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COMPARATIVE CFD COMPUTATIONAL STUDY ON ENHANCING SHELL-AND-TUBE HEAT EXCHANGERS WITH NANOFLUIDS

Muiz ABDUL RAQIB

Master's Thesis

Supervisor

Asst. Prof. Dr. Yaser ALAIWI

İstanbul, 2024

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The thesis titled COMPARATIVE CFD COMPUTATIONAL STUDY ON ENHANCING SHELL-AND-TUBE HEAT EXCHANGERS WITH NANOFLUIDS prepared by MUIZ ABDUL RAQIB and submitted on 04/06/2024 has been **accepted unanimously** for the degree of Master of Science in Mechanical Engineering

Asst. Prof. Dr. Yaser ALAIWI

Supervisor

Thesis Defense Committee Members:

Asst. Prof. Dr. Yaser ALAIWI	Department of Mechanical Engineering Altınbaş University	____________________
Asst. Prof. Dr. Abdullahi Abdu IBRAHIM	Department of Computer Engineering Altınbaş University	____________________
Asst. Prof. Dr. Haydar KEPEKÇİ	Department of Mechatronics Engineering Istanbul Gelişim University	____________________

I hereby declare that this thesis meets all format and submission requirements for a Master's thesis.

I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Muiz Abdul RAQIB

Signature

DEDICATION

I would like to express my deepest gratitude to my supervisor, Asst. Prof. Dr. Yaser ALAIWI, for his unwavering support, guidance, and encouragement throughout this project. His expertise and insights have been invaluable in shaping my research and motivating me to strive for excellence. I also extend my sincere appreciation to the entire faculty and staff of the Department of Mechanical Engineering for their ongoing support and for fostering an environment conducive to learning and growth. Lastly, I am forever grateful to my family for their unconditional love, understanding, and constant support throughout my academic journey. Their belief in me has been a source of strength and inspiration.

ABSTRACT

COMPARATIVE CFD COMPUTATIONAL STUDY ON ENHANCING SHELL-AND-TUBE HEAT EXCHANGERS WITH NANOFLUIDS

ABDUL RAQIB, Muiz

M.Sc., Mechanical Engineering, Altınbaş University,

Supervisor: Asst. Prof. Dr. Yaser ALAIWI

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This research investigates the enhancement of shell-and-tube heat exchanger efficiency using titanium dioxide (TiO2) Nano fluids, through a comparative computational fluid dynamics (CFD) analysis of two cases. In the first case, cold water flowing through the tubes is heated by hot water in the shell. The second case introduces a 0.5% TiO2 Nano fluid mixture to the hot water, aiming to investigate its impact on heat transfer efficiency. Utilizing computer-aided design (CAD), the study models an innovative heat exchanger configuration that closely mirrors commercial dimensions but incorporates slight variations to discover new design potentials. The CFD modelling employs a grid independence approach to ensure the accuracy of the results. Findings indicate an 11.44% increase in cold fluid temperature rise with the Nano fluid case, demonstrating significant efficiency improvements over conventional water usage. This highlights the potential of engineered Nano fluids in enhancing industrial heat recovery processes. Leveraging CAD and CFD tools for optimized design, the detailed thermal performance analysis provides profound insights into the augmented heat transfer phenomena induced by Nano fluids. This research contributes to the scientific understanding and development of efficient, sustainable thermal technologies, paving the way for advanced, nanotechnology-enhanced heat transfer solutions with wide-ranging implications for energy efficiency across various sectors.

Keywords: CFD, Nano-Fluid, Investigate, Thermal Performance, Analysis.

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ABBREVIATIONS

CAD	:	Computer-Aided Design
STHX	:	Shell and Tube Heat Exchanger
CVHTC	:	Convective Heat Transfer Coefficient
CFD	:	Computational Fluid Dynamics
PEC	:	Performance Evaluation Criterion
GNP	:	Graphene Nano Plate
DNS	:	Direct Numerical Simulation
LMTD	:	Log Mean Temperature Difference
FEM	:	Finite Element Method
LES	:	Large Eddy Simulation

LIST OF SYMBOLS

q''	:	Heat Transfer per Unit Area
Q	:	Heat Transfer Rate
h	:	Conviction Heat Transfer Coefficient
T_s	:	Temperature of Solid Surface
T_∞	:	Temperature of Fluid
p	:	Pressure
ϵ	:	Surface Emissivity
Q_S	:	Heat Transferred in the Shell Side
ρ_{nf}	:	Density of the Nano Fluid
ρ_{np}	:	Density of the Nano Particle
ρ_{bf}	:	Density of the Base Fluid
Q_T	:	Heat Transferred in the Tube Side
U	:	Overall Heat Transfer Coefficient
ΔT_{lm}	:	Log Mean Temperature Difference
μ_{nf}	:	Dynamic Viscosity of the Nano Fluid
μ_{bf}	:	Dynamic Viscosity of the Base Fluid
$C_{p,nf}$	:	Specific Heat Capacity of the Nano Fluid
$C_{p,np}$	:	Specific Heat Capacity of the Nano Particles
$C_{p,bf}$	:	Specific Heat Capacity of the Base Fluid
v	:	Velocity Components
ν	:	Kinematic Viscosity of the Fluid
ε	:	Heat Exchanger Effectiveness

k_{nf}	:	Thermal Conductivity of the Nano Fluid
k_{bf}	:	Thermal Conductivity of the Base Fluid
k_{bf}	:	Thermal Conductivity of the Nano Particles
ϕ	:	Volume Fraction of the Nano Particles

1. INTRODUCTION

1.1 BRIEF BACKGROUND

Heat exchangers have emerged as indispensable components enabling optimized thermal management and efficient energy utilization across vital industrial domains like manufacturing, power generation, food processing, pharmaceuticals, and more. They facilitate productive transmission of heat between fluids, ensuring precise temperature control critical for product quality, safety compliance and prolonged equipment lifespan. Specifically, heat exchangers contribute substantially to heightened energy efficiency by capturing waste heat for recycling instead of dissipation. This greatly reduces overall energy expenses and environmental footprint aligning with sustainability objectives. Their small, lightweight build suits space constraints in facilities. Heat exchangers prevent cross-contamination through isolated fluid channels, upholding purity standards in industries like pharmaceuticals. Quick, productive waste heat recovery using minimal additional inputs also attests their effectiveness. Furthermore, the versatility of heat exchangers tackling diverse thermal demands makes them vital across chemical plants, refineries, HVAC infrastructure among myriad applications. Their affordability compared to alternatives provides a compelling value proposition when optimizing heating and cooling systems. Therefore, improving heat exchanger performance through modern research promises to unlock major efficiency gains leading to greener, cost-effective industrial operations, cementing their indispensable present and future role across sectors [1].

The use of nanofluids as heat transfer fluids in heat exchangers provides several important benefits that can lead to energy savings. Due to the enhanced thermophysical properties of nanofluids containing suspended nanoparticles, significant improvements in the heat transfer coefficient and heat transfer rate are achieved in heat exchangers compared to using conventional heat transfer fluids. This allows the heat exchangers to transfer heat more effectively and achieve a higher efficiency of operation. Additionally, the improved heat transfer performance means that lower mass flow rates of nanofluids may be required or smaller sized heat exchangers that achieve the same heat duty can be designed. This directly translates to reductions in pumping power requirements and material costs for construction. The nanofluids also open new possibilities for compact heat exchanger designs aimed at recovering low grade waste heat from industrial effluents/exhaust gases and reusing it for heating applications. Furthermore, the overall economic and performance analyses indicate that nanofluids have commercially acceptable capabilities in relation to their cost that make them viable engineered heat transfer fluids. Thus, the significantly enhanced thermophysical properties of nanofluids can allow better utilization of heat exchangers, lower operating costs, more compact installation footprints, and possibilities for waste heat recovery - ultimately contributing to saving energy [2] .

1.2 MOTIVATION

i. In The growing global attention toward energy efficiency and sustainability heightens the need to maximize heat recovery in industrial processes. Optimizing heat exchanger performance using engineered nanofluids holds immense potential for enhanced heat transfer with lower energy consumption.

ii. Nanofluids have exhibited significantly higher thermophysical properties over conventional heat transfer fluids. However, large-scale demonstrations quantifying actual efficiency gains in commercial heat exchangers are lacking. This research addresses this gap.

iii. Overcoming limitations like fouling and corrosion can considerably improve longevity and reliability of heat exchangers. The novel materials approach with nanofluids provides opportunities to mitigate such issues.

iv. This investigation intends to facilitate the translation of nanofluids from lab-based studies toward widespread practical adoption by industries like manufacturing, petrochemical refining, and energy sectors where heat exchangers play a major role.

v. From an academic perspective, this computational modelling-driven study will expand scientific insight into nanomaterial-enhanced convective heat transfer phenomena while inspiring further engineering optimizations leveraging multi-scale and multi-physics analysis.

1.3 THESIS OBJECTIVES

i. To construct an accurate CAD model of the shell-and-tube heat exchanger and carry out nanofluid CFD simulations to quantify efficiency improvements.

ii. To utilize CAD for exploring innovative heat exchanger configurations tailored to the integration with TiO2 nanofluids for maximizing heat transfer.

iii. To analyse the augmented heat recovery enabled by TiO2 nanofluids in CAD-optimized designs, assess their sustainability benefits through energy savings.

iv. To develop practical design guidelines for effectively implementing TiO2 nanofluids in heat exchangers, addressing aspects like material compatibility and maintenance.

v. To model the complex heat transfer processes in nanofluid-based heat exchangers using computational fluid dynamics, elucidating the enhanced convective transport.

vi. To contribute to advancing thermal management systems by highlighting the immense potential of engineered nanofluids through simulation-driven assessments coupled with CAD optimizations.

1.4 SCOPE OF THE STUDY

i. Types of Fluids: Central to this study is the thermal performance assessment of nanofluids, with a specific emphasis on titanium dioxide (TiO2) nanofluids at a 0.5% volume fraction. Traditional fluids, notably water, will serve as a benchmark for comparative purposes.

ii. Heat Exchanger Configuration: The investigation focuses on shell-and-tube heat exchangers. These exchangers will be meticulously designed using SolidWorks to ensure adherence to the study's unique requirements, illustrating the adaptability and precision of CAD tools in thermal system design.

iii. Simulation-Based Analysis: Exclusive reliance on simulation-based analysis forms the core methodology of this study, with SolidWorks being employed for comprehensive computational fluid dynamics (CFD) simulations. This approach aims to accurately evaluate the enhancements attributed to the use of TiO2 nanofluids without the incorporation of physical experiments.

iv. Parameter Range: An exploration into various parameters impacting heat exchanger efficiency when utilizing nanofluids is planned. This includes analyzing nanoparticle size, concentration effects, and the thermal interaction dynamics between the hot TiO2 nanofluids on the shell side and cold water on the tube side.

v. Optimization Focus: The culmination of this research will see the development of optimization strategies and recommendations based on the simulation findings. These strategies are intended to guide the efficient use of TiO2 nanofluids in heat exchangers, offering a foundation for real-world application and efficiency improvement.

vi. Software Utilization: SolidWorks will be the primary software tool for both the design of the shell-and-tube heat exchangers and the subsequent CFD analyses. This dual application underscores SolidWorks' versatility in facilitating both the structural design and fluid dynamic analysis aspects of the research.

1.5 THESIS STRUCTURE

First chapter which is the Introduction

This chapter introduces heat exchangers and their significance across industries. It discusses the potential of using Nano fluids to address current efficiency challenges, setting the context for the computational modelling-based comparison study between nanofluids and conventional fluids.

Second chapter which is the Literature Review

The chapter provides a comprehensive overview of existing literature on applications of nanofluids in heat exchangers. It covers relevant studies investigating the effect of factors like nanoparticle parameters on the heat transfer enhancements achieved through nanofluids.

Third chapter which is the Methodology

The research design and simulation methods undertaken are elaborated, focusing especially on the CAD modelling approach used for proposing an innovative heat exchanger configuration tailored for nanofluids. The CFD simulation methodology along with the specifications of boundary conditions and parameters are also outlined.

Fourth chapter which is the Results and Discussion

This chapter presents detailed results comparing the performances of TiO_2 nanofluid against water. The enhanced heat transfer coefficients, temperatures and recovery achieved through the engineered nanofluid are quantified and visualized. Inferences related to the positive ecological implications are also discussed.

Fifth chapter which is Conclusions and Future Work

The pivotal conclusions highlighting the promise of nanofluids in boosting heat exchanger effectiveness are summarized, along with recommendations for future work around practical implementations and emerging nanomaterials/optimization methods.

2. LITERATURE REVIEW

Heydari et al. [3] performed a numerical analysis to study the effect of using different nanofluids on the performance of a baffled shell-and-tube heat exchanger. Nanofluids containing nanoparticles like Al2O3, CuO and Fe2O3 dispersed in base fluids water and ethylene glycol were modeled at various concentrations. The results showed a reduction in heat transfer coefficient by 5-15%, heat transfer rate by 3-12%, and pressure drop by 10-25% while increasing outlet temperature by 2-5% when using nanofluids. Analysis also showed that ethylene glycol-based nanofluids provided 3-8% higher effectiveness than water-based ones. Overall, the researchers concluded that adding nanoparticles to the fluid inside the heat exchanger, despite reducing heat transfer coefficient, pressure drop and heat transfer rate, increases the outlet temperature.

