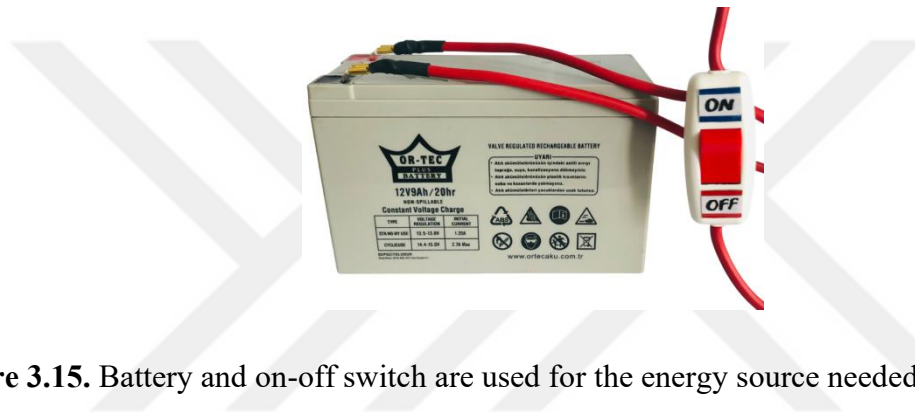


Figure 3.15. Battery and on-off switch are used for the energy source needed for electrolysis

The primary function of the battery is to provide the electric current required for ion transfer between the probes within the hydrogen generation unit. To control the current flow from the battery to the hydrogen generation unit, an on/off switch was installed at the intermediate connection point, as shown in Figure 3.15.

3.4.7. Probes Used as Anode and Cathode

Hydrogen production is achieved using a 1-liter capacity plastic container, within which two A2 304-grade stainless steel rods, each 6 mm in diameter and 200 mm in length, are mounted at equal distances (Figure 3.16). A total of 32 stainless steel washers, each Ø40×8×1 mm in size and made of 304-grade stainless steel, are installed on these rods. The washers are secured in place using 34 nuts (M6 size) and 64 mini washers (Ø12×6×1 mm), all made of A2 304-grade stainless steel. The probes, also referred to as electrodes, are positioned through the plastic lid using sealing materials such as gaskets and silicone. The part of the probe connected to the positive terminal of the battery functions as the anode, while the part connected to the

negative terminal functions as the cathode. Additionally, to prevent short-circuiting by avoiding contact between the probes, the distance between them is fixed and adjusted using a plastic support apparatus placed at the bottom.



Figure 3.16. Probes used as anode and cathode

3.4.8. Distilled Water

The plastic container in which the probes were placed was filled with 0.95 liters of distilled water (Figure 3.17).

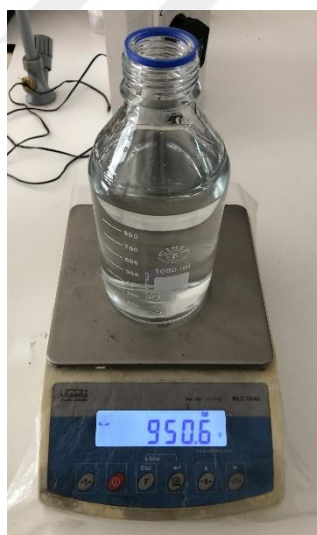


Figure 3.17. Distilled water used in the experiment

The main reason for using distilled water contains fewer foreign compounds, making it more purified than normal water. Another important factor is the absence of chlorine, which prevents the formation of chlorine gas during the reaction, thereby allowing the production of pure

hydrogen gas. Although distilled water exhibits lower electrical conductivity than normal water, its conductivity was enhanced by the addition of an electrolyte. Table 3.4 gives the technical specifications of the distilled water used in the experiment.

Table 3.4. Specifications of the distilled water

Properties	Notes
Manufacturer	Medisin Pharma (Povilon)
Appearance	Colorless, odorless, clear liquid
Production method	Modern reverse osmosis
Purity level	99.9 %
Electrical conductivity	~ 0
Ph degree	6.5 - 7.0
Boiling point	100 °C
Freezing point	0 °C
Density	~ 0.998 g/cm ³ (at 4 °C)

3.4.9. Electrolyte

To prepare the electrolyte solution, 50 grams of NaOH were added to 0.95 liters of distilled water to enhance conductivity, ensuring a homogeneous mixture (Figure 3.18). This mixture can also be prepared using KOH instead of NaOH, as an alternative. NaCl should not be used in the mixture, as it can lead to the release of chlorine gas during electrolysis.



Figure 3.18. Granulated sodium hydroxide is used as an electrolyte

3.4.10. Hydrogen Production Unit

The hydrogen gas (HHO) released as a result of the electrolysis process occurring within the hydrogen production unit (Figure 3.19) was directed through a pneumatic apparatus and a hose mounted on the plastic cap. Following this stage, the pressure of the generated gas was measured using a manometer (Figure 3.12) and then transferred to the backfire flame control

unit (Figure 3.13). This mechanism operates in the same manner as the one used in the other line. Hydrogen, being the smallest atom found in nature, possesses a highly explosive character. Therefore, the backfire flame control units are among the most critical components of the experimental setup.



Figure 3.19. Hydrogen production unit

3.4.11. Thermal Camera

In the experiment, a thermal camera of the Testo 875 model shown in Figure 3.20 was used to examine the flame temperature distribution, geometry, and flame characteristics. Thermal cameras operate by detecting infrared radiation emitted by objects, and since they are sensitive to heat rather than visible light, they are capable of capturing images even in complete darkness.



Figure 3.20. Thermal camera

3.4.12. Magnetic Stirrer

The ISOLAB magnetic stirrer was used to mix distilled water with sodium hydroxide. This device operates by generating a magnetic field, which rotates a flat-shaped magnetic stir bar placed inside the mixing vessel. Through the rotation of this stir bar at the desired speeds, the electrolyte solution was mixed homogeneously. As shown in Figure 3.21, sodium hydroxide and distilled water were mixed until a homogeneous solution was achieved at a stirring speed of 1000 revolutions per minute (rpm).



Figure 3.21. Magnetic stirrer

3.4.13. Precision Balance

The use of RADWAG WLC 20/A2 precision balance ensures accurate measurement of both distilled water and the added electrolyte material (NaOH). The device shown in Figure 3.22 is capable of performing measurements with a precision of ± 0.1 g.

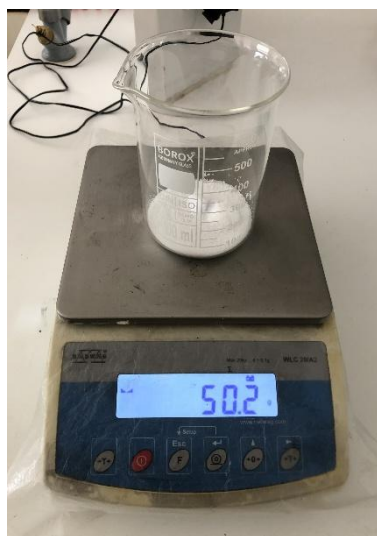


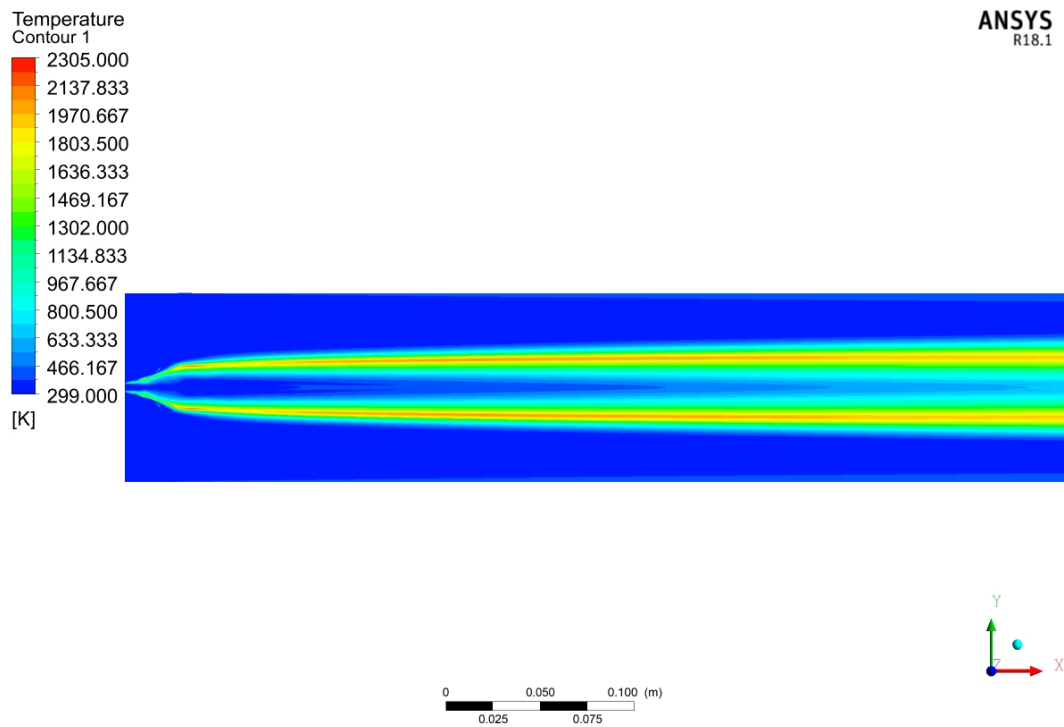
Figure 3.22. Precision balance

4. RESULTS AND DISCUSSION

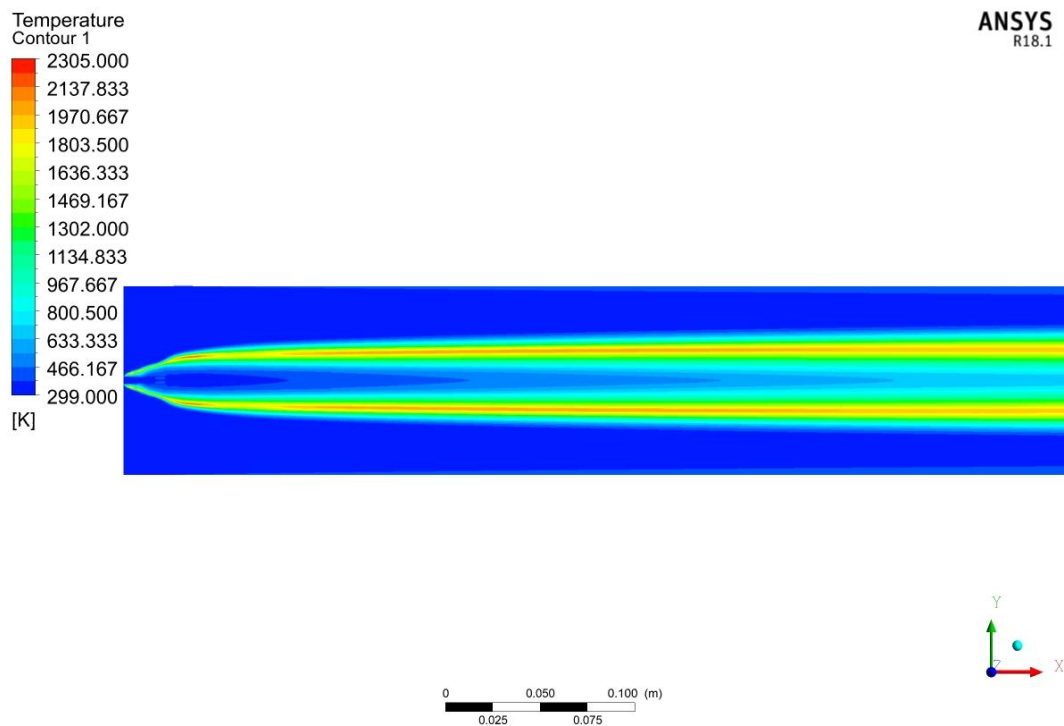
In this thesis, CFD analyses were conducted using ANSYS Fluent to evaluate the flame characteristics resulting from the enrichment of methane fuel with low hydrogen concentration increases in the specially designed burner. Furthermore, a predictive model for maximum flame temperatures was developed using Artificial Neural Networks (ANN). To verify the accuracy of the maximum temperature obtained for pure methane combustion, validation was performed based on experimental studies available in the literature. Additionally, the results of experimental studies carried out within the scope of the thesis were also evaluated. Under this section, CFD analysis results, ANN prediction outcomes, validation data, and experimental findings are presented through figures, tables, and graphical representations.