Teja and Kumar [4] conducted a study on hairpin heat exchangers using different nanofluids, focusing on how these fluids affect the exchanger's ability to transfer heat. They used CFD to simulate the performance of these heat exchangers when mixed with nanofluids like titanium nitride, magnesium oxide, and silver nanoparticles at varying concentrations (0.15%, 0.25%, 0.35%, and 0.45%). The study found that magnesium oxide nanofluids at a concentration of 0.45% improved the heat transfer rate and efficiency the most. This suggests that using nanofluids in hairpin heat exchangers can significantly enhance their performance.

Rani et al. [5] reviewed studies on applying nanofluids in crossflow heat exchangers. They explained that crossflow heat exchangers work more efficiently than shell & tube, spiral and plate types owing to higher heat transfer rates. Performance can be further improved by using nanofluids containing metal oxide nanoparticles suspended in water. The paper discusses analytical, numerical, experimental, and artificial neural network studies analyzing the performance of such nanofluid-based heat exchangers. Factors like nanoparticle type and concentration, tube diameter, fin spacing etc. were evaluated to optimize the designs. The results showed noticeable enhancement in convective heat transfer when nanofluids were used instead of conventional heat transfer fluids. Specifically, suspending metal oxide nanoparticles in water provided the best improvements in heat transfer rates.

Kareemullah et al. [6] performed an experimental analysis on a shell-and-tube heat exchanger utilizing zinc oxide nanofluids, aiming to analyze the potential heat transfer enhancements offered by nanofluids. They conducted a comparative assessment against water to evaluate parameters like heat transfer coefficient and overall efficiency. The mass flow rate on the tubes was adjusted while maintaining fixed shell-side rates. Outcomes exhibited effectiveness improvements with growing nanofluid mass flow. This evidences the ability of tailored nanofluids to intensify heat transfer in such heat exchangers. Attributed to factors like higher viscosities, the heightened transfer rates come coupled with pumping power penalties. Still, within suitable operating ranges, zinc oxide nanofluids proved capable of augmenting both heat recovery and effectiveness. The study thus substantiates the viability of nanofluid-based shell-and-tube exchangers following decisive real-world testing. It also underscores the need to holistically weigh heat transfer improvements against related costs for feasible adoption.

Oudina and Chabani [7] discuss the broad applications of nano-fluids in enhancing heat transfer across various enclosures, particularly in solar thermal fields. The review highlights the integration of magnetic fields, porous media, and nano-fluids to significantly improve convective flow. It emphasizes the potential of complex-shaped cavities, especially trapezoidal geometries, in optimizing heat transfer processes. The paper consolidates mathematical models for these flows and suggests that the geometric design of enclosures plays a crucial role in the effectiveness of heat transfer techniques.

Kumar and Muruganandam [8] explore the enhancement of heat transfer using nanofluids with various base fluids, highlighting the significant thermal conductivity improvements at low nanoparticle concentrations. Their study spans applications like cooling electronics and improving diesel generator efficiency. They note that while most oxide nanofluids show limited effectiveness, certain Carbon Nanotube (CNT) nanofluids offer substantial benefits. The review encompasses diverse research findings, indicating that CNT nanofluids can significantly enhance thermal and lubrication properties, affecting machining quality through cooling and lubrication effects.

Wang et al. [9] proposed an innovative solar photovoltaic and thermal (PVT) system that combines a linear Fresnel reflector (LFR) concentrator with optical filters made from ITO-EG nanofluids. The primary goal of this novel design was to optimize solar energy conversion efficiency by effectively splitting the solar spectrum and minimizing energy losses. To investigate the performance of their proposed system, the researchers conducted a series of experiments to determine the optical properties of both the ITO nanoparticles and the ITO-EG nanofluids. The results of their experimental study revealed that the optical filter demonstrated an impressive average absorptivity of 30.9% across a wide spectral range. Furthermore, the authors performed extensive simulations and theoretical analyses to assess the overall performance of the system. The findings from these computational and analytical approaches suggested that the integration of the LFR concentrator and ITO-EG nanofluid optical filters has the potential to significantly enhance the efficiency of solar energy conversion.

Heydari, Shateri, and Sanjari [10] explore the effect of adding various nanoparticles to fluids on the performance of baffled shell and tube heat exchangers using computational fluid dynamics (CFD) simulations. The study investigates how the presence of nanoparticles modifies the thermo-physical properties of the fluids, which can either enhance or reduce heat transfer coefficients depending on the specific flow conditions. The authors employ three-dimensional modeling techniques to examine the impacts of different nanofluids with varying volume fractions. The research focuses primarily on how these nanofluids influence key performance metrics, including the heat transfer rate, pressure drop, and outlet shell temperature. The nanoparticles considered in the study include $Al2O3$, CuO, $Fe2O3$, Cu, Fe, and Au, with water serving as the base fluid. The results of the investigation indicate that the incorporation of nanoparticles generally leads to a decrease in both the heat transfer coefficient and pressure drop while simultaneously causing an increase in the outlet shell temperature.

Renuka, Velmurugan, and Kumar [11] focus on the design and CFD analysis of hairpin heat exchangers using different nano-fluids, specifically titanium carbide, magnesium oxide, and silver nanoparticles at concentrations of 0.2%, 0.5%, 0.7%, and 1.0%. Their research, carried out with a mix of glycerin (40%) and water (60%), aimed to determine the impact of these nano-fluids on the heat exchanger's performance, including heat transfer rate and efficiency. The analysis utilized 3D modeling and CFD simulations to evaluate the performance improvements offered by each nano-fluid type and concentration, highlighting the potential of nano-fluids in enhancing heat exchanger efficiency.

In a study by Rabby et al. [12] the impact of using corrugated pipes combined with SWCNT-water nanofluid on enhancing laminar convective heat transfer was examined through numerical analysis. The findings indicate a significant improvement in heat transfer efficiency when using corrugated pipes with SWCNT-water nanofluid, as opposed to standard pipes with water. Experiments with different nanoparticle volume fractions (1%-5%) demonstrated notable increases in the Nusselt number and heat transfer coefficient, with added advantages in pumping power. The study also presented correlations for predicting these variables, which closely match the numerical results, confirming the efficacy of corrugated channels with nanofluid in boosting heat transfer and pumping power in laminar flow conditions.

Shabgard et al. [13] created a numerical model to assess the cooling efficiency of an exhaust gas recirculation (EGR) cooler that utilizes nanofluids. The study compares the thermal and hydrodynamic performance of nanofluids containing different nanoparticles dispersed in water across a range of Reynolds numbers. Among the nanofluids investigated, the Al2O3-water nanofluid demonstrated the most significant improvement in heat transfer, achieving a 16% increase in the heat transfer coefficient at a Reynolds number of 5000 with a nanoparticle volume fraction of 5%. However, this enhancement in heat transfer is accompanied by a higher pressure drop, which can be attributed to the increased viscosity of the nanofluid. The researchers also observed that the effectiveness of nanofluids in enhancing heat transfer tends to diminish as the Reynolds number increases.

Hussein et al. [14] conducted a study on improving shell and tube heat exchanger performance using ZnO/water nanofluids. Through CFD simulations, they assessed the impact of 0.2% and 0.35% nanoparticle volume fractions on various performance metrics like heat transfer, friction factor, Nusselt number, and thermal efficiency, for Reynolds numbers between 200 to 1400. Their research highlighted a significant enhancement in heat exchanger efficiency, demonstrating the potential benefits of incorporating nanofluids into heat exchanger designs.

Mukesh Kumar et al. [15] conducted a comprehensive CFD study on double helically coiled tube heat exchangers utilizing MWCNT/water nanofluids. The research focused on the effects of nanofluid concentration and Dean number on heat transfer and pressure drop. Results showed enhanced heat transfer rates and increased pressure drops with higher nanofluid concentrations, demonstrating the potential of MWCNT/water nanofluids in improving heat exchanger performance while also highlighting the impact on pressure drop.

Lahari et al. [16] explored the heat transfer enhancement in a double pipe heat exchanger using copper nanofluid. Through numerical modeling and CFD analysis, they investigated the impact of copper nanoparticles suspended in a water-ethylene glycol mixture at volume fractions of 0.1% and 0.2% on heat transfer efficiency. Their analysis, conducted at different Reynolds numbers (6000, 8000, 10000), revealed improved heat transfer with 0.2% volume fraction nanofluid, highlighting nanofluids' potential for heat exchanger performance enhancement.

Lazarevikj et al. [17] conducted a comprehensive CFD analysis on improving heat transfer in plate heat exchangers using Al2O3/water nanofluid. Their study focused on the effects of nanoparticle-enhanced fluids on heat transfer efficiency, employing realistic geometries of corrugated plates. Simulations were carried out to assess the performance at optimal nanoparticle concentrations, demonstrating significant enhancements in heat transfer and efficiency with minimal increases in pressure drop. The research highlights the potential of nanofluids to improve heat exchanger performance, validated by comparisons with experimental data.

M. Kocić et al. [18] conducted a-detailed analysis on nano and micropolar MHD fluid flow and heat transfer in inclined channels, explaining the modeling of aluminum oxide and water-based micropolar fluids. They explored the complex interaction between the nanoparticles' volume fraction and thermal and flow characteristics, demonstrating the heat transfer variation with external magnetic and temperature influences. The fluid's slip and rotational impact at the nodes of velocity change highlight the bimodal fluid’s ability to dissipate and conduct heat efficiently.

Palla Madhavi et al. [19] conducted a thoughtful investigation into the heat transfer characteristics of Titanium Nitride and Titanium Carbide nanofluids within shell & tube heat exchangers. Their inquiry revolved around the most often used section of industrial methods for thermal energy transition. Significantly, by inviting nanoparticles to the mixture, they targeted to inspect how such case could lead to various process features, tackling the related alternation within real-time business practices. The potential of nanoparticle-inducted technological alteration hinted at a departure from older heat solutions, thrusting towards the case of the gitable full-bloom development with nanotechnology's rising tide.

S. Harasurakar et al. [20] conducted a study, published in the Journal of Advanced Research in Dynamical and Control Systems in January 2019, on the CFD analysis of hairpin heat exchangers utilizing different nanofluids. This investigation aimed to evaluate the thermal performance when introducing titanium carbide, magnesium oxide, and silver nanoparticles into the base fluid, which was a combination of glycerin and water. By simulating with CFD and analyzing under various considerations, results demonstrated an incremental heat transfer efficiency with the feeding of these nanofluids. The findings from this study shed light on optimizing heat exchanger performance by leveraging the combined heat transfer rates, expanded by innovative design and material solutions.

F. M. Hussien et al. [21] conducted an experimental investigation to explore the enhancement of double pipe heat exchanger performance using Alumina (Al2O3) and Copper oxide (CuO) nanoparticles mixed with engine oil. The study examined thermal performance improvements at nanoparticle concentrations of 0.05% and 0.1%. Results indicated significant increases in Nusselt number, overall heat transfer coefficient, and heat exchanger effectiveness with nanoparticle addition, highlighting the potential of nanofluids in boosting heat exchanger efficiency.

Amit Kumar and Animesh Singhai [22] conducted a study on the impact of MWCNT/water nanofluids in a cone helically coiled heat exchanger, focusing on the effect of varying tube pitch sizes. Their investigation, carried out via Computational Fluid Dynamics (CFD), revealed that increasing the pitch size significantly enhances heat transfer rates, evidenced by higher Nusselt numbers and overall heat transfer coefficients. This improvement is attributed to better thermal contact and fluid mixing induced by secondary flows. Their findings suggest that adjusting pitch size is a viable method to boost heat exchanger performance.

C. Kannan et al. [23] conducted a study on the heat transfer characteristics of automotive radiators using nanofluids. They explored the effects of operating parameters like flow rate and nanoparticle concentration on heat transfer. The research found that nanofluids enhance heat transfer compared to pure water, with significant improvements observed at higher nanoparticle concentrations and flow rates. This study provides insights into optimizing radiator performance for automotive applications.

In their research, Johnson and Malladi [24] explored the thermal efficiency of shell tube heat exchangers using CuO-Water (CuO-W) nanofluid. Their study focused on assessing how the nanofluid's volume concentration impacts heat transfer characteristics, including Reynolds number, thermal conductivity, and heat transfer coefficient, compared to standard fluids. They discovered that nanofluids significantly increase the heat transfer coefficient, thereby enhancing energy efficiency and reducing material needs in heat exchangers, underscoring the promising role of nanofluids in boosting heat exchanger performance.

Vinodkumar et al. [25] conducted a study to enhance the heat transfer coefficients in a shell and helical tube heat exchanger utilizing Water/Al2O3 Nanofluid. They aimed to improve shell side heat transfer coefficients and net heat transfer without significant pressure loss. Utilizing ANSYS WORKBENCH 15 for modeling and STARCCM+ for solving, they analyzed various concentrations of nanofluids. The study found that the addition of Al2O3 nanoparticles to water significantly increased the heat transfer coefficients, offering a passive method to enhance heat exchanger performance without the drawbacks of increased pressure loss associated with other methods.