4.1. CFD-Based Analysis Results of the Study

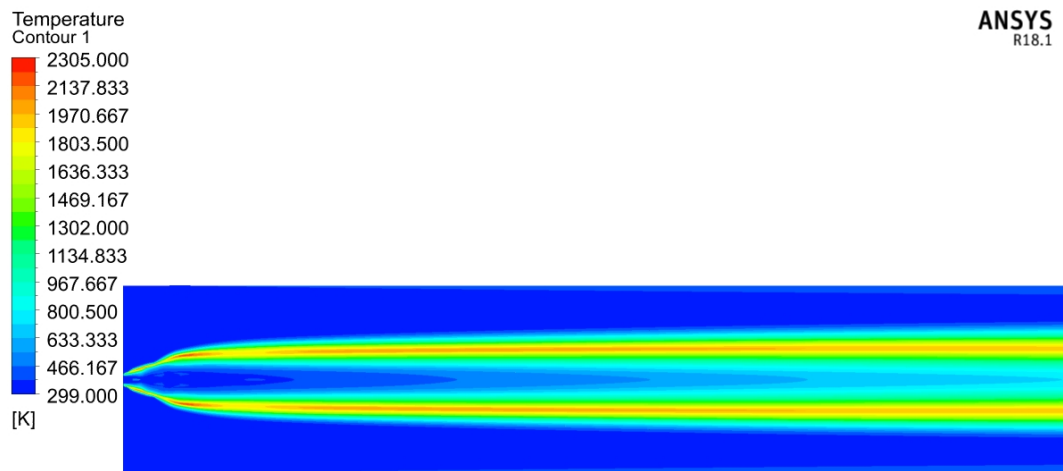
The flame temperature values resulting from the use of methane-hydrogen blended fuel in the burner shown in Figure 3.1 were analyzed through CFD. In the study, pure methane was initially used, followed by enrichment of the fuel mixture with hydrogen in 2.5% increments. These concentration increases, ranging from 0% to 30%, were analyzed through 13 different simulations. The resulting flame temperature distributions from the combustion reactions are presented in Figure 4.1.