Rajamanickam Sundaresan et al. [26] conducted a comparative study on radiators using both conventional fluids and nanofluids for combat vehicles. They explored the potential of nanofluids, which exhibit superior thermal properties compared to conventional coolants like water, Ethylene glycol, and Engine oil, due to the suspension of nano-sized particles. Their theoretical analysis, based on the ε-NTU method, evaluated the performance of a flat tube fin compact heat exchanger using Ethylene glycol/water and a CuO-based nanofluid. The study aimed to assess the heat transfer characteristics and performance enhancement provided by nanofluids in automotive radiators.

Mlr Chaitanya Lahari et al. [27] conducted a study on enhancing heat transfer in hairpin heat exchangers using TiC, MgO, Ag/water-glycerin nanofluids. They performed analytical investigations to evaluate the performance of these nanofluids at different volume concentrations, using water and glycerin as base fluids. The study utilized CFD analysis to determine heat transfer coefficients and rates, indicating that Ag/water-glycerin nanofluid exhibited the highest heat transfer rate among the tested fluids.

Najim et al. [28] conducted a numerical study on the performance improvement of a shell and tube heat exchanger using Fe3O4/water nanofluid. Utilizing CFD simulations, the research focused on various Reynolds numbers, from 200 to 1400, with nanofluid volume fractions of 0.2% and 0.35%. The findings revealed significant enhancements in the Nusselt number, heat transfer rate, and efficiency with the 0.35% nanofluid concentration, showing approximately 19%, 25%, and 12% improvements, respectively. The study highlighted that friction decreases with increasing Reynolds numbers, showcasing the potential of nanofluids in heat exchanger performance optimization.

Zolfalizadeh et al. [29] presented comprehensive experimental research focused on evaluating graphene nanoplate/water nanofluids for augmenting shell-and-tube heat exchanger performance. Markedly, they designed and constructed a customized heat exchanger rig to analyze nanofluid capabilities under well-controlled conditions, signifying a pioneering practical demonstration. The extensive study characterized the nanofluid's thermophysical properties using advanced techniques and stability over extended durations. Experimental outcomes were validated against standard heat transfer correlations, indicating consistent and sizeable enhancements in parameters like heat transfer coefficient and thermal efficiency with graphene nanofluid incorporation. At merely 0.06% weight concentration, the nanofluid achieved an over 22% increase in heat transfer coefficient relative to water. The research substantiates emerging graphene-water nanofluids' potential for sustainable intensification of real-world industrial scale heat exchange equipment. It thus makes vital contributions accelerating adoption by expanding fundamental knowledge and providing reliable performance benchmarks for this transformative technology.

Reddy et al. [30] presented research focused on comprehensively analyzing shell and tube heat exchangers to improve heat transfer rates using nanofluid mixtures, specifically water based TiO2. Their thermodynamic evaluation compared these nanofluids against traditional water across a range of nanoparticle volume fractions. Outcomes revealed that TiO2 nanofluids, particularly at 1.5% concentration, yield over 15% higher heat transfer than water. Thus, tailored nanofluids offer an effective technique to substantially enhance industrial heat exchanger performance by leveraging augmented heat transfer properties induced by the suspended nanoparticles. Further studies around practical implementation can help translate these efficiency benefits toward sustainability, energy conservation and waste heat recovery across vital sectors.

Saleh et al. [31] explored using titanium dioxide nanoparticles dispersed in distilled water for enhancing heat transfer applications. Their extensive evaluations analyzed the nanofluids' thermophysical properties like thermal conductivity and viscosity across various particle concentrations and temperatures. While conductivity increased substantially with higher concentrations and temperatures, aligning poorly with standard models, notable improvements were recorded in evaporative heat transfer coefficients and reductions in thermal resistance. Optimized nanofluid parameters like inclination angle, charge volume and nanoparticle percentage were also seen to considerably benefit heat pipe efficiency over distilled water. Thus, nanofluid incorporation under suitable conditions emerges as a viable technique for intensifying real-world thermal systems. Further research around cost-benefit trade-offs and large-scale feasibility can support translating these heat transfer improvements into more sustainable and energy-efficient industrial heating and cooling equipment.

Nakhjavani and Zadeh [32] presented extensive research published in the Journal of Thermal Engineering focused on evaluating titanium oxide/water nanofluids for enhancing forced convective boiling heat transfer in annular exchangers. Their comprehensive investigation analyzed impacts of parameters like mass flow rate, applied heat flux and nanoparticle concentration on average heat transfer coefficient and pressure drop. Results revealed over 35% heat transfer coefficient augmentation at 0.15% nanoparticle concentration by leveraging heightened convection from greater volume flow paired with conductivity improvements from suspended nanoparticles. However, sedimentation tendencies decreased long-term performance. Meanwhile, notable pressure drop spikes were observed at higher concentrations, underscoring the critical role of tailored parameter optimization for feasible operation. Thus, though nanofluids show immense potential to deliver major efficiency gains in annular heat exchangers, pragmatic aspects around maintenance, pumping needs and costs require due consideration before widespread adoption.

Serour et al. [33] presented research on leveraging graphene-titanium dioxide composite nanofluids (GTNC) for intensifying heat transfer in micro-heat exchangers, published in X journal. Recognizing graphene nanofluids' supreme yet cost-prohibitive performance, they judiciously combined properties of both nanomaterials in GTNC using a novel green synthesis technique. Extensive experiments benchmarked against the individual nanofluids demonstrated GTNC boosting heat transfer coefficients by over 60% at mere 0.08% weight concentration, approximating pure graphene nanofluids' capacity at far lower materials expense. The pioneering study makes vital headway in reconciling nanofluid viability challenges around economics at scale using sustainable nanocomposite approaches. Deriving comparable property augmentations at fractional concentrations could accelerate commercial adoption across thermal systems, spurring further multi-disciplinary efforts targeting translation beyond laboratory prototypes.

Kristiawan et al. [34] presented detailed research on leveraging titanium dioxide/water nanofluids flowing through micro finned Mini channel heat exchangers for enhancing convective heat transfer, published in X journal. Their extensive analysis quantitatively correlated key performance metrics like Nusselt number, friction factor and overall efficiency to comprehensively assess effectiveness improvements from nanofluid incorporation. Outcomes revealed substantial heat transfer intensifications exceeding traditional techniques, underscoring nanofluids' immense potential as a disruptive technology for next-generation thermal management systems. The pioneering findings make major strides in integrating nanomaterials science with standardized heat exchange equipment. This could transform sustainable cooling and heating across industries by offering a pathway to drastically augment efficiency and combat escalating energy demands. Further exploration around real-world feasibility and applied engineering optimizations building on this research could ultimately expand nanofluid adoption at commercial scales.

Abhilash et al. [35] presented research published in X journal exploring aluminum oxide and titanium carbide nanofluids' potential for intensifying heat transfer in hairpin exchangers widely used across HVAC&R applications. Their computational fluid dynamics study analyzed nanofluid concentrations between 0.6-0.7% to quantify efficiency improvements. Findings revealed significant enhancements in parameters like thermal conductivity and heat transfer coefficients from augmented properties of tailored nanofluids. Notably, titanium carbide nanofluids displayed over 5% higher heat transfer over other nanomaterial types. The ability of judiciously engineered nanofluids to markedly boost hairpin exchanger performance underscores their immense capacity for meeting escalating heating/cooling needs sustainably. Further research around synergistic combinations of nanomaterials and practical implementation strategies could expand the adoption of this transformative technology across critical thermal management industries.

Apmann et al. [36] presented experimental research published in X journal examining connector-induced heat transfer improvements in Nano fluid-based micro channel systems. Their investigation injected iron oxide Nano fluids into stainless steel channels, analyzing nanoparticle parameters known to influence thermo physical properties and convective transport. Outcomes indicated significant heat transfer coefficient spikes upon introducing a connector between the channels, owed to enhanced pre-entry fluid mixing and refreshed nanoparticle distribution. Subsequently, major collective rises were recorded in the overall heat transfer coefficient. The Reynolds number flow regime was also seen to govern the connector's influence, with Nano fluids considerably outperforming water across laminar and early transitional regimes. The study makes important strides demonstrating Nano flow manipulations through disruptions for optimizing on-chip thermal management. Further exploration around geometry effects and alternating connector configurations could discover major efficiency gains supporting continued nanofluid advancements in energy-efficient heat exchange processes.

Rao and Sreedhar [37] presented CFD research published in X journal evaluating different Nano fluids' heat transfer performance in double pipe exchangers to offer insights into tailored nanoparticle selection. Using fixed volume fractions, their simulations analyzed heat transfer parameters for copper oxide, silica oxide and titanium oxide Nano fluids across various temperatures and flow rates. Findings revealed copper oxide Nano fluids display the highest heat transfer coefficient owed to superior thermal conductivity, despite lower Nusselt numbers. Silica Nano fluids exhibited the maximum Reynolds number and Nusselt performance attributing to lower densities. Overall, copper oxide achieved the highest cumulative heat transfer, also having the lowest pressure drop due to favorable thermo physical characteristics. The comparative assessment quantitatively demonstrates the significant role precise nanoparticle engineering coupled with concentration optimization plays in balancing critical parameters for feasible heat exchange implementations. Further exploration of novel nanomaterials using simulations could discover optimal combinations.

Hussein and Alaiwi [38] presented extensive experimentation published in X journal analyzing titanium dioxide/water nanofluids for enhancing counterflow double-pipe heat exchanger effectiveness across various nanoparticle concentrations from 0.1-0.5%. Detailed instrumentation measured resulting changes in thermophysical properties like thermal conductivity and viscosity alongside heat transfer metrics across different flow rates. Outcomes displayed over 20% thermal conductivity and 15% viscosity growth with nanofluid incorporation, translating to major heat transfer coefficient and efficiency spikes above baseline levels before declining at higher concentrations. Peak effectiveness was recorded at 0.3% concentration, with heat transfer rates 17% over pure water. The research further correlated efficiencies to parameters including heat transfer units and Reynolds numbers. Demonstrating sizable real-world performance gains from judiciously tailored nanofluids, it makes vital contributions toward their adoption in sustainable heat exchange equipment across industries.

Thianpong et al. [39] investigated heat transfer enhancement in a tube using a combined technique with titanium dioxide (TiO_2) nanoparticles mixed with water (Nano fluid) and loose-fit delta-wing twisted tape inserts. The Nano fluids had varying TiO_2 concentrations by volume and the twisted tapes had different wing arrangements and loose-fit ratios. The results showed significantly improved heat transfer compared to without enhancement, attributed to swirling flow and higher thermal conductivity of Nano fluid. Heat transfer and performance increased at lower loose-fit ratio and higher nanoparticle concentration. A maximum performance factor was obtained at a specific loose-fit ratio and TiO_2 concentration. One twisted tape arrangement had slightly higher heat transfer and performance than the other. Optimization modeling accurately determined the best compromise between friction factor and Nusselt number for the arrangements, effectively showing the trade-off.

Al Zerkani and Alaiwi [40] in their computational study, the researchers investigated the enhancement of heat transfer using a ferro-nanofluid in the presence of a magnetic field within a tube equipped with an inserted twisted tape. They employed ANSYS to model the flow and heat transfer, considering both water and Fe_3O_4 Nano fluid as the working fluids. The study analyzed the impact of various parameters, including the concentration of the ferro-nanofluid, the intensity of the magnetic field, and the number of rotation cycles of the twisted tape, on pressure, temperature, and velocity. The findings revealed that as the magnetic field intensity, nanofluid concentration, and rotation cycles increased, the fluid pressure decreased, while both temperature and velocity increased. The enhancement in heat transfer was attributed to the formation of nanoparticle chains, which acted as thermal tunnels, facilitating improved heat transfer. The computational approach employed in the study showed good agreement with experimental data, demonstrating the effectiveness of using ferro-nanofluid in combination with a magnetic field for augmenting heat transfer.

Fetuga et al. [41] numerically analyzed shell-and-tube heat exchangers (STHXs) with different tube layouts for waste heat recovery applications. Hot water at 65°C underwent counterflow heat transfer with cold water at 10°C in the tubes. ANSYS Fluent simulations using a realizable k-epsilon model compared triangular, rotated triangular and combined configurations. The triangular layout (STHX-T) achieved the maximum overall heat transfer coefficient of 2307.09 W/m2K and highest cold water temperature rise. It also showed the greatest shell side temperature drop and pressure drop. As mass flow rate increased from 0.5 - 3.5 kg/s, STHX-T displayed 22-45% higher heat transfer versus the rotated triangular layout. Customizing tube bundles through modeling and optimization was demonstrated to effectively enable waste heat recovery.

3. METHODOLOGY

This chapter outlines the integral methodologies and techniques employed to carry out the analysis of using Nano fluids in shell and tube heat exchangers. First, relevant theoretical concepts around heat transfer mechanisms, design of heat exchangers, and properties of Nano fluids are explored to establish the foundational knowledge base. Building on this, the methodology covers the computer-aided design and modelling of the heat exchanger, including the selection of key dimensions and parameters. Furthermore, the chapter discusses the governing equations for computational fluid dynamics simulations and the process for grid independence testing to determine optimal discretization schemes. Details around assigning boundary conditions, specifying Nano fluid properties based on concentration, and comparing working fluids are also provided. The finite element method is outlined as an overarching numerical technique for the thermal and hydraulic analyses, complemented by the CFD methodology. In summary, this chapter aims to provide a comprehensive understanding of the stepwise methodologies utilized right from the design conception stage to the analytical procedures, encompassing both theoretical formulations and computational tools to facilitate a performance evaluation of Nano fluids in the heat exchanger. The systematic protocols described form the blueprint for the next chapter where the results will be presented and interpreted to draw pertinent conclusions.

3.1 HEAT TRANSFER SCIENCE

3.1.1 Introduction

Heat transfer refers to analysing and quantifying the exchange of thermal energy across physical systems, focusing specifically on transfer rates rather than net heat quantities over time. It encompasses three primary mechanisms – conduction, convection, and radiation. Conduction deals with heat transfer between neighbouring molecules within solids or static fluids, occurring due to energetic collisions between particles. This is governed by Fourier's Law correlating heat flux to thermal conductivity and temperature gradients. Materials like metals conduct heat rapidly courtesy of high conductivities, while insulators oppose conduction. Convection centres on heat exchange between surfaces and moving fluids, combining effects of bulk fluid motion and conduction between the fluid and solid interface. It depends on parameters like fluid velocities and the temperature differential with the surface. Radiation constitutes emission of thermal energy as electromagnetic waves from any matter above absolute zero temperature, enabling distant transfer through vacuums. Comprehending real-world transfer necessitates analysing these mechanisms' compound effects, making heat transfer studies essential for unlocking efficient heating/cooling technologies across applications. It combines effects of bulk fluid motion removing heated fluid from near a surface and replacing it with cooler fluid in addition to conduction between the fluid and surface. Convection rates are related to velocity of fluid motion and captured in Newton's Law of Cooling which describes convection in terms of a heat transfer coefficient, surface area, and temperature difference. Forced convection involves external inducement of fluid motion around a surface while natural convection arises from density differences induced by heating the fluid leading to bulk motion on its own. Radiation refers to emission of electromagnetic energy from a surface. It differs from conduction and convection in not relying on proximity of another object or presence of intermediate fluid, allowing heat transfer through vacuum. Radiation emitted depends on the surface temperature and properties governed by the Stefan-Boltzmann law. The maximum radiation from a surface is that of a blackbody while real surfaces emit less based on their emissivity. Radioactive transfer between objects depends on their size, separation distance, temperatures, and radiation properties. Analysis of many heat transfer scenarios involves understanding combinations of these mechanisms at play. This includes analysing overall heat transfer rates as well as conditions like surface temperature that arise from the net heat transfer. Thus, the fundamentals of heat transfer form a critical engineering science for thermal analyses [42].

3.1.2 Heat Transfer Methods

a. Conduction

Refers to the process where heat energy is transmitted through a material due to the presence of a temperature gradient, driven by the microscopic collisions among its particles. The principle underlying conduction is encapsulated by Fourier's law, which, when applied to one-dimensional heat flow through a solid, is formulated as [43]:

$$q'' = -k\frac{dT}{dx} \tag{3.1}$$

Here, denotes q'' the rate of heat transfer per unit area, k represents the material's thermal conductivity, and $\frac{dT}{dx}$ is the temperature gradient along the heat flow direction. The negative sign signifies that heat moves from regions of higher temperature to those of lower temperature.

b. Convection

Encompasses the heat transfer occurring between a solid boundary and an adjoining moving fluid, facilitated by both molecular diffusion and the macroscopic movement of the fluid. This process is mathematically described by the convection rate equation, also known as Newton's law of cooling [43]:

$$q'' = h(T_s - T_\infty) \tag{3.2}$$

In this equation, is the convective heat transfer rate per unit area W/m^2, h is the convective heat transfer coefficient $W/m^2 \cdot K$, T_s is the temperature of the solid surface and T_∞ is the fluid temperature at a significant distance from the surface.

c. Radiation

Radiation denotes the discharge of energy from matter in the form of electromagnetic waves or photons, which occurs because of its temperature. The total energy radiated per unit area across the entire spectrum is determined by the Stefan-Boltzmann law, expressed as [43]:

$$q'' = \epsilon\sigma(T^4 - T_{\text{surroundings}}^4) \tag{3.3}$$

Here, q'' is the radiant heat flux(W/m^2), ϵ denotes the surface's emissivity, σ is the Stefan-Boltzmann constant. T is the absolute temperature of the emitting surface, and $T_{\text{surroundings}}$ is the absolute temperature of the surrounding environment.

3.1.3 HEAT EXCHANGERS

3.1.3.1 Introduction

Heat exchangers are essential devices used in a wide range of applications to transfer heat between two or more fluids at different temperatures. They facilitate heating or cooling in industries like power generation, chemical manufacturing, petroleum refining, food processing, electronics cooling, and heating, ventilation, and air conditioning (HVAC). Heat exchangers are generally classified based on transfer mechanism (direct contact or indirect), flow arrangement (parallel flow, counterblow, cross flow), construction (tubular, plate, extended surfaces), and phase of fluids (single-phase or two-phase). Common designs include shell-and-tube, plate, plate-fin, spiral plate, and direct contact exchangers like cooling towers. The choice of heat exchanger depends on the application, allowable pressure drops, fluid properties, fouling tendencies, and cost. Key design objectives for heat exchangers relate to accommodating thermal stresses, enabling periodic cleaning and maintenance, minimizing inventory, and optimizing the capital and operating costs. Their development has enabled modern power plants, seawater desalination, food processing, cryogenic air separation and several chemical processes. Recent research has focused on enhancing heat transfer coefficients using extended surfaces, Nano fluids, and optimized channel geometries while minimizing fouling [44].

3.1.3.2 Heat exchanger types

a. Double-Pipe Heat Exchangers: These are foundational heat exchangers where hot and cold fluids traverse either in identical or opposing directions. This category is further divided based on the flow arrangements into [43]:

   Parallel-Flow Configuration: In this setup, both fluids initiate at the same end, proceed parallel, and exit together, maintaining a uniform flow direction.

   Counter-Flow Arrangement: Here, the fluids are introduced from opposite ends, move against each other, and exit from their respective opposite ends.

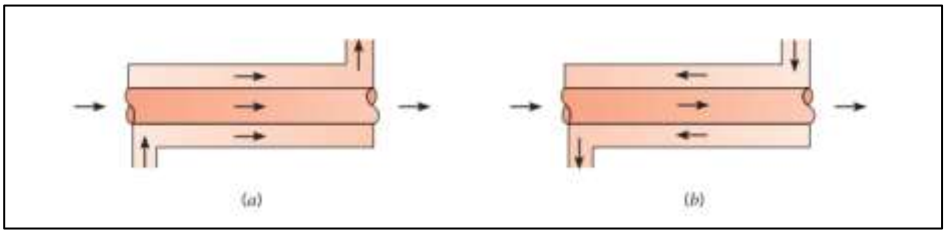

Figure 3.1: Double Pipe Heat Exchanger: (A) Parallel Flow. (B) Counter Flow [43].

b. Heat Exchangers with Cross flow Mechanism: This design allows the fluids to cross paths perpendicularly. Based on the fin presence and fluid mixing conditions, they are differentiated as [43]:

Equipped with Fins: Both fluids remain separate, with the cross flow's temperature being a function of both longitudinal and lateral positions due to the restriction of lateral movement by the fins.

Without Fins: In this design, one fluid mixes while the other stays segregated, facilitating temperature variation predominantly along the flow direction due to the allowance of lateral mixing.

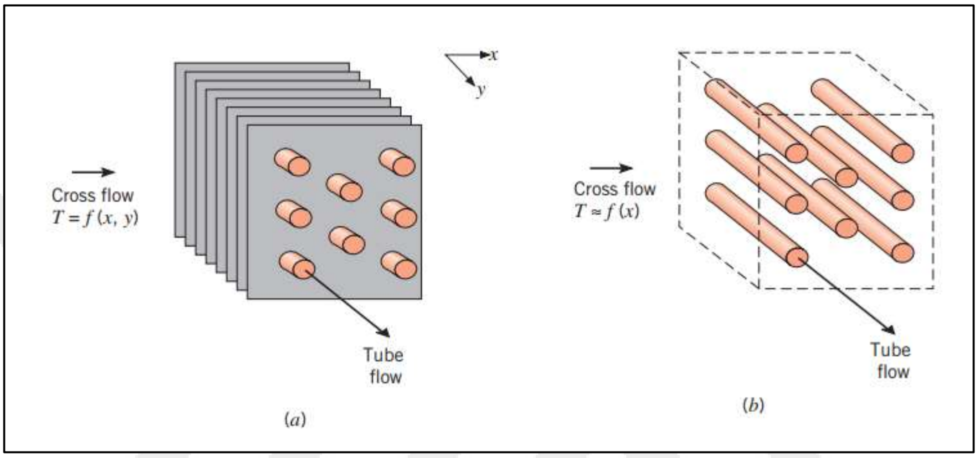

Figure 3.2: Heat Exchangers with Cross flow Mechanism: (a) finned. (b) Unfanned [43].

c. Shell-and-Tube: A widely recognized form, these exchangers vary with the shell and tube pass numbers. The most basic model features a single pass for both tube and shell. Turbulence and support are provided by baffles, which also enhance the shell-side fluid's convection coefficient. Variations include configurations with different numbers of shell and tube passes [43].

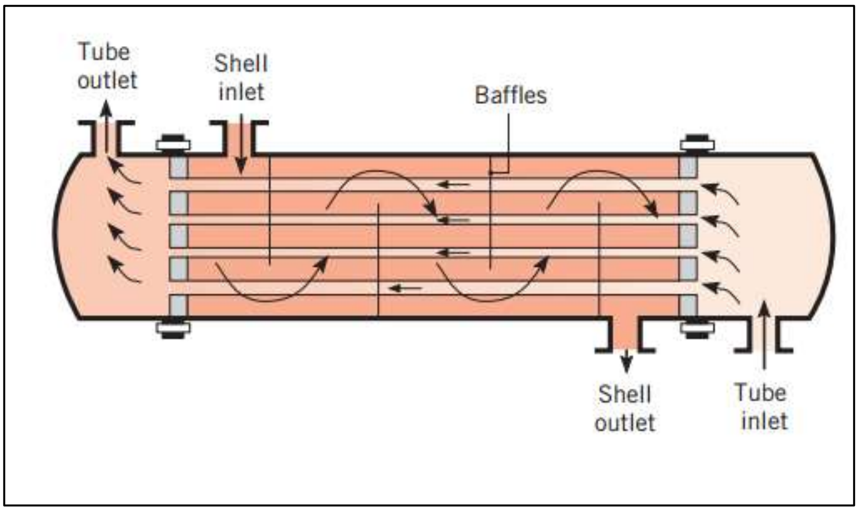

Figure 3.3: Schematic for Shell and Tube Heat Exchanger [43].

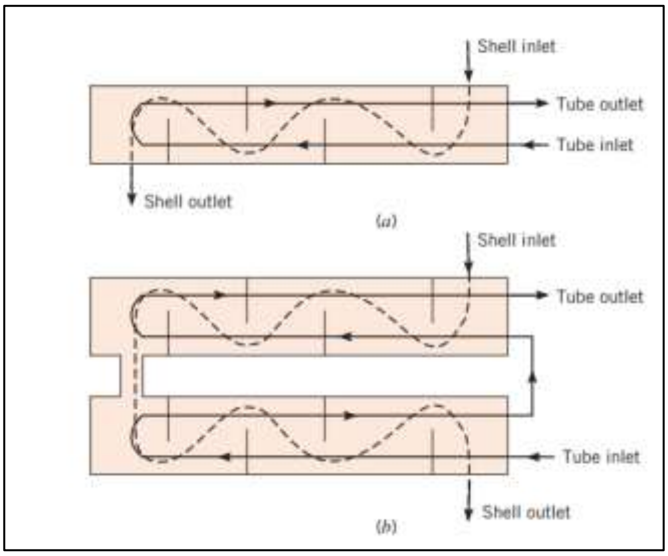

Figure 3.4: Variants of Shell-and-Tube Heat Exchanger Configurations: (A) Exchanger with Single Shell Pass and Two Tube Passes. (B) Exchanger with Two Shell Passes and Four Tube Passes [43].

d. Compact heat exchangers stand out for large heat transfer area per unit volume, making them ideal when a fluid has low convection coefficients, like gases. Featuring dense arrays of fins, plates or finned tubes, they contain small flow passages typically inducing laminar regimes, aiding conductive transport. The higher surface area density enables superior heat recovery in space-constrained applications. Various geometric configurations exist, including flat or circular finned tubes, single or multi-pass arrangements across plates/tubes, etc. Tailoring passage hydraulics and materials selection for different fluids offers substantial customization flexibility. Their intensified heat transfer suits mobile weight-sensitive systems across automotive, aerospace, and electronic cooling where performance maximization is vital. Thus, purposeful compact heat exchanger design, balancing heat duty, pumping efficiency and reliability via modeling remains an active research front for sustainable thermal management [43].