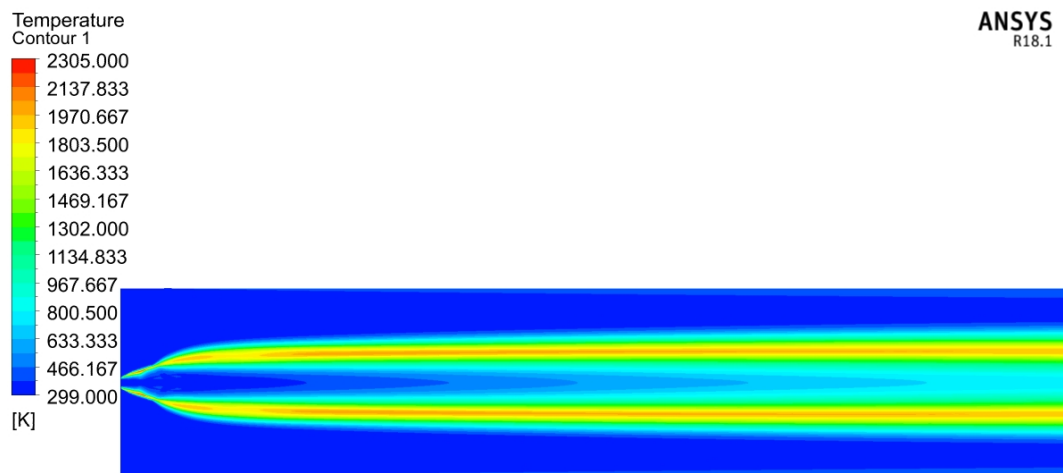
a) 0 % Hydrogen – 100 % Methane



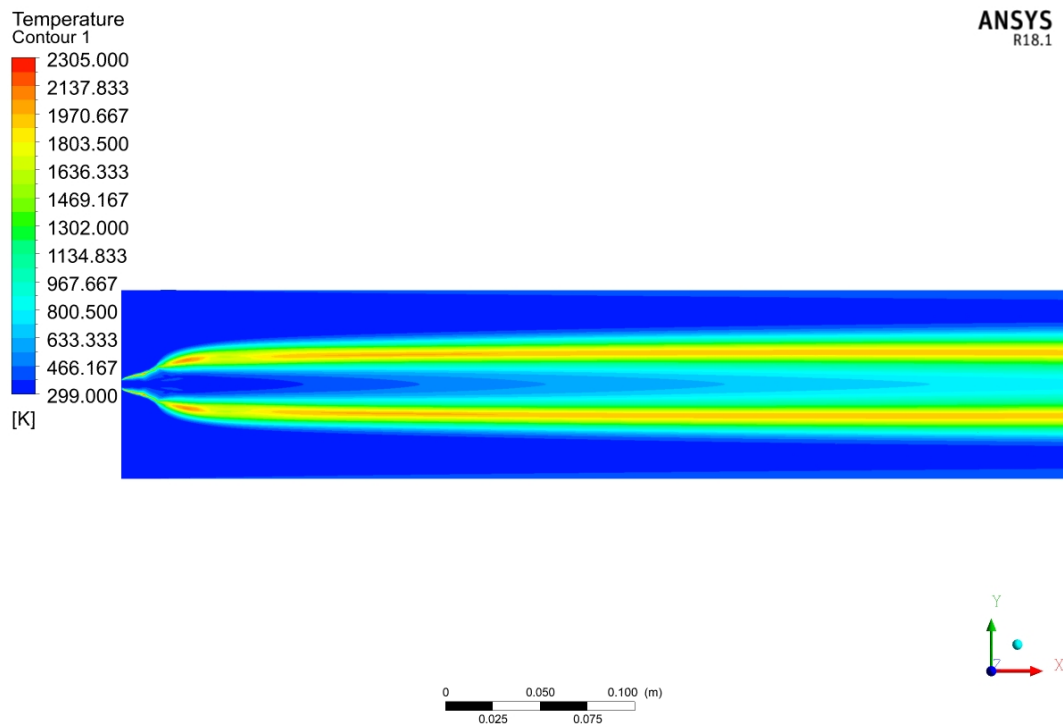
b) 2.5 % Hydrogen – 97.5 % Methane



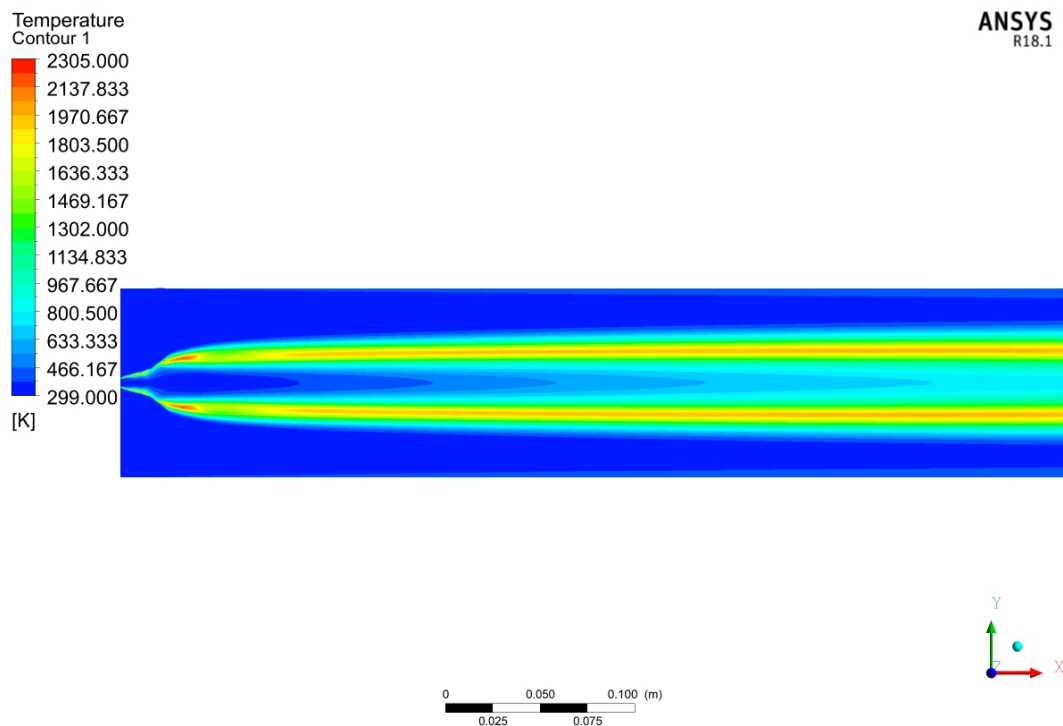
c) 5 % Hydrogen – 95 % Methane



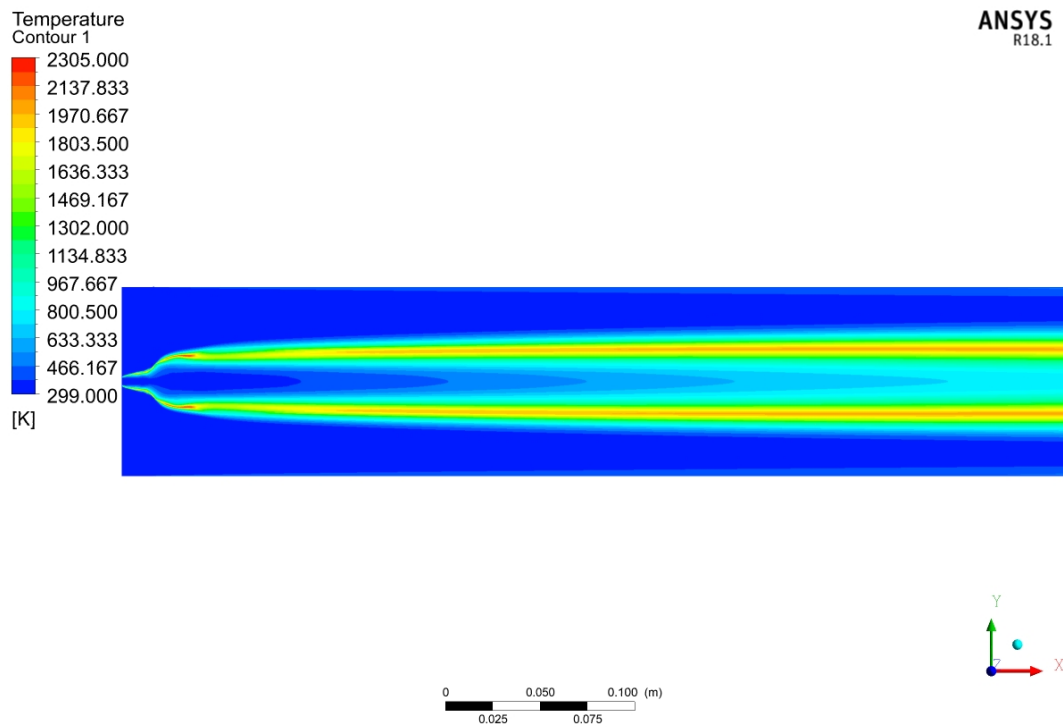
d) 7.5 % Hydrogen – 92.5 % Methane



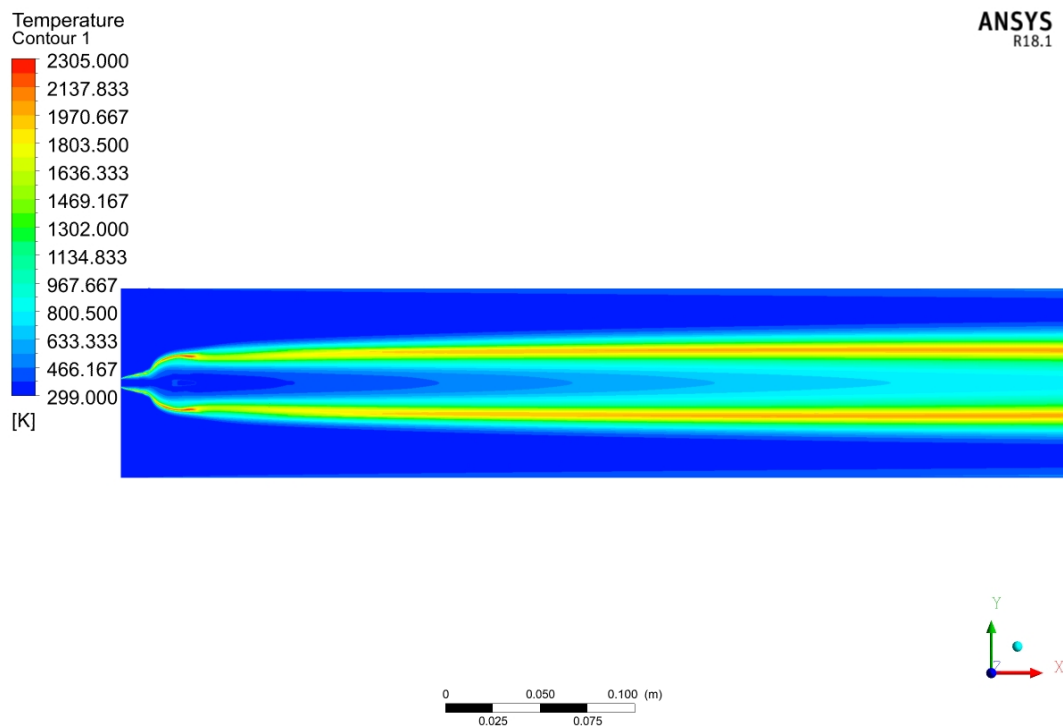
e) 10 % Hydrogen – 90 % Methane



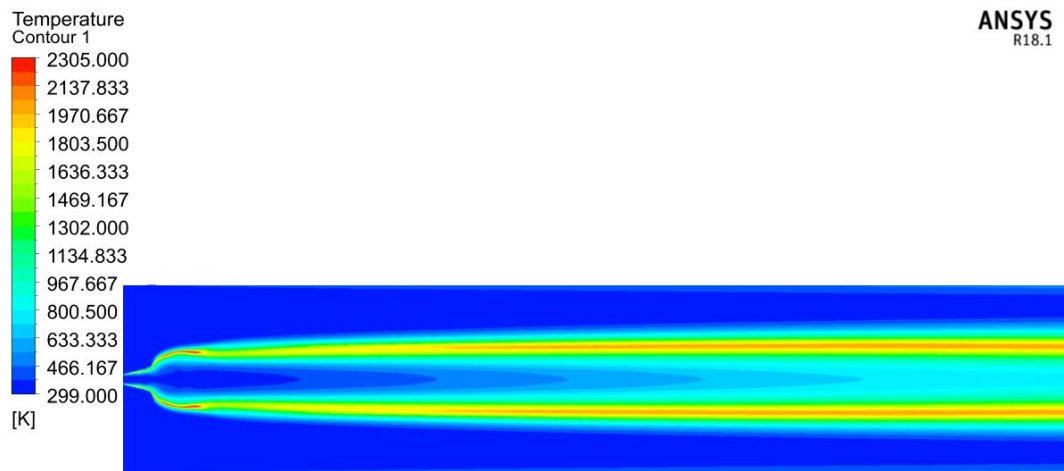
f) 12.5 % Hydrogen – 87.5 % Methane



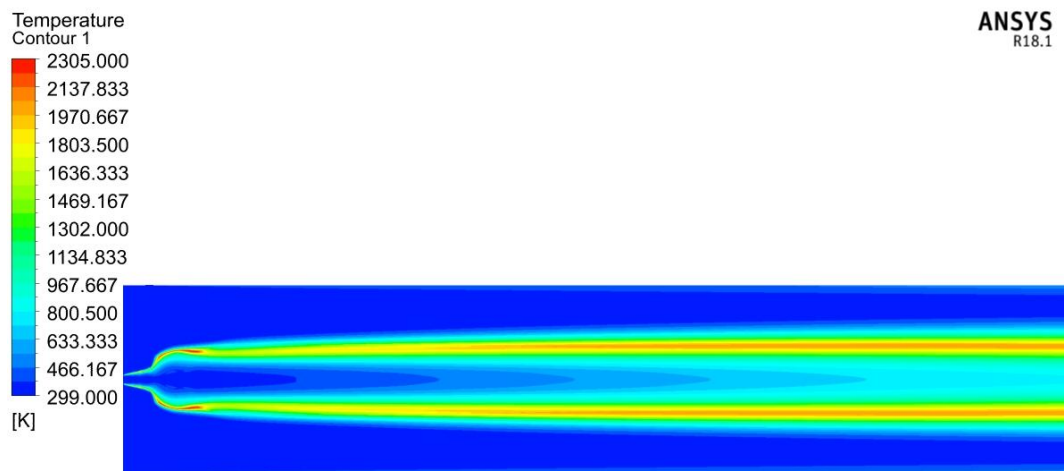
g) 15 % Hydrogen – 85 % Methane



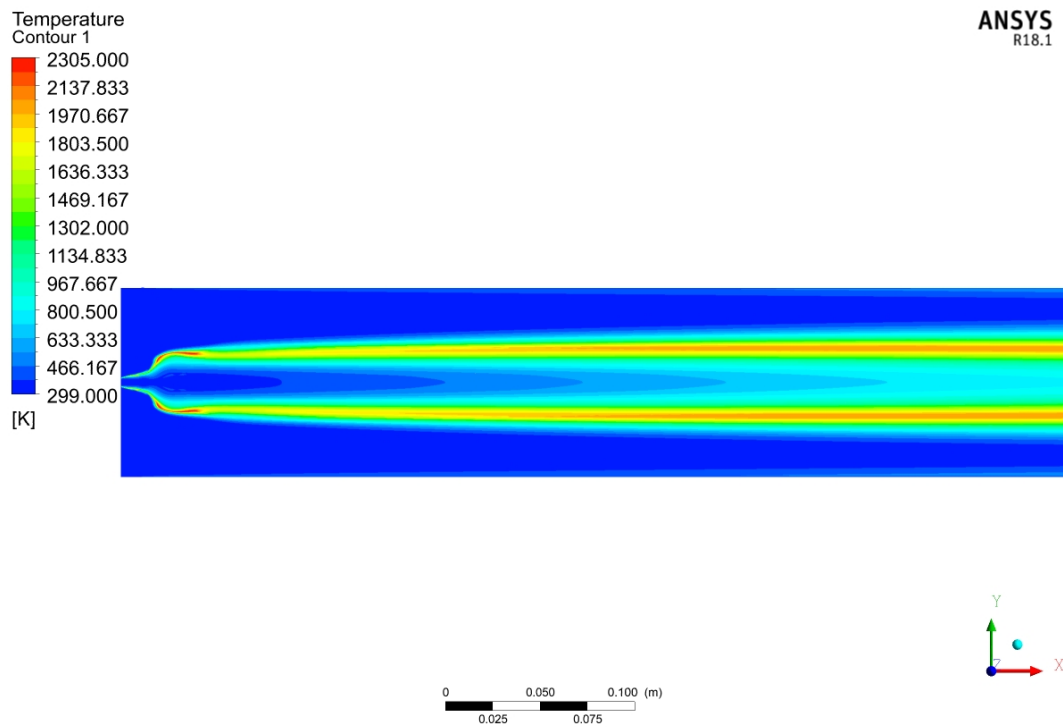
h) 17.5 % Hydrogen – 82.5 % Methane



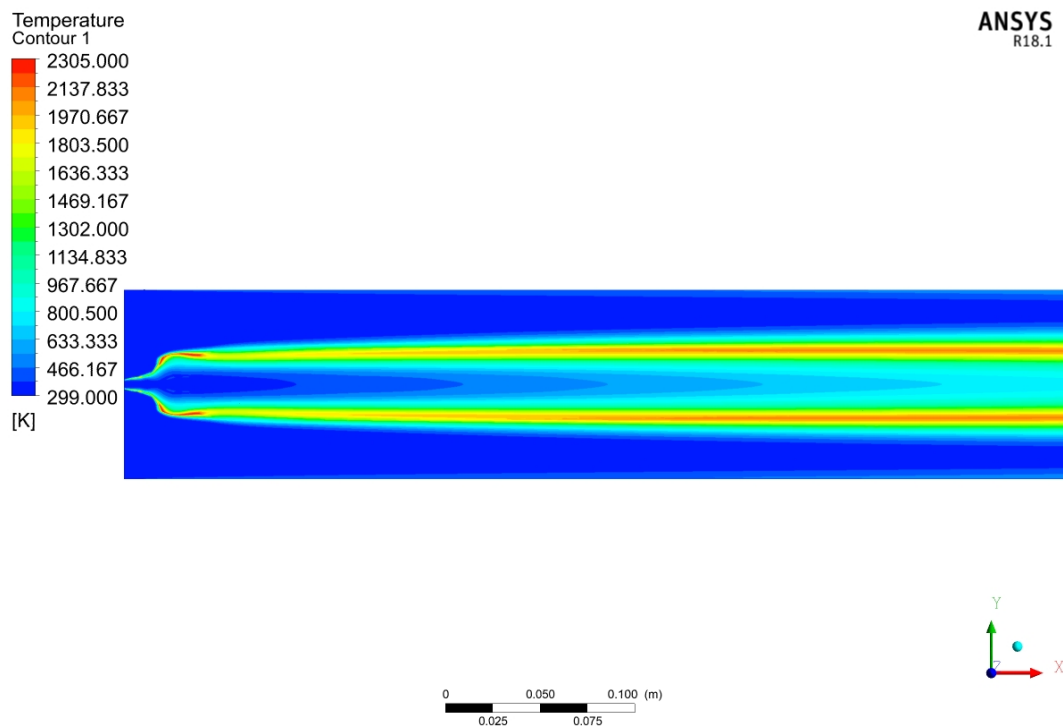
i) 20 % Hydrogen – 80 % Methane



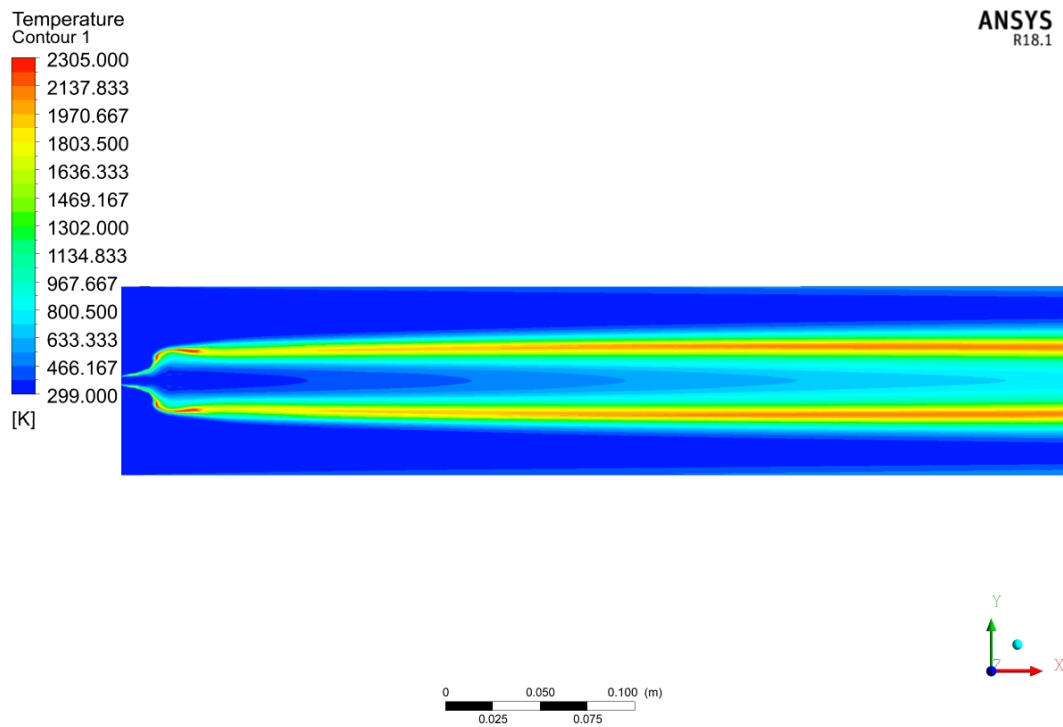
j) 22.5 % Hydrogen – 77.5 % Methane



k) 25 % Hydrogen – 75 % Methane



l) 27.5 % Hydrogen – 72.5 % Methane



m) 30 % Hydrogen – 70 % Methane

Figure 4.1. Combustion temperature distribution of the burner at different fuel input rates

The flame distribution and geometry resulting from the combustion reaction are shown in Figure 4.1. According to the fixed temperature scale ranging from 299 K to 2305 K, the flame temperatures vary depending on the hydrogen concentration in the fuel mixture. The flame structure exhibited an increase in temperature along the upper and lower regions parallel to the burner axis. In particular, an increase in flame width was observed at the burner inlet as the hydrogen content increased, with higher flame temperatures occurring in these regions. Similar findings were reported by Öztuna and Büyükkakın (2020), who noted that the addition of hydrogen to methane led to an expansion in the flame structure due to the resulting combustion reaction. They concluded that enriching methane with hydrogen reduces flame density and increases flow velocity, thereby causing the flame to widen.