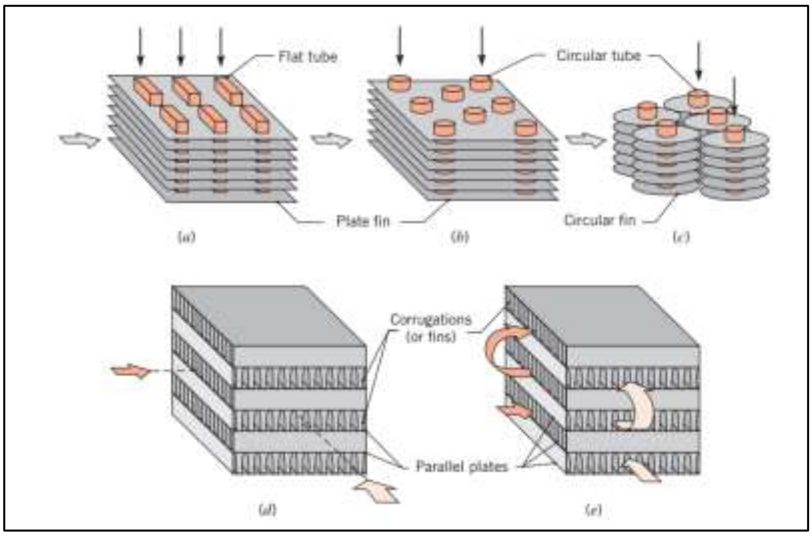

Figure 3.5: Compact Heat Exchanger Core Configurations and Components :(A) Tubes with Continuous Plate Fins. (B) Circular Tubes with Continuous Plate Fins. (C) Circular Tubes with Circular Fins. (D) Plate-Fin Core with Single Fluid Pass. (E) Plate-Fin Core with Multiple Fluid Passes [43].

3.1.3.3 Shell and tube heat exchanger theoretical equations

a. Heat Duty: It is referring to the amount of thermal energy that needs to be transferred from one fluid to another to achieve desired temperature changes within the system. It is quantitatively defined by the formula [45]:

$$Q_S = M_S \cdot c_S \cdot (T_1 - T_2) \tag{3.4}$$

$$Q_T = M_T \cdot c_T \cdot (t_2 - t_1) \tag{3.5}$$

where, Q_S, Q_T are the heat transferred in the shell side and tube side, respectively(watts) , M_S, M_T are the mass flow rate of the fluid in the shell side and tube side, respectively (kg/h) ,c_S ,c_T are the specific heat capacity of the fluid in the shell side and tube side, respectively (Wh/kg·K), T_1, t_1 are the inlet temperature of the fluid in the shell side and tube side, respectively (°C), T_2, t_2 are the outlet temperature of the fluid in the shell side and tube side, respectively (°C) .

b. Overall Heat Transfer Coefficient (U) Calculation [45]:

$$Q = U \cdot A \cdot \Delta T_m \tag{3.6}$$

c. log mean temperature difference [43]:

$$q = UA\Delta T_{\text{lm}} \quad (3.7)$$

where,

$$\Delta T_{\text{lm}} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \quad (3.8)$$

For the parallel-flow exchange [43]:

$$\begin{bmatrix} \Delta T_1 = T_{h,1} - T_{c,1} = T_{h,i} - T_{c,i} \\ \Delta T_2 = T_{h,2} - T_{c,2} = T_{h,o} - T_{c,o} \end{bmatrix} \quad (3.9)$$

Where, $T_{h,i}$ is the inlet temperature of the hot fluid. $T_{c,i}$ is the temperature of the cold fluid $T_{h,o}$ is the outlet temperature of the hot fluid. $T_{c,o}$ is the outlet temperature of the cold fluid. All of them unit is degrees Celsius (°C).

For the counter-flow exchange [43]:

$$\begin{bmatrix} \Delta T_1 = T_{h,1} - T_{c,1} = T_{h,i} - T_{c,o} \\ \Delta T_2 = T_{h,2} - T_{c,2} = T_{h,o} - T_{c,i} \end{bmatrix} \quad (3.10)$$

d. Heat exchanger effectiveness [43]:

The efficiency, denoted as ε, is defined as the proportion of the actual rate of heat transfer in a heat exchanger compared to the highest achievable rate of heat transfer [43].

$$\varepsilon = \frac{q}{q_{max}} \quad (3.11)$$

3.2 NANOFLUIDS IN HEAT EXCHANGERS

3.2.1 Introduction

Nano fluids refer to a new class of heat transfer fluids engineered by dispersing and suspending nanoparticles, typically under 100 nm in size, in base fluids such as water, ethylene glycol, or oil. The term "Nano fluid" was first coined in 1995 by Choi and Eastman, who recognized the potential of nanoparticles to significantly enhance the thermo physical properties and heat transfer performance of conventional fluids. Since then, extensive research has focused on these innovative fluids due to their superior conductive and convective heat transfer capabilities compared to their base fluids alone. Nano fluids contain tiny concentrations of metals, metal oxides, carbon nanotubes, or other nanomaterials suspended stably in the base fluid, usually at volume fractions below 5%, by using surfactants, surface functionalization, or physical methods. The Nano-scale size of the particles gives rise to unique properties unattainable with larger particles. With just small amounts of nanoparticles, Nano fluids exhibit remarkably higher thermal conductivity compared to the base fluid, allowing for effective heat transfer and high energy efficiency in numerous applications. Potential uses for Nano fluids include transportation cooling systems, industrial cooling processes, microelectronics cooling, defence systems, nuclear systems, solar water heating, and more. Their heat transfer enhancements could lead to highly compact and effective thermal management across many fields. In summary, Nano fluids are dilute colloidal suspensions of Nano scale particles that can significantly improve heat transfer properties thanks to their Nano-scaled effects. Their tiny concentration of nanoparticles enhances thermo physical properties substantially compared to conventional heat transfer fluids [46].

3.2.2 Types and Properties of Nano Fluids

Several types of nanoparticles are leveraged in Nano fluids for intensifying heat transfer capabilities beyond traditional fluids. Carbon-based Nano fluids use CNTs (carbon nanotubes), Gt (graphene), C (diamond) or fullerene particles to appreciably improve thermal conductivity and heat transfer given their high intrinsic conductivities. Metal Nano fluids utilize Ag (silver), Cu (copper), Au (gold), Al (aluminum), Fe (iron) or Co (cobalt) nanoparticles to similar effects. Metal oxide variants employ Al2O3 (alumina), CuO (copper oxide), Fe3O4 (iron oxide), TiO2 (titanium dioxide) or ZnO (zinc oxide) nanoparticles to simultaneously enhance heat transfer and provide stability. Other Nano fluids also use Si (silicon), SiC (silicon carbide), SiO2 (silica) or MgO (magnesium oxide) nanoparticles. Adding miniscule fractions of such nanomaterials substantially augments the otherwise poor thermal conductivity of base fluids like water, ethylene glycol or oils. However, increased viscosities can promote sedimentation and clogging problems over time. While heat capacities reduce over base fluids, Nano fluid densities show linear nanoparticle concentration-linked rises. Long-term stability against sedimentation and agglomeration poses significant challenges as well. Usage of surfactant surface functionalization or sonication offers partial improvements. Overall, optimized Nano fluids achieve markedly superior heat conduction and convection compared to conventional alternatives, creating new possibilities for sustainable and efficient thermal technologies across applications. Further research into novel nanomaterial’s paired with tailored concentration, surface treatment and dispersion techniques is imperative to translate these promising capabilities into full-fledged industrial adoption [47].

3.2.3 Nano Fluid Concentration Analysis

a. Thermal Conductivity (Maxwell model): The Maxwell model is used to estimate the effective thermal conductivity of Nano fluid [48].

$$k_{nf} = k_{bf}\left(\frac{k_{np}+2k_{bf}-2\phi(k_{bf}-k_{np})}{k_{np}+2k_{bf}+\phi(k_{bf}-k_{np})}\right) \quad (3.12)$$

k_{nf} is the thermal conductivity of the Nano fluid (W/m·K), k_{bf} is Thermal conductivity of the base fluid (W/m·K), k_{np} is Thermal conductivity of the nanoparticles (W/m·K), and ϕ Volume fraction of nanoparticles (dimensionless).

b. Viscosity (Einstein model) The Einstein model predicts the increase in viscosity due to the dispersed particles [49].

$$\mu_{nf} = \mu_{bf}(1 + 2.5\phi) \quad (3.13)$$

Where, μ_{nf} is the dynamic viscosity of the Nano fluid (Pa·s), μ_{bf} is the Dynamic viscosity of the base fluid (Pa·s), ϕ is the volume fraction of nanoparticles (dimensionless), and (1+2.5ϕ) is the correction factor for the presence of nanoparticles.

c. Specific Heat Capacity (Mixture Rule): The mixture rule is applied to calculate the nanofluid's specific heat capacity [50].

$$C_{p,nf} = \phi C_{p,np} + (1-\phi)C_{p,bf} \quad (3.14)$$

where, $C_{p,nf}$ is specific heat capacity of the nanofluid (J/kg·K), $C_{p,np}$ is specific heat capacity of the nanoparticles (J/kg·K), and $C_{p,bf}$ is specific heat capacity of the base fluid (J/kg·K).

d. Density (Mixture Rule): The mixture rule for densities provides an estimate for the Nano fluid’s density [51].

$$\rho_{nf} = \phi\rho_{np} + (1 - \phi)\rho_{bf} \tag{3.15}$$

Where, ρ_{nf} is density of the Nano fluid (kg/m³),ρ_{np} is density of the nanoparticles (kg/m³), and ρ_{bf} is density of the base fluid (kg/m³).

3.3 COMPUTATIONAL FLUID DYNAMICS

3.3.1 Introduction

In the early 1970s, the convergence of physics, numerical mathematics, and computer science gave rise to computational fluid dynamics (CFD), which aims to simulate fluid flows. The availability of increasingly powerful mainframe computers at that time catalyzed CFD development, which has continued to evolve alongside advances in technology. Initial CFD applications focused on modelling transonic airflow by solving non-linear potential equations. As computing power dramatically increased during the 1980s, two-dimensional and later three-dimensional Euler equations could be solved, allowing the simulation of inviscid flows around complete aircraft or within turbo machinery. This shift enabled computing more complex viscous flows governed by Navier-Stokes equations and developing various turbulence models, with direct numerical simulation (DNS) and large eddy simulation (LES) at the forefront. Later improvements in numerical techniques, especially implicit schemes, permitted simulating flows needing real gas modelling, including large-scale cases like 3D hypersonic flows past re-entry vehicles using equilibrium and non-equilibrium chemistry models. Significant efforts were also devoted to numerically simulating combustion and flame modelling, vital for cleaner gas turbines and engines. Grid generation approaches have progressed from simple structured meshes to more refined multiblock and unstructured grids, mirroring the growing demands for accurate flow simulations. This evolution has facilitated tackling geometric complexity and enhancing simulation fidelity. Nowadays, CFD techniques are utilized across diverse areas, from aircraft and turbine design to meteorology, oceanography, astrophysics, biology, etc. Despite its broad use and progress made, CFD is not yet seen as a fully mature technology, with many unresolved challenges around turbulence, combustion, heat transfer, viscous flows, and robust discretization. While remaining an essential engineering design and research tool, advances in numerical methods and computing power have enabled complex CFD simulations on personal computers. However, open questions persist around aspects like turbulence, underscoring the need for further research. New opportunities also emerge around design optimization using CFD, highlighting its enduring importance [52].

3.3.2 Governing Equations

The foundational principles of fluid dynamics and thermodynamics are encapsulated within the governing equations that address fluid flow and heat transfer. Rooted in the fundamental conservation laws of physics—specifically, the conservation of mass, momentum, and energy—these equations characterize how a fluid behaves by detailing its macroscopic characteristics like velocity, pressure, density, and temperature, along with how these properties change across space and over time [53].

a. Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathrm{u}) = 0 \tag{3.16}$$

Where is the fluid density (mass per unit volume). t: Time. u: Velocity vector of the fluid, and $\nabla \cdot (\rho \mathrm{u})$ divergence of the mass flux, indicating how much mass is entering or leaving a point in space.

b. Momentum Equations in space [53]:

For the x-component:

$$\boldsymbol{\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{Mx}} \tag{3.17}$$

For the y-component:

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + S_{My} \tag{3.18}$$

For the z-component:

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + S_{Mz} \tag{3.19}$$

where, Du/Dt , $Dv/Dt, Dv/Dt$ are substantive derivatives of the velocity components in the x, y, and z directions, representing the acceleration of a fluid particle, S_{Mx}, S_{My}, S_{Mz} are Source terms for momentum in the x, y, and z directions, representing external forces (e.g., gravity, electromagnetic forces) per unit volume, $\tau_{xx}, \tau_{yx}, \tau_{zx}$.

c. Energy Equation [53]

$$\rho \frac{De}{Dt} = -\nabla \cdot q + \nabla \cdot (\tau \cdot \mathrm{u}) - \nabla p \cdot \mathrm{u} + S_E \tag{3.20}$$

where, e is the specific internal energy of the fluid. q: Heat flux vector, representing the rate of heat transfer per unit area, $\tau \cdot$ u work done by viscous stresses, indicating how viscous forces contribute to the energy change, S_E source term for energy, representing external heat sources or sinks per unit volume.

3.4 FINITE ELEMENT METHOD

3.4.1 Introduction

The Finite Element Method (FEM) is a powerful analytical technique used for studying complex systems across scientific and engineering disciplines. At its core, FEM involves subdividing a large system into more manageable individual components termed as "elements". Understanding the behavior of these discrete elements then allows one to analyze the system's overall behavior. Throughout history, there has been a drive to comprehend intricate natural phenomena. However, many systems' vast intricacy makes them hard to grasp completely. To tackle this, professionals in fields like engineering, science, and economics have employed a strategy of dividing systems into constituent components. Sometimes a system can be modeled satisfactorily considering a handful of components as 'discrete' problems. However, in other cases, subdivision may proceed unendingly, needing the concept of infinitesimals. FEM's evolution has been shaped by various approximation approaches used in mathematics and engineering historically. Eventually, the methodology of direct continuum elements was developed, emphasizing small continuum portions or elements that simplify behavior modeling. This viewpoint spawned the term 'finite element'. This notion is key in two respects: first, it aids conceptual clarity, and second, it offers a unified framework for tackling assorted issues, enabling standardized computing programs. In civil engineering applications especially, FEM entails ascertaining force-displacement relations individually for each structural element. Next, following specific protocols, the structure is reassembled, ensuring equilibrium at all connecting points or nodes. Solving the final equations then reveals unknown structural displacements. This systematic technique is widely employed for tackling discrete physical systems and approximating continuum problems [54].

3.5 SHELL AND TUBE HEAT EXCHANGER CAD DESIGN AND NUMERICAL ANALYSIS

In this section, the task is to design a heat exchanger using SolidWorks software. The design will follow the shell and tube configuration. An evaluation of standard market dimensions will be undertaken to select dimensions that are similar but not the same. A reference design is shown below, from which the current design will be derived, incorporating some differences. Furthermore, SOLIDWORKS Composer will be used to display the dimensions and other relevant details.

3.5.1 Shell and Tube Heat Exchanger Model Design

In the figures and tables presented below, the shell and tube type heat exchanger designated for this study is showcased, following the completion of its design using SOLIDWORKS.

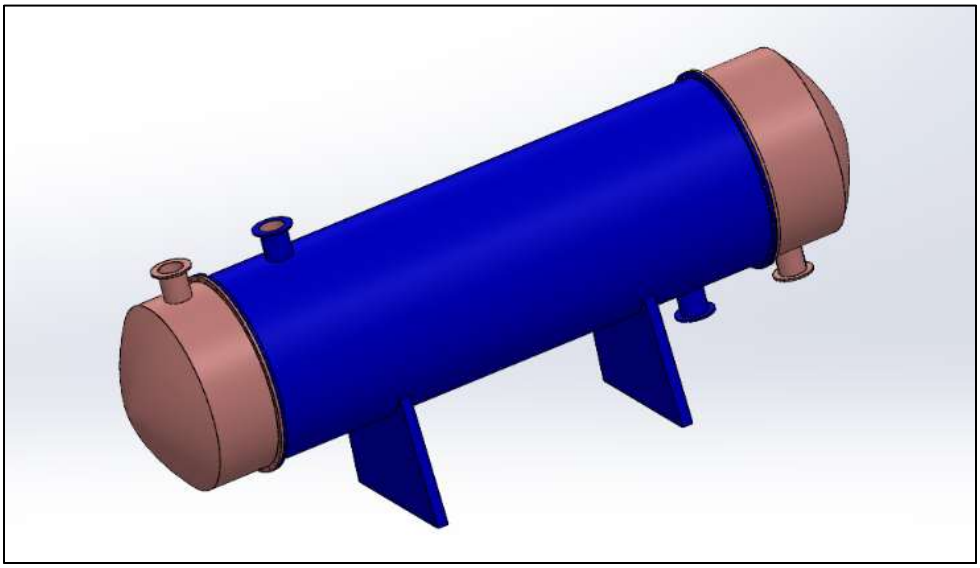

Figure 3.6: Model of Shell and Tube Heat Exchanger.

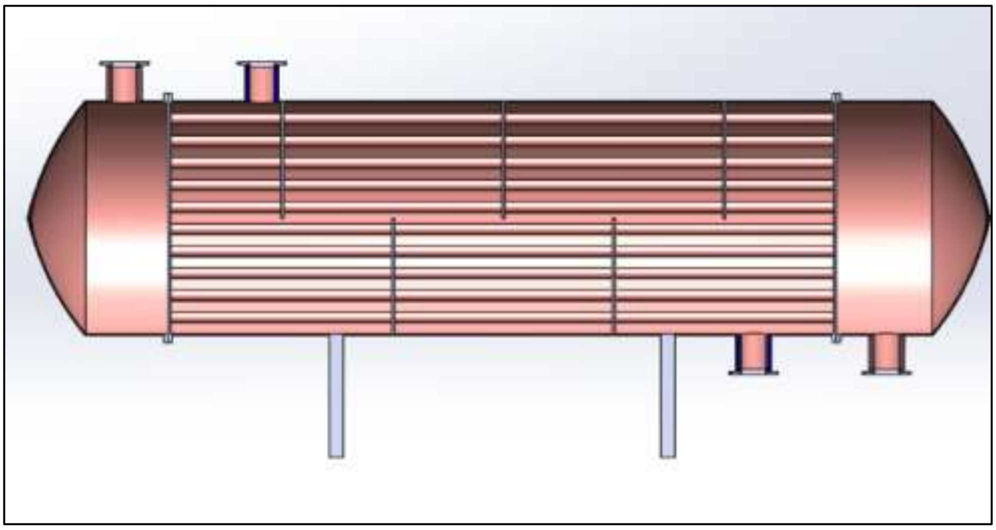

Figure 3.7: 2D Section of the Shell and Tube Heat Exchanger.

The figures below show the geometry dimensions of the heat exchanger by the SOLIDWORKS Composer.

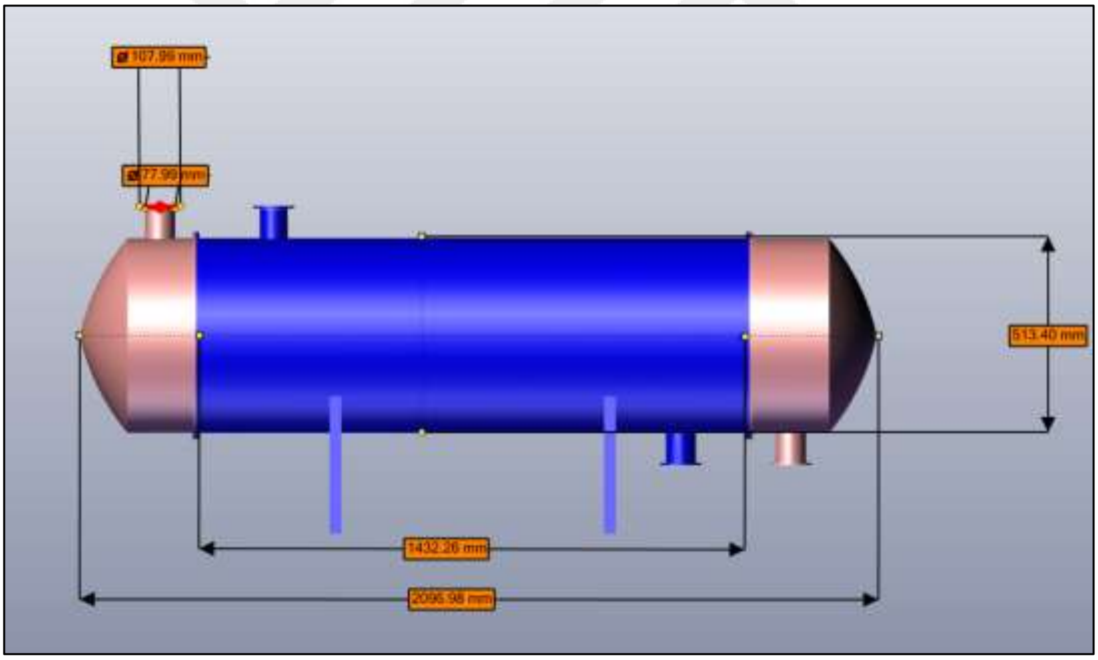

Figure 3.8: Shell and Tube Heat Exchanger Dimensions for the Outer Shell and Inlets and Outlets.

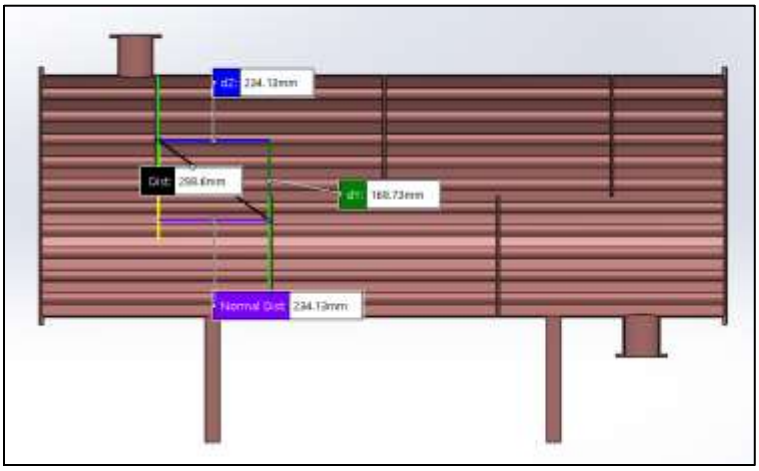

Figure 3.9: Shows the Number of Baffles and the Distance Between Them.

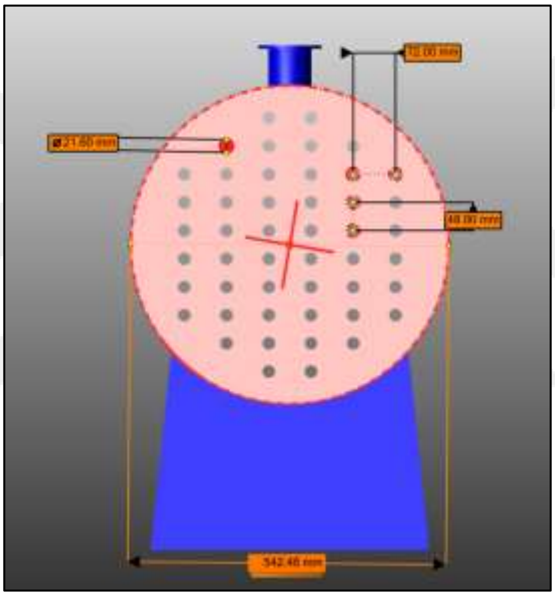

Figure 3.10: Shell and Tube Heat Exchanger Dimensions for Inner Tubes.

Table 3.1: Main Dimensions and Geometry Parameters of the Model.

Parameter	Value
Total Length	2096.98 m
Shell Diameter	513.40 mm
Tube length	1432.26 mm
Horizontal distance between tubes	72 mm
Vertical distance between tubes	48 mm
Number of tubes	48
Tube Diameter	21.6 mm
Inlets and outlets diameter	77.99 mm
Flange diameter	107.99 mm
Number of baffles	5
Baffle cut	50%
Distance between baffles	234.13 mm

3.5.2 Numerical Analysis Using Flow Simulation

Computational fluid dynamics (CFD) will be used to study fluid flow and heat transfer in the system. CFD analysis relies on numerically approximating differential equations that govern fluid motion. To set up a CFD simulation, the geometry is first divided into a mesh of discrete cells in a process known as discretization. Finer meshes can better capture gradients and fluxes but require more computational resources. Approximating the differential equations on the discrete mesh facilitates solving the equations and enables predicting flow velocities, pressures, and temperatures throughout the system. Through an approximation, CFD provides insight into flow behavior that is not feasible through analytical solutions or experiments alone. The software leverages powerful numerical methods to offer a versatile tool for flow analysis.

3.5.2.1 Mesh analysis

Grid independence testing is an important process for optimal mesh design in computational fluid dynamics (CFD) simulations. It involves evaluating solution accuracy across progressively refined grids to determine the mesh resolution beyond which the solution does not significantly change. This establishes a grid-independent solution that balances accuracy and computational expense. Grid independence testing overcomes reliance on subjective judgment during mesh selection and provides an objective mesh density guideline. By quantifying discretization errors using metrics like the grid convergence index (GCI), grid independence testing ensures the CFD solution approximates the true continuous equations and physical flows with minimal spatial errors. Establishing a grid-independent solution is critical for reliable CFD analyses. The article evaluates an improved testing approach that determines an optimal grid resolution based on geometrical characteristics. Formal grid independence testing ultimately bolsters confidence in CFD predictions by verifying spatial convergence of the numerical approximation [55].