Maximum flame temperatures, one of the core research topics of this study, represent a highly significant parameter in both academic research and the industrial sector. In hydrogen burner design, one of the critical factors is the maximum flame temperature resulting from combustion reactions. This parameter influences multiple aspects of burner design and has direct

implications for environmental factors such as radiation and emissions. Therefore, the analyses conducted in this study serve as a valuable reference for researchers working in this field.

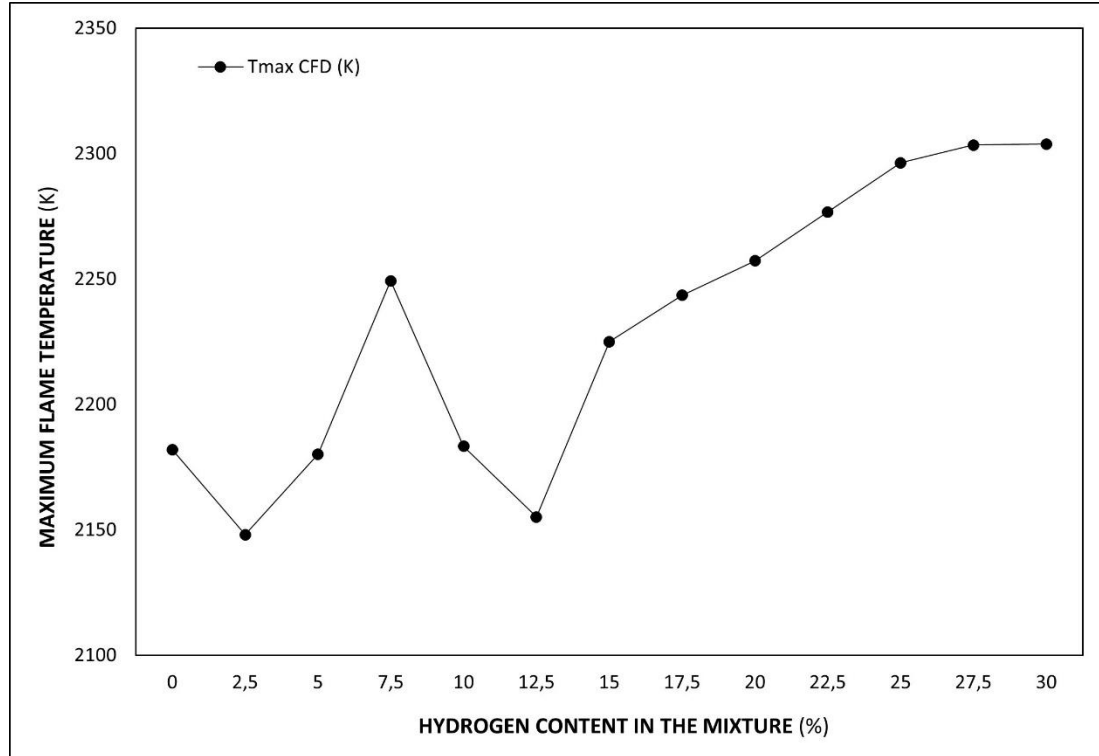


Figure 4.2. Effect of hydrogen enrichment on maximum flame temperature in methane-based combustion

The effect of varying hydrogen fuel ratios added to methane on the maximum flame temperature resulting from the combustion reaction is presented in Figure 4.2. Upon examining these values, it is observed that irregular temperature distributions occurred when hydrogen was added up to 12.5%. However, at hydrogen concentrations of 15% and above, a consistent increase in maximum flame temperatures was recorded. This behavior is attributed to the expansion of the diffusion flame structure caused by hydrogen, which, in the burner model used in this study, enhances the mixing ratios of reactants and combustion products. Consequently, at these hydrogen concentrations, a decrease in the maximum flame temperature is observed. A similar phenomenon was reported in a study involving a methane-hydrogen mixture, where the researchers observed a drop in flame temperatures for hydrogen concentrations below 15%, while consistent increases in flame temperatures were obtained for concentrations above 15%.

The authors attributed this behavior to the burner and flame structure used in their study (Öztuna & Büyükakın, 2020).

According to the results obtained in the study, the maximum temperature recorded with the use of pure methane gas was 2181.98 K. Based on the conducted analyses, the highest temperature value was observed at 2303.82 K with a 30% hydrogen blending ratio, representing a 5.584% increase compared to the pure methane flame temperature. As shown in Figure 4.2, the maximum flame temperature resulting from the combustion reaction peaked at 30% hydrogen addition and exhibited an axial increase. In other words, the temperature difference between the 27.5% and 30% hydrogen blending ratios is minimal. This suggests that beyond these points, the methane-hydrogen mixture may begin to exhibit rich mixture characteristics. An experimental study on hydrogen enrichment of methane similarly indicated that a 30% hydrogen and 70% methane mixture could serve as an alternative fuel for existing combustion systems (Ilbas, Crayford, Yılmaz, Bowen, & Syred, 2006)

Table 4.1. Axial temperature values of the burner at the different fuel contents

Fuel content in the burner (%)		Temperature values measured from some points on the burner axis and the maximum temperature value in the burner (K)										
H ₂	CH ₄	T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	T ₉	T ₁₀	T _{max}
0 %	100 %	300.000	369.839	390.901	422.678	457.353	456.435	502.318	567.576	610.735	638.731	2181.980
2.5 %	97.5 %	300.000	348.186	427.742	440.597	504.068	545.834	572.134	609.212	658.284	655.595	2148.103
5 %	95 %	300.000	374.836	424.422	447.363	499.339	547.557	592.79	642.855	687.593	673.676	2180.221
7.5 %	92.5 %	300.000	362.911	400.114	453.372	525.377	582.98	634.897	682.089	722.991	698.243	2249.331
10 %	90 %	300.000	319.315	403.553	478.868	547.229	599.852	645.255	689.804	730.321	713.97	2183.342
12.5 %	87.5 %	300.000	325.173	398.708	468.256	540.251	605.381	651.614	691.042	727.176	732.936	2155.155
15 %	85 %	300.000	351.588	395.351	458.805	523.69	585.251	642.234	688.263	720.848	744.668	2225.040

17.5 %	82.5 %	300.000	350.758	401.063	464.35	530.292	594.138	652.868	704.721	738.514	763.643	2243.561
20 %	80 %	300.000	346.576	400.851	466.42	533.472	600.258	661.374	714.775	754.482	778.783	2257.255
22.5 %	77.5 %	300.000	348.314	400.024	465.466	529.34	596.329	657.745	712.746	758.425	784.123	2276.786
25 %	75 %	300.000	354.636	397.049	461.064	522.911	587.959	647.248	702.431	747.894	779.316	2296.366
27.5 %	72.5 %	300.000	352.709	392.93	452.863	512.294	572.58	629.13	681.107	725.354	756.044	2303.368
30 %	70 %	300.000	346.149	390.304	446.433	504.313	560.435	612.223	658.635	700.77	728.282	2303.820

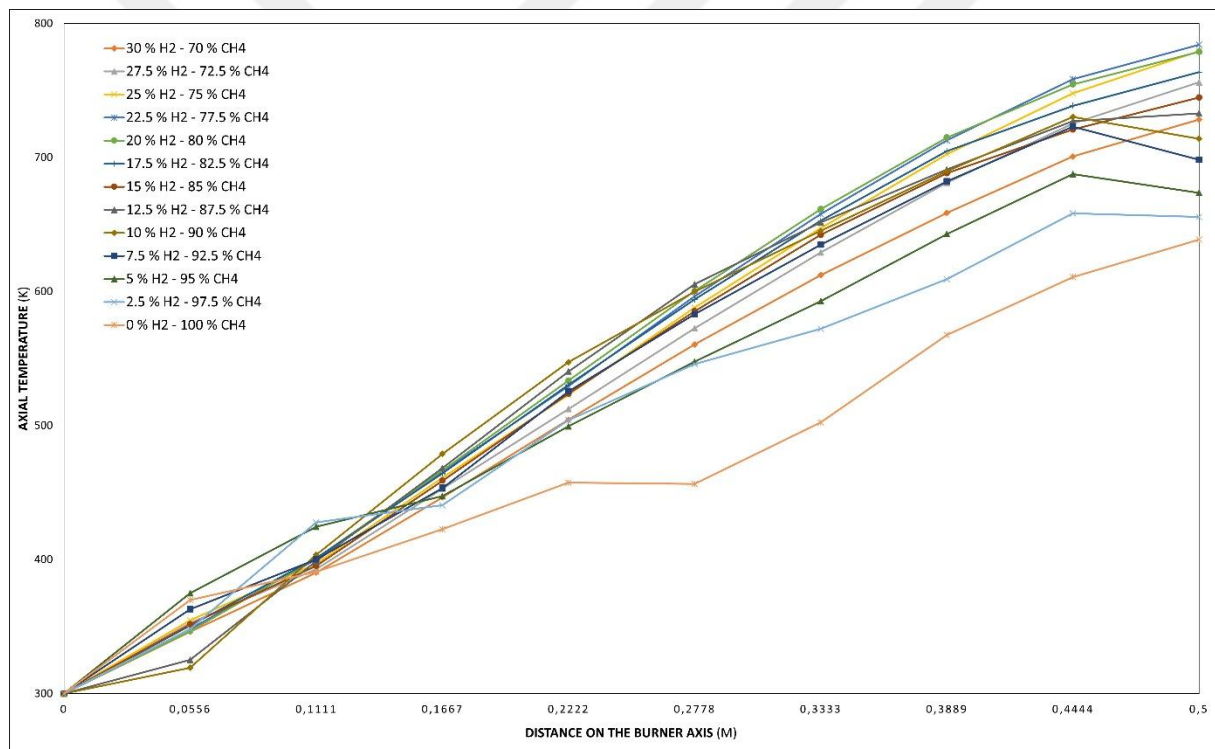


Figure 4.3. Axial temperature profiles at varying hydrogen concentrations

Table 4.1 presents the temperature values measured along the burner axis for different methane-hydrogen mixture percentages. During this study, values were obtained from 10 equally spaced points along the burner axis, as schematically illustrated in Figure 3.2. These results were compared and graphically represented in Figure 4.3. The collected data indicate that increasing hydrogen concentration leads to a rising trend in the temperature distribution along the burner

axis. The temperature curves in Figure 4.3 exhibit similar formations, and the temperatures tend to consolidate horizontally toward the downstream end of the burner. Since this axial increase remains below the maximum flame temperatures, it does not pose any adverse effects on the burner. To better understand the observed increase in axial temperatures, which range from 300 K to 779.316 K depending on the hydrogen ratio, it is necessary to examine the physical and chemical properties of hydrogen. When these properties are considered, it is known that the lower heating value of hydrogen is 118.8 MJ/kg (Table 1.1), whereas this value for methane is 50 MJ/kg (Habib, Abdulrahman, Alquaity, & Qasem, 2024). Therefore, during combustion, hydrogen releases significantly more energy compared to an equivalent amount of methane, resulting in a greater increase in reaction temperature. Hydrogen combustion occurs very rapidly, with a reported laminar flame speed of approximately 3.06 m/s. This is nearly eight times higher than that of methane, which has a laminar flame speed of around 0.37 m/s (Figure 1.3). This rapid combustion leads to higher energy density and, consequently, elevated temperatures. Additionally, due to its chemical structure, hydrogen exhibits highly reactive characteristics. It rapidly generates radicals such as H, O, and OH, which accelerate the reaction kinetics and result in a more intense energy release within a shorter time frame. Moreover, hydrogen's high diffusivity enables better mixing with oxygen, promoting more homogeneous combustion. As a result, the increase in hydrogen concentration leads to a corresponding rise in temperature.

Studies examining the combustion specifications and emission characteristics of natural gas-fueled household gas stoves with hydrogen concentrations of 0%, 10%, 20%, and 30% (Ozturk, Sorgulu, Javani, & Dincer, 2023; Sorgulu, Ozturk, Javani, & Dincer, 2023), gas water heaters (Choudhury, McDonell, & Samuelsen, 2020; Zhan, Chen, & Qin, 2022), and wall-mounted gas boilers (Yan, Gao, Zhang, & Zhang, 2018) have shown that an increase in hydrogen concentration leads to a gradual decrease in the primary air coefficient, heat load, and CO and NO_x content in the exhaust gases (İlbaş & Candan, 2023; Sahin, Doner, & İlbaş, 2024), while thermal efficiency progressively increases.

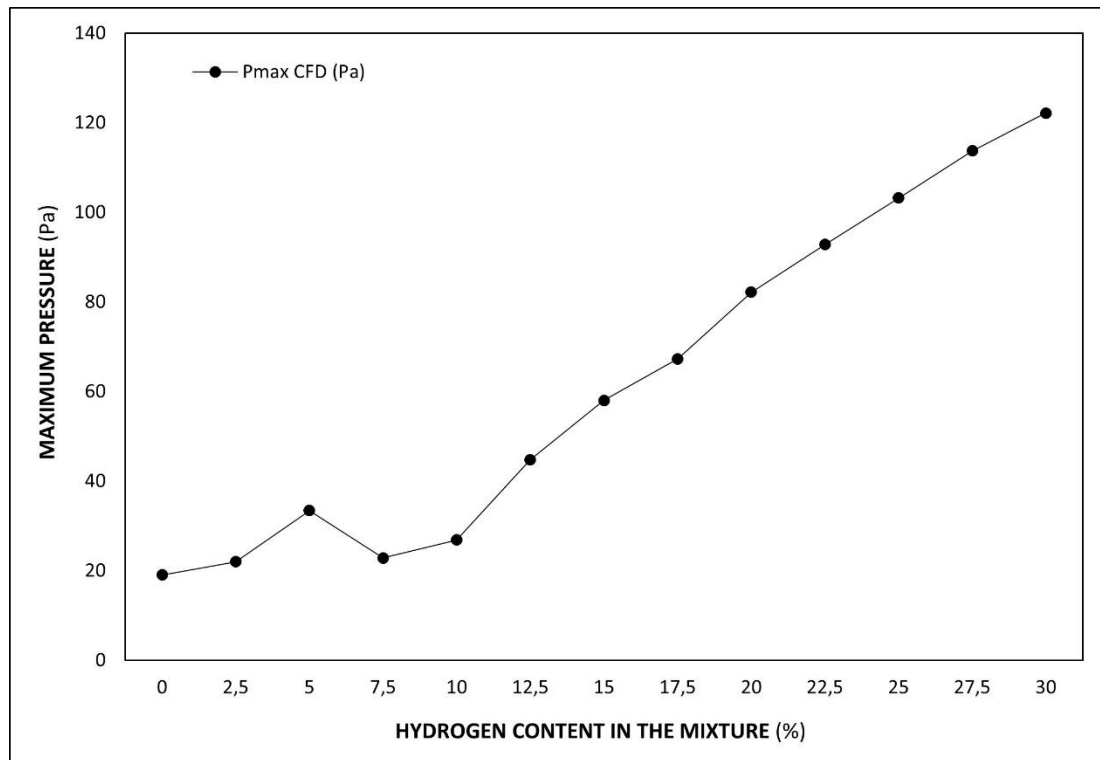


Figure 4.4. Peak pressure behavior in the burner with varying hydrogen fractions

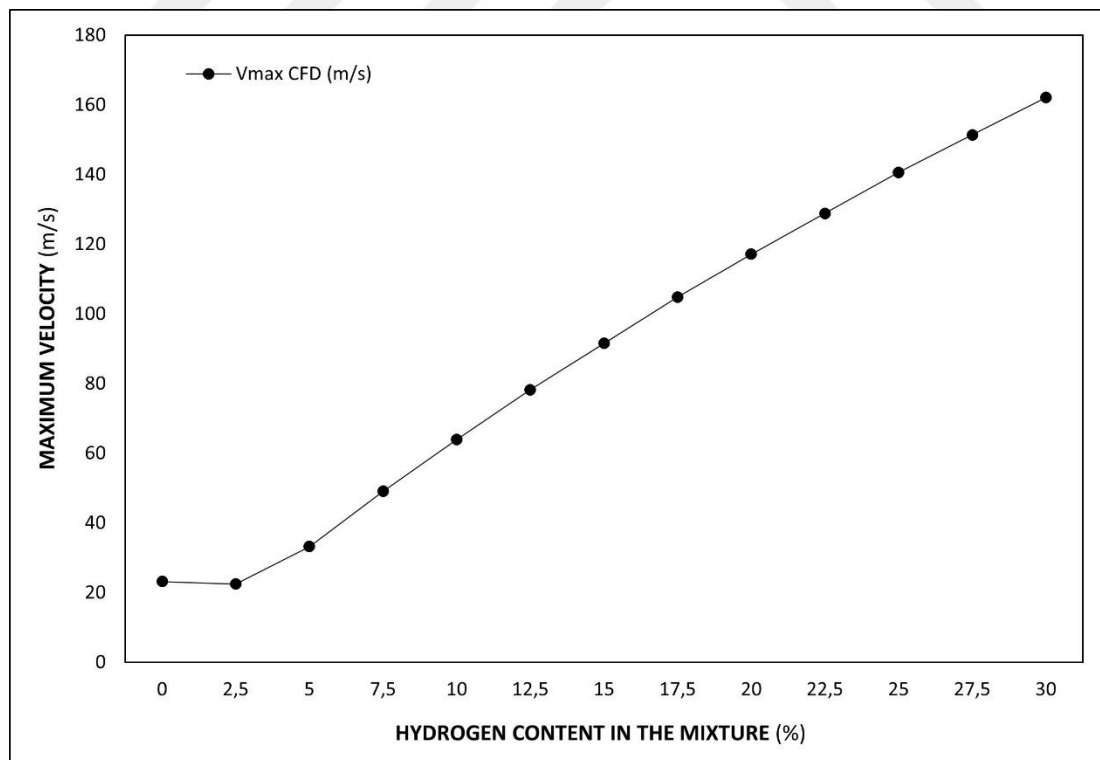


Figure 4.5. Peak velocity behavior in the burner with varying hydrogen fractions

Table 4.2. Maximum pressure and velocity measurements in the combustion chamber for different fuel compositions

Fuel content in the burner (%)		The maximum pressure and velocity values in the burner	
H ₂	CH ₄	P _{max} (Pa)	V _{max} (m/s)
0 %	100 %	19.081	23.166
2.5 %	97.5 %	22.003	22.502
5 %	95 %	33.409	33.244
7.5 %	92.5 %	22.842	49.099
10 %	90 %	26.856	63.931
12.5 %	87.5 %	44.779	78.252
15 %	85 %	58.038	91.550
17.5 %	82.5 %	67.318	104.847
20 %	80 %	82.205	117.122
22.5 %	77.5 %	92.828	128.885
25 %	75 %	103.217	140.649
27.5 %	72.5 %	113.751	151.390
30 %	70 %	122.155	162.130

The maximum pressure and velocity values resulting from combustion in the chamber for different hydrogen blending ratios are presented in Figures 4.4 and 4.5, respectively. Upon examining these results, it is observed that the increase in hydrogen concentration leads to a local rise in maximum pressure due to the corresponding increase in flame temperature. However, due to the open-ended burner structure used in the study, the resulting pressure remains close to atmospheric pressure or only slightly above it. As shown in Table 4.2, the highest pressure and flow velocity values were obtained with a mixture of 70% methane and 30% hydrogen. The maximum flow velocity was measured as 162.13 m/s, and it was found that increasing the hydrogen ratio in the fuel mixture directly contributes to an increase in flow velocity.

This phenomenon can be attributed to two main reasons. First, when considering the open-ended burner used in the study and applying the ideal gas law, the rise in reaction temperature causes gas expansion, which increases the thrust force. As the thrust increases, so does the

kinetic energy of the gas, resulting in higher flow velocity. The second reason is that hydrogen, compared to methane, has a lower molar mass—meaning it is a lighter gas—with a higher diffusion coefficient, which enhances its fluidity. Furthermore, the high combustion chamber temperatures resulting from hydrogen combustion also play a significant role in increasing the flow velocity.

In a study conducted on a closed system spark-ignition (SI) engine, it was reported that maximum pressure values exhibited an increasing trend with higher hydrogen addition in the mixture (Molina, Novella, Gomez-Soriano, & Olcina-Girona, 2021). Additionally, in both experimental and numerical studies on methane-hydrogen mixtures, it was concluded that hydrogen addition to methane reduces flame density while increasing flow velocity (Öztuna & Büyükkakın, 2020).

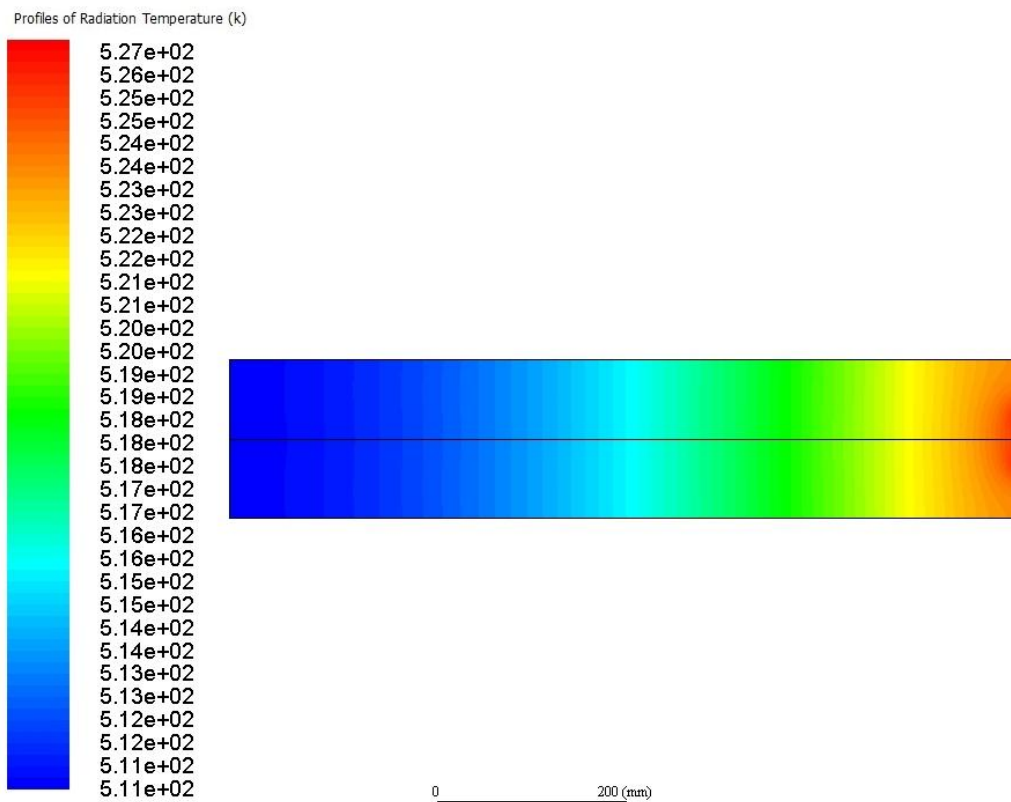


Figure 4.6. Radiation temperature profiles for a 30% Hydrogen – 70% Methane fuel mixture

Radiation temperature is a hypothetical temperature related to the amount of radiative energy emitted by or absorbed from the surroundings by a surface, and it is a significant parameter, particularly in systems where high temperatures are present, such as combustion chambers. The distribution of radiation temperature corresponding to the 30% hydrogen blending ratio—at which the maximum flame temperature was obtained—is presented in Figure 4.6. According to the analysis, the maximum radiation temperature was found to be 526.531 K. This result indicates that the system can emit heat as if it were surrounded by an environment at a temperature of 526.531 K. A study on combustion indicated that as the hydrogen concentration in the fuel mixture increases, heat loss due to radiation from the flame is expected to decrease. The study also determined that existing natural gas burners can operate with fuel containing up to 30% hydrogen without requiring major modifications (Yilmaz & İlbaş, 2008).

To control the amount of radiation generated as a result of combustion, it is essential to first regulate the flame temperature. Instead of using fuel-rich or fuel-lean mixtures, complete combustion should be achieved by minimizing excessive hydrogen usage. The concentrations of radiative gases such as H_2O and CO_2 should be reduced. Additionally, the flame should be positioned away from the burner surface, and a more compact and shorter flame structure should be preferred. Radiation-absorbing materials should be incorporated into the internal structure of the burner.

4.2. ANN Modeling Results of the Study

In this thesis, two different ANN models were employed. In the first model, only the fuel mixture ratios and temperature values were used as input parameters, as detailed in Table 3.1. In contrast, the second model incorporated multiple input parameters, including fuel mixture ratios, temperature (T), pressure (P), and velocity (V). The relative error rates of these prediction models compared to CFD results are presented in Table 4.3. In both prediction models, the maximum flame temperature (T_{max}) was defined as the target parameter. According to the table, the ANN model developed with multiple input parameters produced relative error rates ranging from 0.044% to 0.371%, indicating results that are very close to the actual values. On the other hand, in the ANN model where the input was limited to only the fuel mixture ratio and temperature, the relative error rates were significantly higher, ranging from -1.463% to 2.984%, demonstrating a more limited accuracy in approximating the real outcomes. This

finding can be explained by the general working principle of ANN models: as the diversity and number of input parameters increase, the learning capacity of the nonlinear model improves, enabling it to predict the target parameter more accurately (Haykin, 2009).