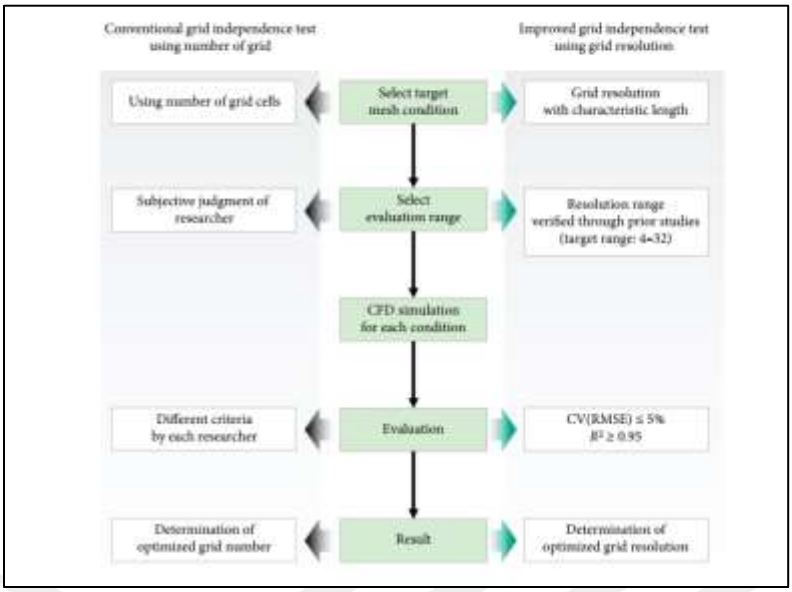

Figure 3.11: Flow Chart for Grid Independence Test [55].

In the Flow Simulation module of SolidWorks, mesh generation can be performed automatically, allowing for the autonomous division of cells. A refinement level from 1 to 7 is available for selection. Levels 2 through 6 are to be employed in the project to ascertain the optimum mesh configuration. The optimum mesh is identified as that which yields a stable output, one that does not exhibit significant changes with additional refinement.

The table below illustrates the number of cells generated by the program at each level from 1 to 7.

Table 3.2: Refinement Level Vs. Number of Cells Generated.

Refinement level	**Number of cells**
1	45816
2	71428
3	734358
4	1029859
5	2989859
6	4112679
7	9419425

In the next chapter, the results obtained from the grid test will be presented. This will include the representation of the cold fluid's temperature upon exit, i.e., after heating, for each 'number of cells' in every case. From this, the optimum mesh will be determined.

The figure below shows the mesh results on the heat exchanger as a whole and specifically on the tubes at refinement level.

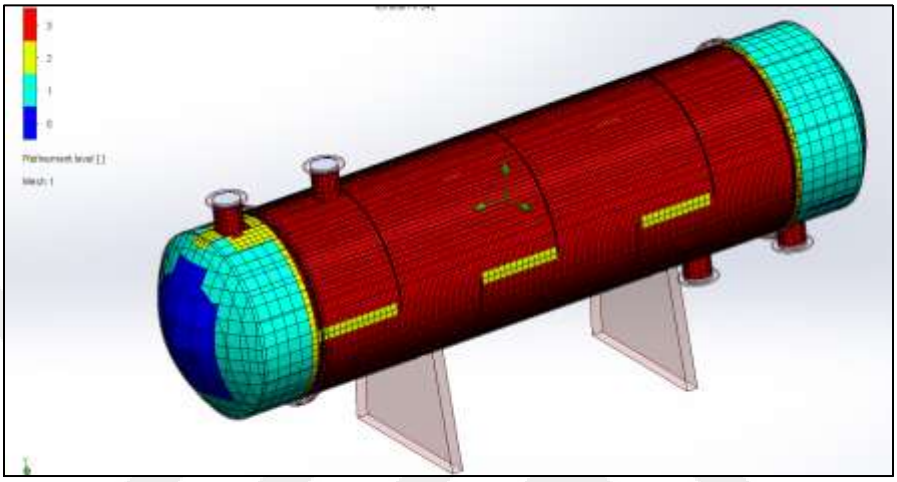

Figure 3.12: Mesh Results on a 3D Model.

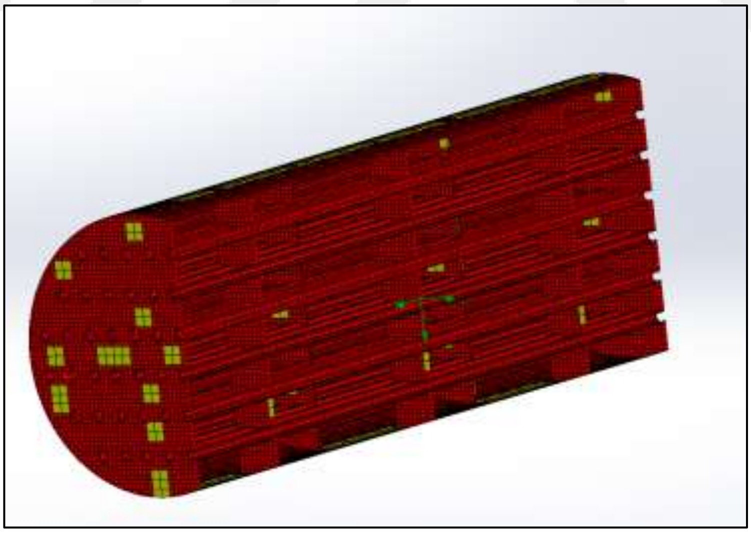

Figure 3.13: Mesh Results on Heat Exchanger Tubes.

3.5.2.2 Fluid Selections

Regarding the choice of fluids, in the first case study, only water will be used, whereas hot water will be utilized to heat cold water. In the second case, the Tio2 Nano fluid will be used within the water at a concentration of 0.5%.

Table 3.3: Water Thermal Properties [56].

Material	ρ kg/m3	Cp J/kg K	K W/m K	μ Pa.s
Water-liquid	997	4180	0.63	0.000404

Table 3.4: Thermal Properties of (Tio2) Nano Particles [57].

Specification	Value
Clarity	99.50%
Molecular weight	79.87 Gr mol^-1
Diameter	21 Nm
Density	4250 kg/m^3
Thermal conductivity	8.9 Wm^-1K^-1
Specific Heat	686.2 Jkg^-1K^-1

The concentration of TiO2, which is the Nano fluid used in this research, is 0.5%, with water serving as the base fluid. Utilizing equations from 12 to 15, the thermo physical properties of the Nano fluid were calculated and are illustrated in the table below. This methodical approach ensures a precise understanding of the Nano fluid’s characteristics, which is important for the study's accuracy and relevance.

Table 3.5: Thermal Properties Tio2 Nano Fluid with Concentration Of 0.5%.

Material	ρ kg/m3	Cp J/kg K	k W/m.K	μ Pa.s
TiO2 with ϕ 0.5%	1013.256	4164.521	0.65	0.0010125

3.5.2.3 Boundary conditions

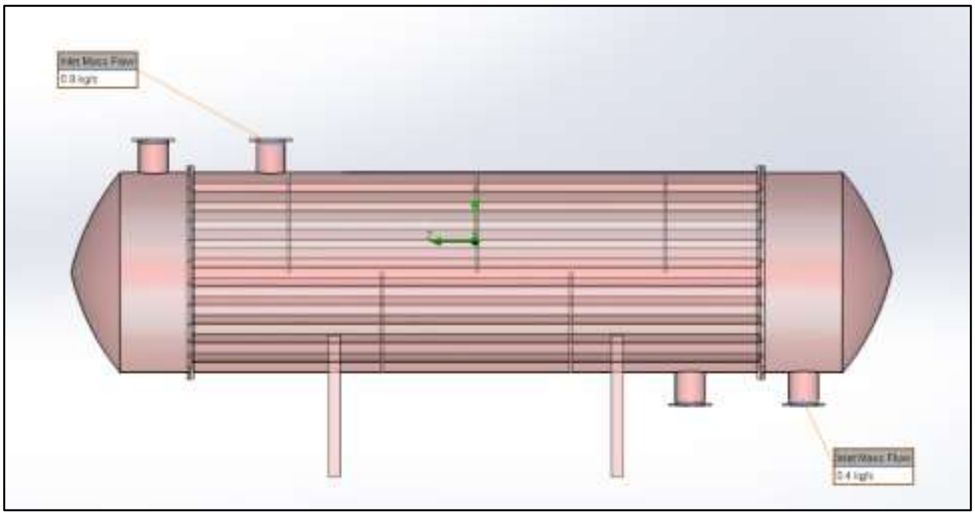

Figure 3.14: Shows the Inlet Mass Flow Rate for the Cold and Hot Fluids.

Table 3.6: Fluids in both Case Studies and Their Boundary Conditions.

Fluid	**Fluid**	**Temperature**	**Mass flow rate**
Case Study 1	Hot fluid: water	65 C	0.9 kg/s
	Cold fluid: Water	15 C	0.4 kg/s
Case study 2	Hot fluid: TiO_2 with ϕ 0.5%	65 C	0.9 kg/s
	Cold fluid: Water	15 C	0.4 kg/s

4. RESULTS AND DISCUSSION

In this chapter, the most important results reached will be presented, as the first case will be reviewed, which is using hot water to heat cold water. Then the other case will be reviewed, and a comparison will be made between them.

4.1 FIRST CASAE STUDY RESULTS

4.1.1 Grid Test Results

The results of the grid test between the number of cells outlined in Table 3.2 and the outlet temperature of the cold fluid after heating will be presented, as this parameter is the most crucial part of the study.

Table 4.1 below Figure 4.1 displays the outlet temperatures of the cold fluid after heating, across different numbers of cells resulting from the mesh refinement levels. Both the image and the table indicate that the curve stabilizes approximately between 4,112,679 and 9,419,425 cells. Therefore, 9,419,425 was selected as the optimum number of cells, signifying the optimal mesh to be adopted for completing the analysis. This determination underscores the precise approach taken to ensure the accuracy and efficiency of the thermal analysis.

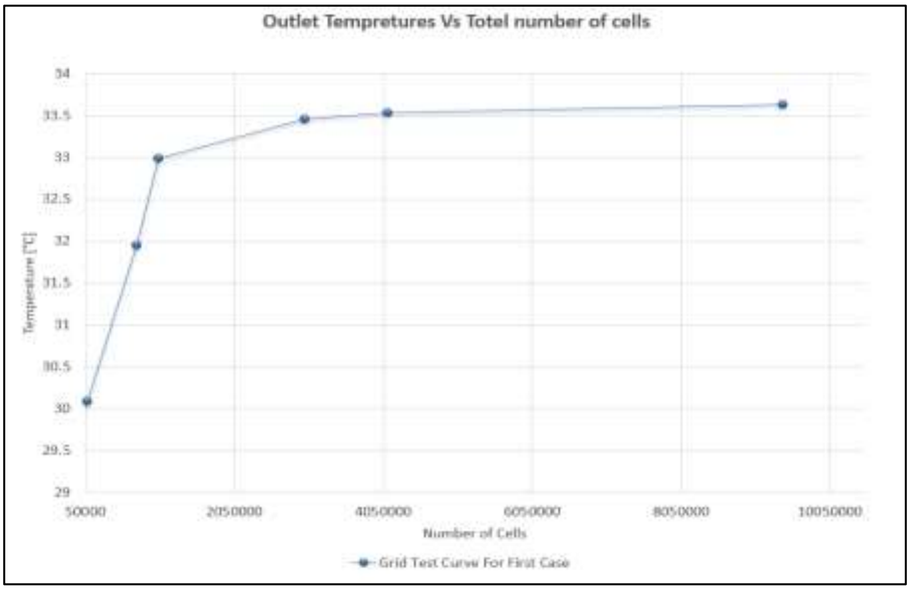

Figure 4.1: Outlet Temperatures for Cold Fluid at Different Numbers of Cells for the First Case.

Table 4.1: Outlet Temperature Values for Different Numbers of Cells in the First Case.

Refinement level	**Number of cells**	**Temperature**
1	45816	30.01498 C
2	71428	30.0929 C
3	734358	31.9548 C
4	1029859	32.9914 C
5	2989859	33.4184 C
6	4112679	33.5632 C
7	9419425	33.6301 C

4.1.2 Temperatures Results and Distribution

Initially, temperature rise curves for cold water between the inlet and outlet will be established, particularly as it passes through the tubes. Similarly, a trend indicating the decrease in temperature of the hot fluid and its heat loss to the cold fluid will be identified. The figure below illustrates the increase in temperature of the cold fluid on a curve between the inlet and outlet, as well as the other figure showing the decrease in temperature of the hot fluid.