Table 4.3. Comparative analysis of relative errors between two ANN architectures

Fuel content (%)	T_{max} (K) (CFD)	T_{max} (K) (ANN with Fuel, T)	Relative error with Fuel and T (%)	T_{max} (K) (ANN with Fuel, T, P, V)	Relative error with Fuel, T, P, V (%)
0 100	2181.98	2198.455	0.755%	2184.77	0.128%
2.5 97.5	2148.103	2178.29	1.405%	2151.81	0.173%
5 95	2180.221	2245.268	2.984%	2181.19	0.044%
7.5 92.5	2249.331	2216.417	-1.463%	2250.48	0.051%
10 90	2183.342	2179.672	-0.168%	2186.45	0.142%
12.5 87.5	2155.155	2182.417	1.265%	2162.22	0.328%
15 85	2225.04	2233.151	0.365%	2229.12	0.183%
17.5 82.5	2243.561	2264.426	0.930%	2250.59	0.313%
20 80	2257.255	2269.467	0.541%	2260.67	0.151%
22.5 77.5	2276.786	2281.621	0.212%	2284.6	0.343%
25 75	2296.366	2293.546	-0.123%	2304.88	0.371%
27.5 72.5	2303.368	2295.944	-0.322%	2308.65	0.229%
30 70	2303.82	2295.259	-0.372%	2308.26	0.193%

Figure 4.7 presents both bar and line graphs of the maximum flame temperature ($T_{\max}$) values provided in Table 4.3. A strong correlation was observed between the CFD-derived $T_{\max}$ values and the predictions of the ANN model incorporating multiple input parameters. In contrast, the alternative ANN model demonstrated a lower level of agreement with the actual results. Notably, the model exhibited greater deviations in its predictions, particularly in cases where low hydrogen percentages (2.5%, 5%, and 7.5%) were used, indicating reduced accuracy under these conditions.

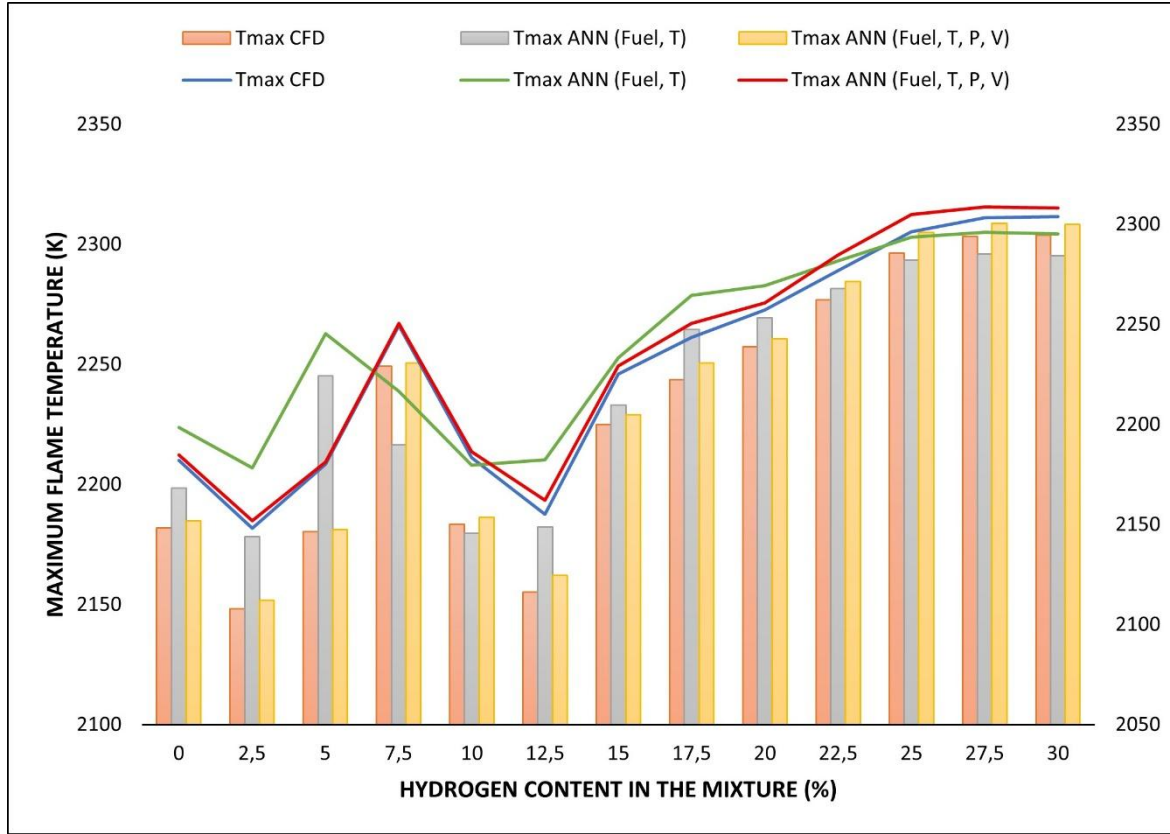


Figure 4.7. Relative error comparison between CFD results and ANN models developed using varying input sets

In industrial burner design, one of the most critical parameters to consider is the maximum temperature that will occur within the combustion chamber. This value directly influences a wide range of design factors, including material selection, burner wall thickness, and the configuration of inlet and outlet ports. Accordingly, the core focus of this study is to investigate the effect of hydrogen concentration on maximum flame temperatures, which were obtained using CFD simulations.

ANN models were developed to validate the accuracy of these temperature parameters. Furthermore, regression equations derived from the ANN approach offer a practical means of testing various fuel ratios in a shorter time frame, contributing to savings in both time and cost.

In Figure 4.8, an ANN prediction model was constructed using only fuel ratios and temperature values as input parameters, with the maximum temperature ($T_{\max}$) set as the target output. The model yielded a coefficient of determination (R^2) of 0.9155, indicating a prediction accuracy

of 91.55%. This result demonstrates consistency with the CFD findings, as an R^2 value close to 1 reflects a high degree of agreement between the predicted and simulated data.

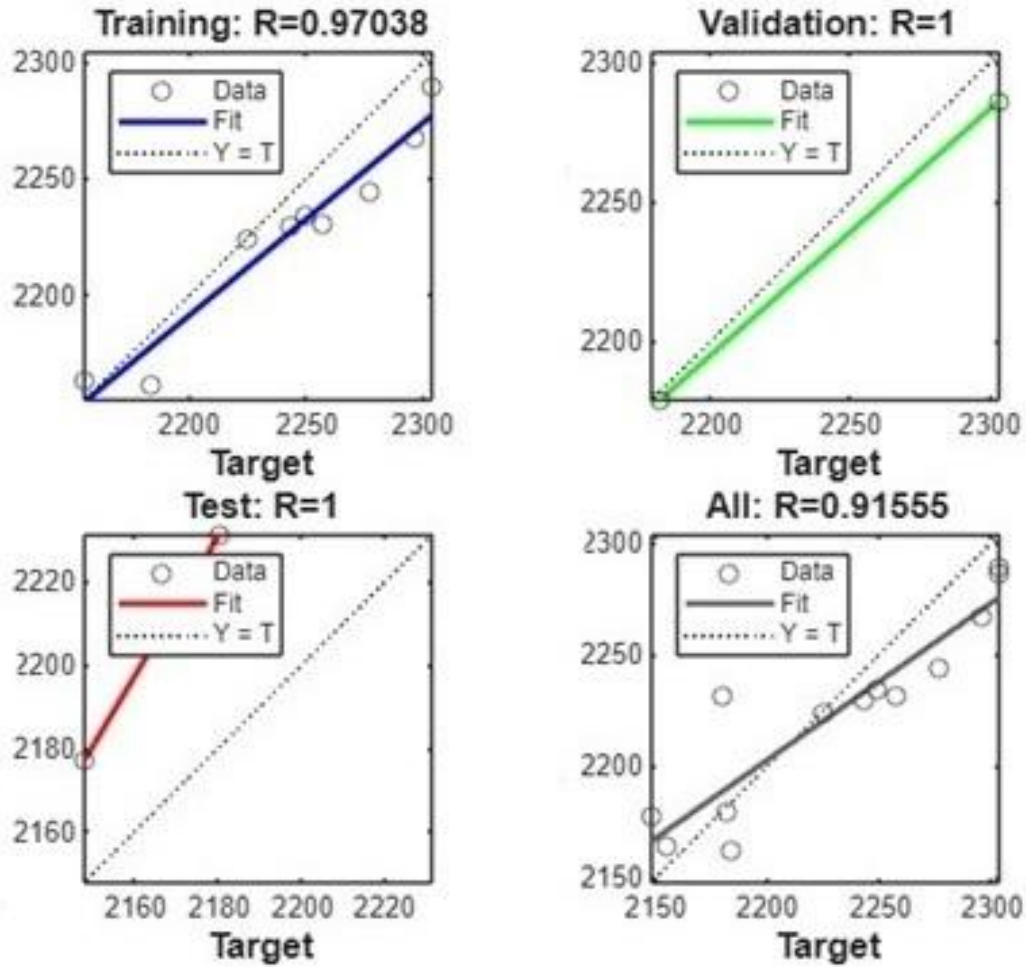


Figure 4.8. R error metrics of the ANN model for Fuel and T inputs

To enhance the ANN model's ability to better interpret the studied process and to improve its predictive performance on outcomes that are not correlated with each other, the number of input parameters was increased. These input parameters included fuel mixture ratios, temperature, pressure, and velocity, while the maximum flame temperature ($T_{\max}$) was designated as the target parameter. The primary objective of this study was to examine the differences between two distinct ANN prediction models. Based on the selected input parameters, the coefficient of determination (R^2) for the ANN model was calculated as 0.92537, as shown in Figure 4.9, corresponding to a prediction accuracy of 92.537%. This result indicates that the ANN model

with multiple input parameters predicted the target parameter, Tmax, 0.987% more accurately compared to the model with fewer input variables. In conclusion, it was observed that increasing the number of input parameters leads to a higher R^2 value, approaching 1, thereby enabling the development of a more accurate and robust prediction model.

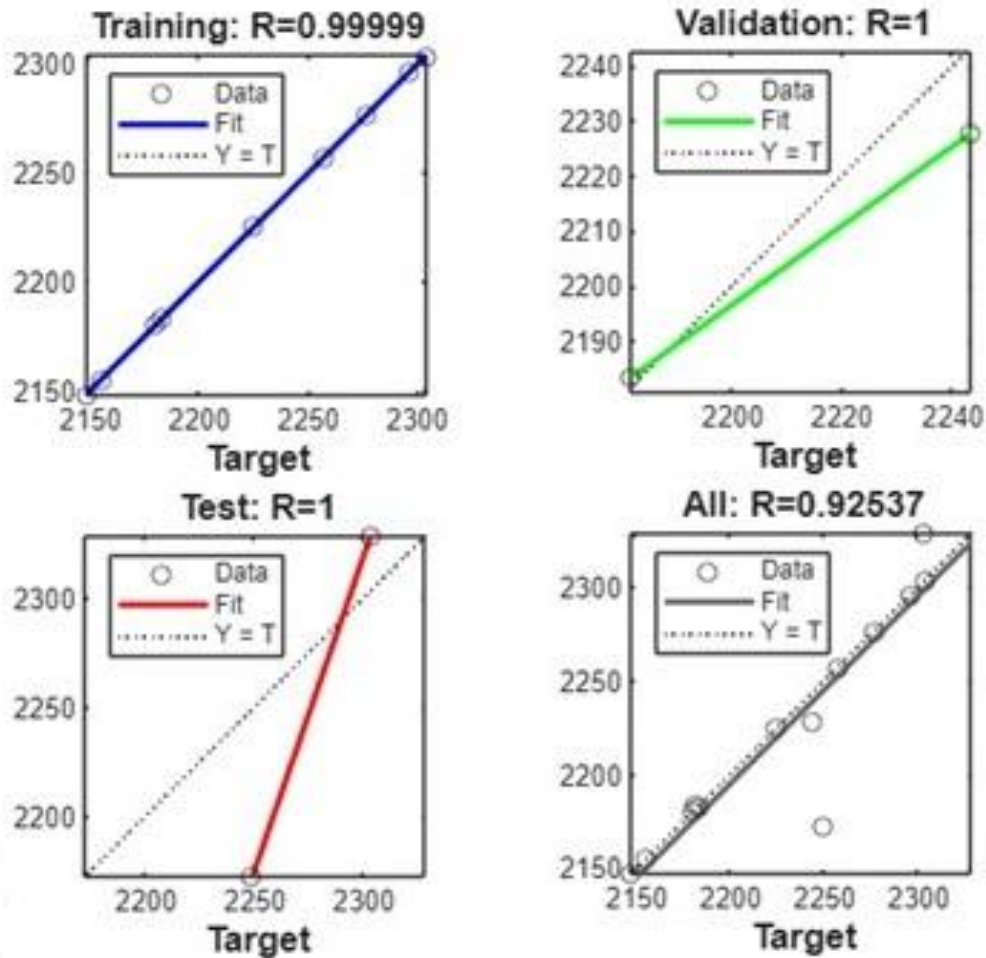


Figure 4.9. R error metrics of the ANN model for Fuel, T, P, and V inputs

In this study, the regression equations presented below were employed to model the relationship between dependent and independent variables. These equations enable the estimation of regression coefficients, the evaluation of model performance through goodness-of-fit metrics such as R^2 , MRE and RMSE, and the visualization of prediction curves alongside the observed data. Within the scope of this thesis, the regression equations, shown in Equations 4.1, 4.2, and 4.3, were obtained separately for temperature, pressure, and velocity, respectively. In these

equations, the parameter "T" represents temperature, "P" denotes pressure, "V" indicates velocity, and the parameter "H" corresponds to the hydrogen concentration in the mixture.

For temperature:

$$T_{\max} = -31746 + 7.31 * H_2 + 110.8 * T_1 + 1.96 * T_2 - 1.74 * T_3 + 0.76 * T_4 + 1.96 * T_5 - 3.63 * T_6 + 1.04 * T_7 + 1.48 * T_8 + 1.163 * T_9 - 1.55 * T_{10} \quad (4.1)$$

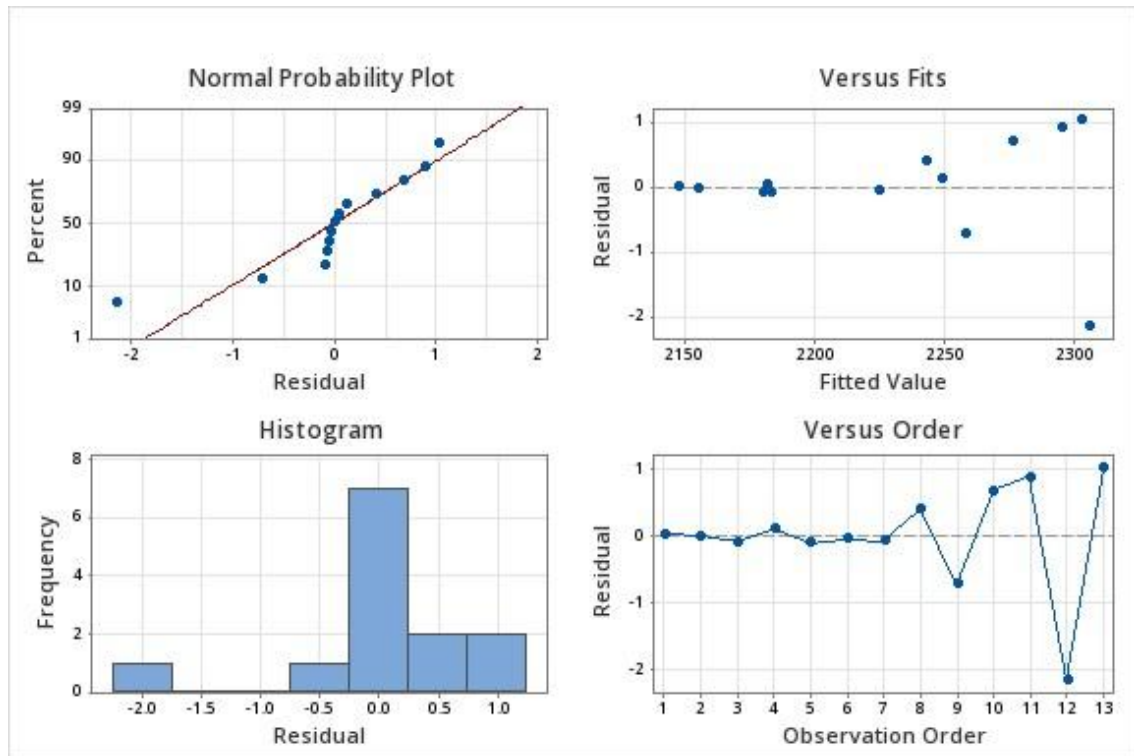


Figure 4.10. Residual plots for maximum temperature using temperature inputs

For pressure:

$$T_{\max} = 1265 - 27.3 * H_2 + 1.0 * P_1 - 10828 * P_2 + 41911 * P_3 - 64772 * P_4 + 29825 * P_5 + 19659 * P_6 - 682 * P_7 + 14449 * P_8 - 67967 * P_9 + 135314 * P_{10} \quad (4.2)$$

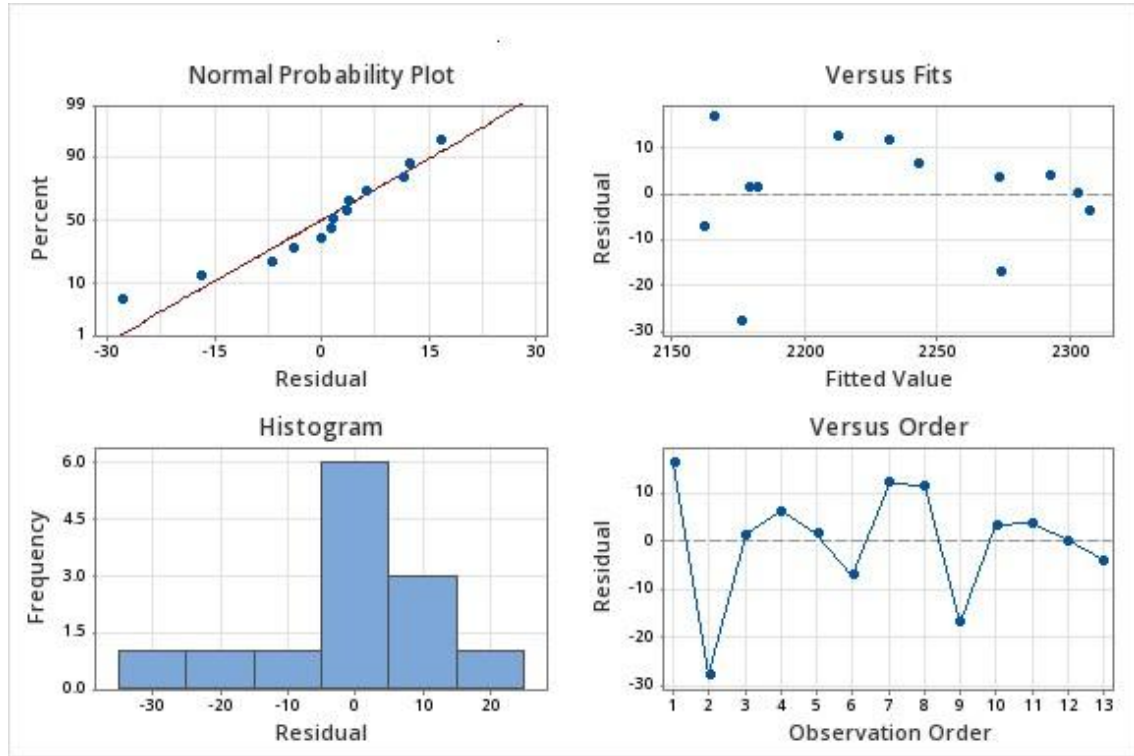


Figure 4.11. Residual plots for maximum temperature using pressure inputs

For velocity:

$$T_{\max} = -1599 + 229 * H_2 + 644 * V_1 + 5914 * V_2 - 4493 * V_3 - 5571 * V_4 - 17167 * V_5 + 8489 * V_6 + 5143 * V_7 - 3919 * V_8 + 3301 * V_9 + 988 * V_{10} \quad (4.3)$$

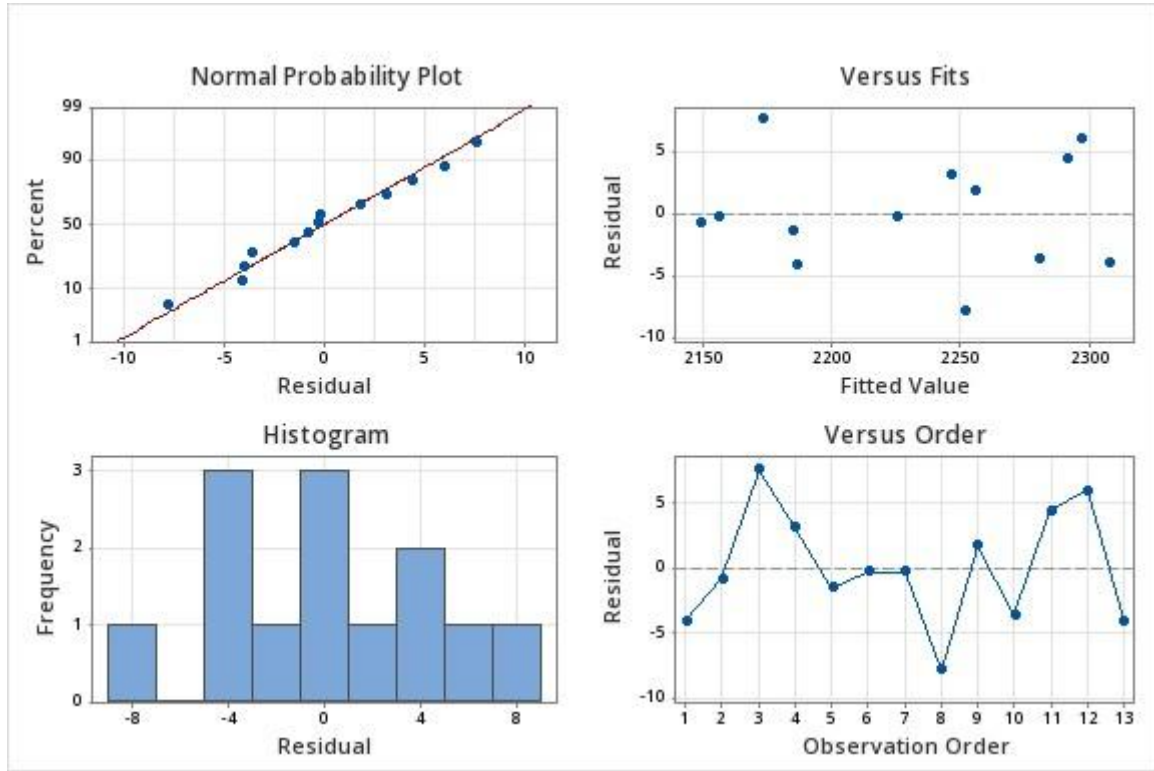


Figure 4.12. Residual plots for maximum temperature using velocity inputs

Figures 4.10, 4.11, and 4.12 were utilized to evaluate the validity of the regression models by analyzing the residuals obtained from the regression analyses conducted for temperature, pressure, and velocity, respectively. The regression model for temperature, as illustrated in Figure 4.10, explains 99.98% of the variability in $T_{\max}$ ($R^2 = 99.98\%$), indicating an excellent fit to the data. In a similar manner, the regression model for pressure presented in Figure 4.11 accounts for 95.36% of the observed variability ($R^2 = 95.36\%$), reflecting a strong model performance. Furthermore, Figure 4.12 depicts the regression model for velocity, which achieves an R^2 value of 99.38%, signifying that it successfully captures a substantial portion of the variance in $T_{\max}$, and thus indicates a highly reliable and consistent fit.

As shown in the equations above, separate regression models were developed for each independent parameter. The use of independent variables such as temperature, pressure, and velocity individually to predict the maximum flame temperature is of great importance in terms of the scientific consistency of the study. In constructing the regression equations, only the hydrogen concentration was taken into account, rather than the hydrogen–methane mixture ratio. This approach was adopted to avoid multicollinearity among the input parameters, which is a key requirement in regression analysis. Specifically, a 2.5% increase in hydrogen concentration corresponds to an equivalent decrease in methane concentration, thereby introducing a linear relationship between the variables and creating an artificial correlation. Such a correlation could negatively affect the accuracy of the model. Therefore, regression models were developed solely based on hydrogen concentration, and this approach was found to have no adverse impact on the predictive accuracy of the model.

4.3. Experimental Validation of the Study Based on Literature Data

In this study, the validation of the results was conducted by comparing the maximum flame temperature obtained through CFD analysis for pure methane combustion with previously published experimental data involving the use of pure methane in the literature. Within the scope of this thesis, the maximum flame temperature resulting from the combustion of pure methane was calculated as 2181.98 K. As illustrated in Figure 4.13, experimental studies reported in the literature yielded similar temperature values, thereby confirming the consistency of the CFD-based findings with experimental observations.

In the experimental studies by Tran et al. (2013), the maximum flame temperature for pure methane combustion was reported as 2100 K. This value is only 3.76% lower than the result obtained in this thesis, indicating an acceptable level of deviation. According to the literature, numerical and experimental result deviations below 15% are considered to be within acceptable limits (Galletti et al., 2013; Liu et al., 2023; Su et al., 2012; Yin, 2017). Minor discrepancies in convergence criteria or experimental setups may account for such differences. Furthermore, the experimental results reported in the literature generally fall within the axial and peak temperature ranges obtained in the present CFD analyses. This further supports the reliability and consistency of the findings presented in this study.

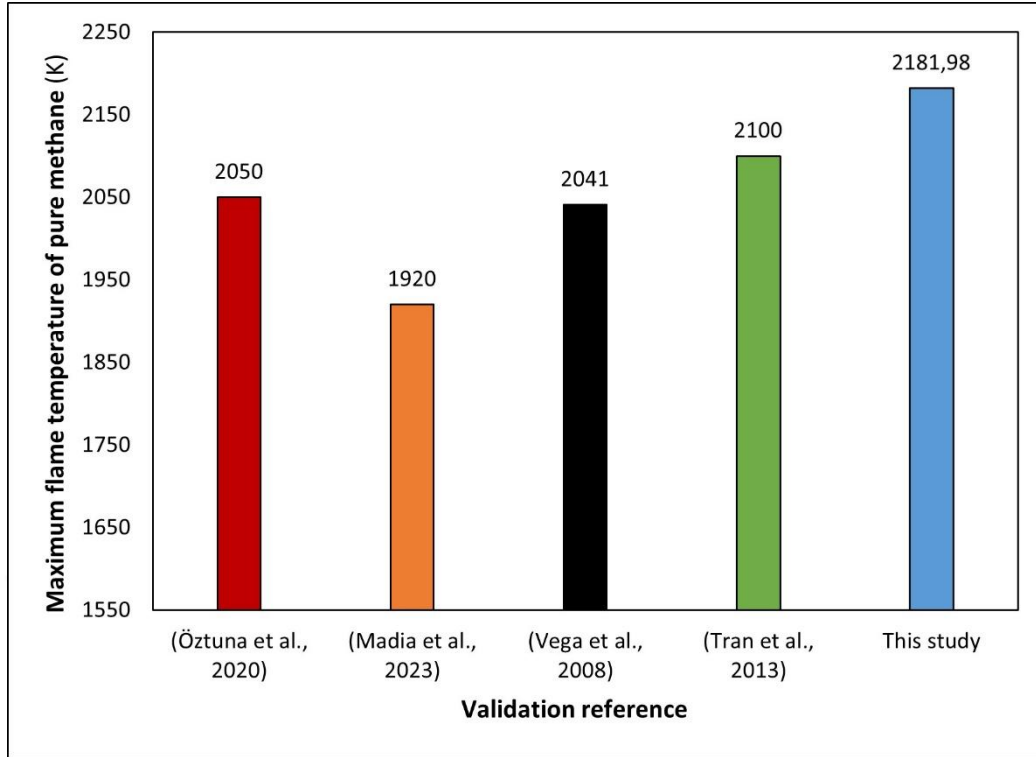


Figure 4.13. Validation of maximum flame temperature for pure methane combustion using experimental data from literature and the present CFD result

4.4. Experimental Results of the Study

During the preliminary experiments conducted within an industrial workshop as part of this study, HHO production was carried out using the equipment described under the Materials and Methods section, as shown in Figure 4.14. Based on measurements taken during the test, the hydrogen production unit was found to have an HHO generation capacity of 0.5665 L/min. As illustrated in Figure 4.14, the application of electrical energy (12V, 9A) from a battery to the production unit results in the formation of a white-colored mixture, with HHO bubbles visibly rising between the electrodes. These rising bubbles represent the produced HHO gas, which is transferred via a transparent pneumatic hose to the backfire flame control equipment, also depicted in the same figure. At this stage, the bubbles reaching the surface of the water at the base of the flame arrestor indicate the availability of HHO gas for combustion in the burner.

However, for this combustion reaction to occur efficiently, the HHO production must be stable and consistent. In practice, electrolysis systems that are not industrially optimized generally fail

to provide a steady and reliable HHO output. This instability arises from multiple factors, one of the most significant being the type of battery used in the experiment. DC power sources that cannot supply a stable current and voltage often lead to inconsistencies in HHO production. In the absence of a constant voltage-current relationship, current fluctuations directly affect hydrogen output, with reduced voltage leading to lower gas production rates.

Another source of instability stems from the heat energy generated during the electrolysis process. While moderate heating of the electrolyte can enhance electrolysis efficiency, excessive heating shortens the lifespan of the electrodes and alters the concentration of the electrolyte solution. In professional electrolysis systems, temperature control mechanisms are employed to prevent such issues. Variations in the concentration of NaOH or KOH within the electrolyte solution—either due to improper initial formulation or the use of water not suitable for electrolysis—can lead to fluctuations in the reaction process, consequently affecting the amount of gas produced. Insufficient surface contact between the electrodes and the electrolyte solution, along with the degree of oxidation on the electrode surfaces, contributes to reduced gas production efficiency.

Unlike professional HHO systems, where hydrogen and oxygen are separated post-generation and steam is condensed or filtered out, the system used in this study lacked such a separation mechanism. As a result, the purity of the produced gas varied, which adversely affected flame stability and ultimately led to a flame backfire incident during combustion.



Figure 4.14. Visualization of the HHO gas flame obtained during the preliminary experiment

The laboratory experiment initially planned and illustrated in Figure 3.9, which aimed to investigate the flame characteristics produced by a mixture of HHO and hydrocarbon-based fuel, could not be carried out due to an explosion in the test setup caused by hydrogen flame backfire (Figure 4.15). During the experiment, the irregular HHO output from the hydrogen production unit resulted in intermittent combustion at the burner outlet. This instability caused the flame to be drawn back into the system through suction. The flame that entered the system subsequently reacted with the accumulated HHO gas inside the backfire flame control device, leading to an explosion. Due to the high reaction rate of hydrogen during the explosion, the resulting flame could not be captured on camera.

Importantly, the explosion did not occur within the hydrogen production unit itself, which is considered a significant factor in ensuring experimental safety and the health of the researchers. In order for the study to proceed efficiently, a more professional setup must be developed by addressing the problems outlined in the previous section. However, the cost of such an advanced system exceeds the financial limitations of the current thesis budget.



Figure 4.15. Image of the structural failure observed in the experimental setup during laboratory testing

Prior to the laboratory experiments, a preliminary combustion test was conducted using a hydrocarbon-based gas in a workshop located within an industrial zone, employing the T-burner setup illustrated in Figure 3.14. The combustion of the hydrocarbon-based gas during this preliminary trial is shown in Figure 4.16. Due to the influence of environmental factors, the resulting flame exhibited a turbulent structure. The flame expanded as it moved away from the burner outlet, and its color spectrum was predominantly composed of yellow and orange hues.

These observations indicate that combustion occurred under fuel-rich conditions in an oxygen-deficient environment, suggesting the presence of diffusion-type combustion resulting from mixing with ambient air. The dominance of yellow and orange colors in the flame further confirms this fuel-rich combustion behavior. In contrast, a stoichiometric or complete combustion process would produce a blue-colored flame with a shorter flame length near the burner neck.

The appearance of an orange flame also implies incomplete combustion of carbon-containing compounds, potentially leading to the formation of harmful by-products such as carbon monoxide (CO). Since the experiment was conducted without premixing, a homogeneous air-fuel mixture could not be achieved, which resulted in unstable and non-uniform flame behavior.



Figure 4.16. Flame appearance observed during the preliminary combustion test

5. CONCLUSION

This study focuses on investigating the temperature parameters resulting from the enrichment of methane gas with hydrogen on a specially designed open-ended burner. The hydrogen concentration in the methane-hydrogen mixture was incrementally increased by 2.5%, covering a range from 0% to 30%. The temperature data obtained from CFD analyses conducted using ANSYS Fluent were compared with results from MATLAB-based ANN predictions and regression models to evaluate the consistency of the study. A validation process was also carried out to assess the compatibility of the maximum temperature results with the existing literature. Additionally, pressure, velocity, and radiation parameters were examined. In the experimental setup, combustion reactions were attempted using a hydrocarbon-based gas.

The hydrogen concentration within the methane–hydrogen mixture has a direct impact on the flame temperatures resulting from the combustion reaction. As the hydrogen concentration increases, the maximum flame temperature also rises, reaching a peak value of 2303.82 K at 30% hydrogen concentration. However, this trend does not hold consistently up to 12.5% hydrogen concentration, where irregularities in maximum flame temperatures are observed. Similar findings have been reported in previous studies, attributing the primary cause to the expanding diffusion flame structure induced by the burner design. Additionally, it was observed that axial temperature profiles exhibit an increasing trend with higher hydrogen concentrations.

In the study, the maximum flame temperature was found to be 2303.368 K at 27.5% hydrogen concentration, while at 30%, it reached 2303.82 K. This indicates that the flame temperature approaches a saturation point after peaking. In the CFD analyses where the P-1 radiation model was employed, the radiation temperature—526.531 K—was recorded at the 70% methane–30% hydrogen mixture ratio, which corresponds to the highest flame temperature observed.

The examined flow velocity data show an increasing trend with rising hydrogen concentration, which is inherently linked to the corresponding temperature increase. This behavior is primarily attributed to the highly reactive nature of hydrogen. Additionally, due to the use of an open-ended burner in the study, pressure values exhibit a slight increase; however, the results remain close to atmospheric pressure levels.

Using the Levenberg–Marquardt algorithm, two distinct ANN models were developed based on different sets of input parameters. In the first model, where only fuel ratio and temperature were used as input parameters and the maximum flame temperature was set as the target variable, the coefficient of determination (R^2) was calculated as 0.91555. In the second model, which included fuel ratio, temperature, pressure, and velocity as input parameters, the R^2 value increased to 0.92537, indicating that the inclusion of additional input variables enhanced the model's predictive performance. Furthermore, separate regression equations were derived for temperature, pressure, and velocity to estimate the maximum flame temperature ($T_{\max}$). When using temperature-based regression equations, the R^2 value was calculated as 99.98%, whereas it was 95.36% when using pressure-based equations and 99.38% for velocity-based equations. These results confirm the reliability of the study, supported by the consistency between the ANN models and the regression analyses.

Experimental studies in the literature utilizing pure methane were reviewed, and the maximum flame temperatures reported in those studies were compared with the maximum flame temperature obtained in the present study using pure methane. Following the validation process, a deviation of 3.76% was identified, which confirms the consistency and reliability of the present study.

Although the desired thermal images could not be captured during the experimental study due to a flame flashback-induced explosion caused by hydrogen, flame images were successfully obtained and evaluated during preliminary workshop trials conducted prior to the experiment using pure hydrocarbon-based fuel. Additionally, the HHO production capacity measured during the preliminary tests was calculated as 0.5665 L/min; however, the HHO generation process exhibited instability.

In this thesis, it has been demonstrated that the designed open-ended atmospheric burner meets the standards required for potential industrial use. The similar Wobbe index values of hydrogen and methane—a parameter indicating the interchangeability of fuels such as natural gas—reduce the impact on heating load when using atmospheric-type burners. Accordingly, the safe transport of hydrogen without explosion risk can be achieved through the utilization of existing natural gas pipeline infrastructure.

The findings obtained from this study may serve as a valuable reference for future research. In subsequent studies, optimization of burner performance will be pursued by incorporating a greater number of input parameters into ANN and regression-based prediction models, with the aim of achieving the most efficient combustion conditions.



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Publication produced from this thesis:

Erkan, A., & Tüccar, G. (2025). The effect of hydrogen ratio on flame temperatures in the methane combustion reaction in the burner. *Cukurova University Journal of the Faculty of Engineering*, 40(2), 361–373.

Publications:

Erkan, A., Tüccar, G., Tosun, E., & Özgür, T. (2021). Comparison of effects of nanofluid utilization (Al_2O_3 , SiO_2 , TiO_2) with reference water in automotive radiators on exergetic properties of diesel engines. *SN Applied Sciences*, 3(365). <https://doi.org/10.1007/s42452-021-04368-z>

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