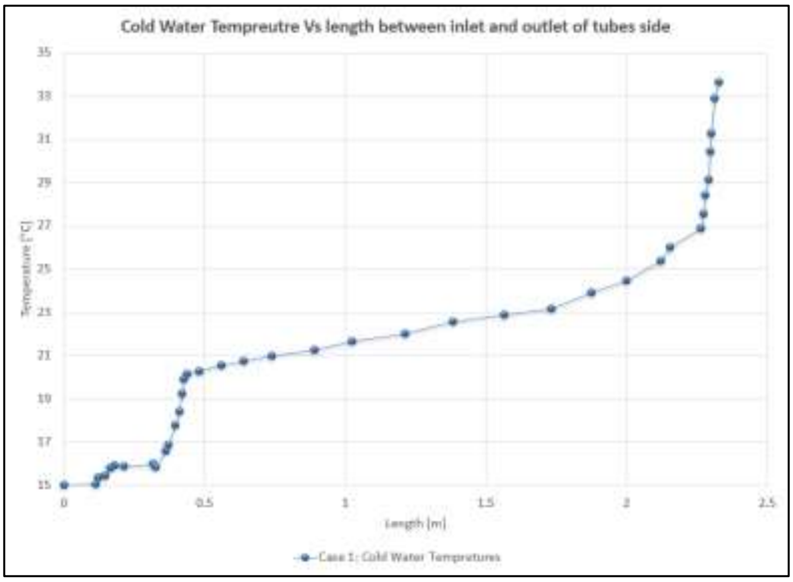

Figure 4.2: Temperatures Rise for Cold Fluid in the Tube Between The Inlet and Outlet.

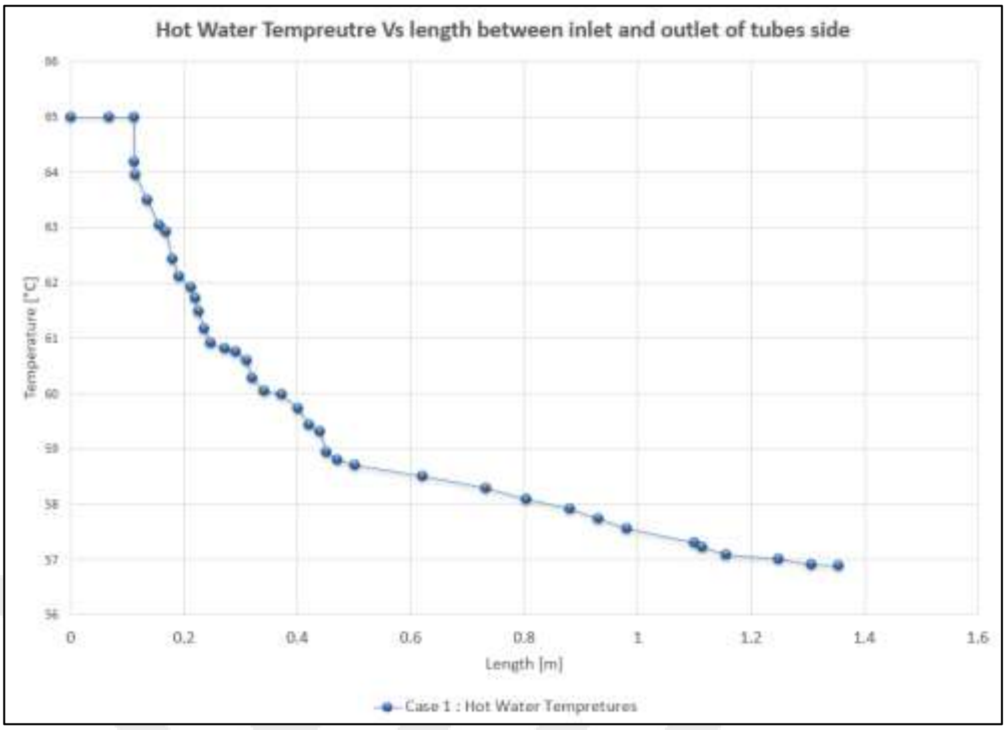

Figure 4.3: Temperatures Decrease for Hot Fluid on the Shell Side Between The Inlet and Outlet.

The two figures below show the temperature contours for the first case study. The first figure illustrates the temperatures at the inlet, which were also set as boundary conditions. The figure below shows the resultant temperatures in both the cold and hot fluids.

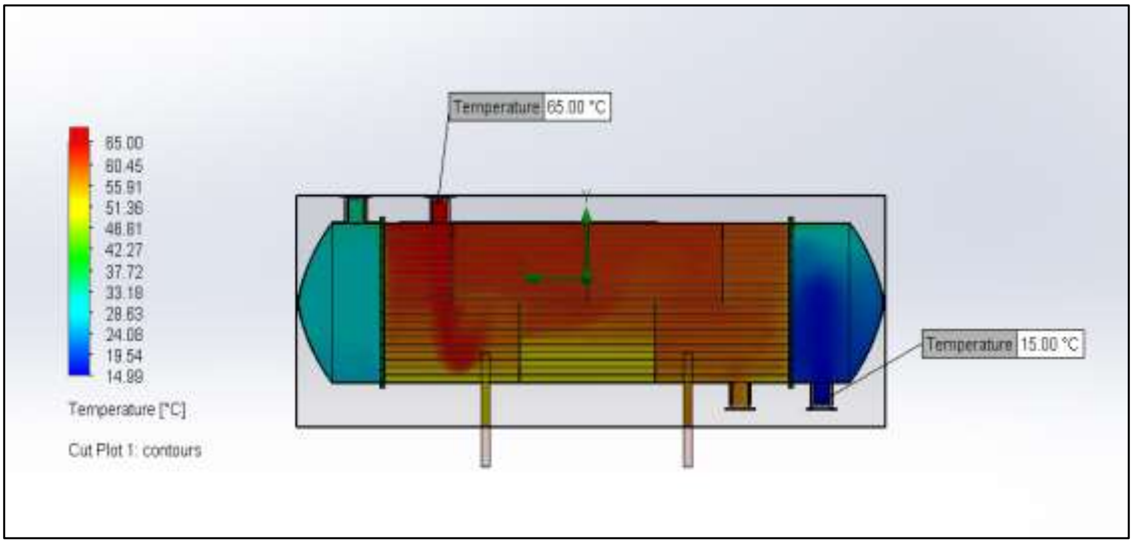

Figure 4.4: Temperature Countors Result in Inlet Temperatures for Both Fluids.

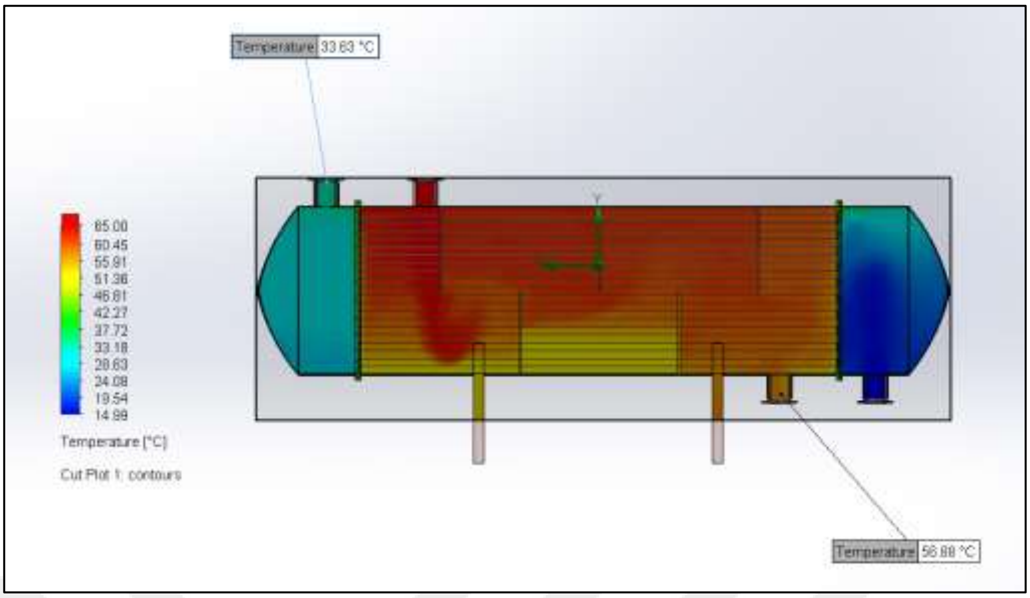

Figure 4.5: Temperature Countors Results and Outlet Temperatures for Both Fluids in the First Case.

The figure below shows the heat distribution on the outer surface of the shell and tube type heat exchanger. This distribution depends on the metal the exchanger is made of, which in this case is copper. As noted, the highest temperatures are in the central region, and the reason is that it is the entrance to the hot fluid.

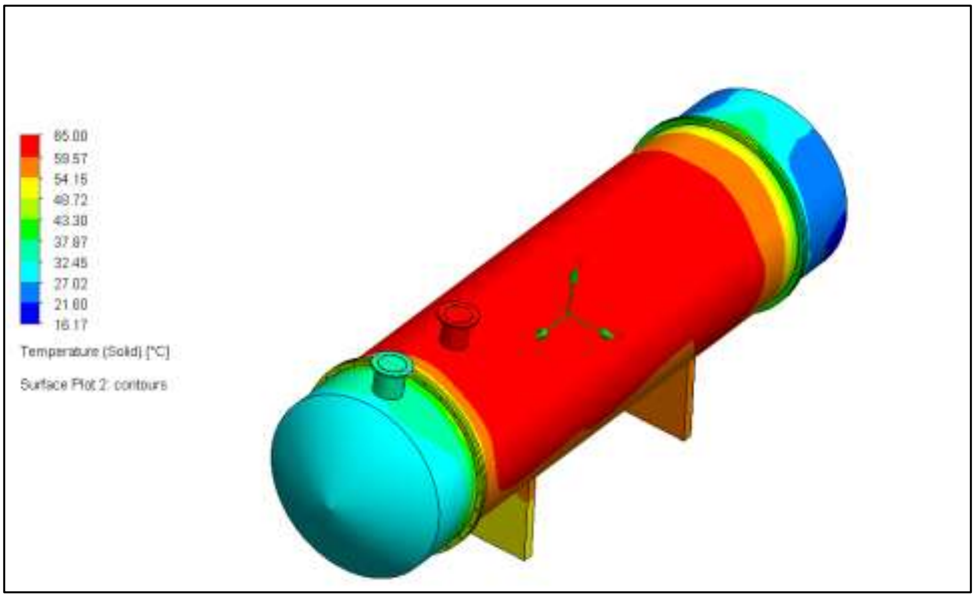

Figure 4.6: Surface Temperature Distribution on the Shell and Tube Heat Exchanger in the First Case.

To also display the thermal distribution in this simulation, several sketches were taken to illustrate how the temperature changes along the length of the heat exchanger, as shown in the figures below.

The figure below shows the temperature distribution along different sections at several locations along z direction for the first case study.

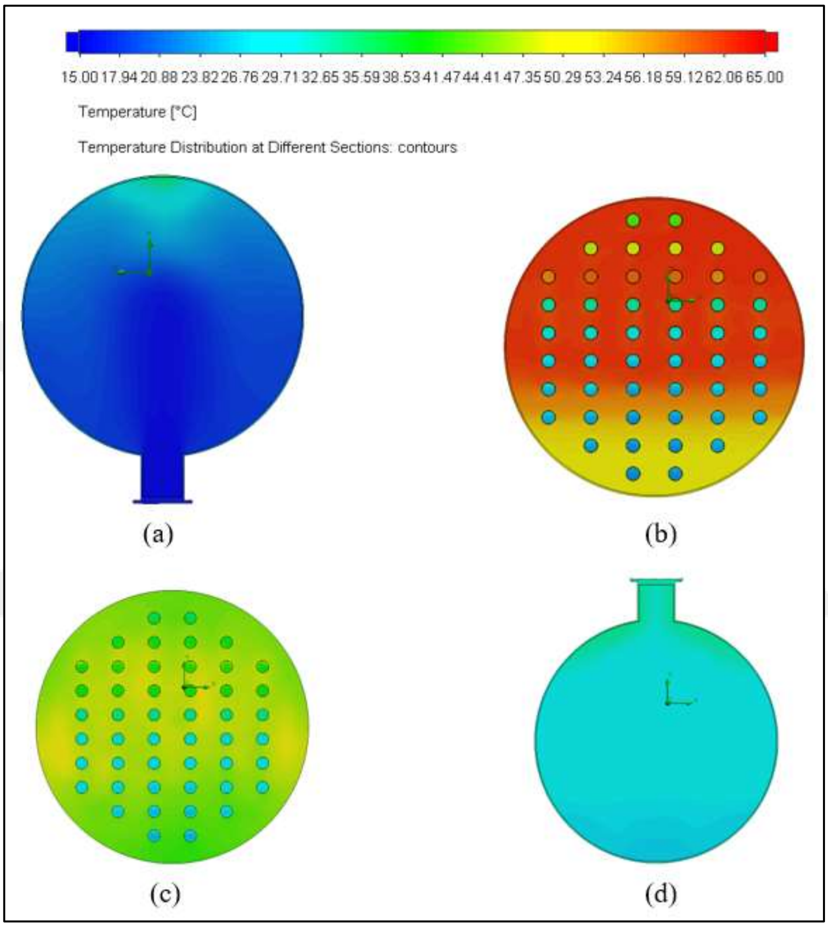

Figure 4.7: (A) Temperature Distribution at the Tube Side Inlet; (B) Temperature Distribution at the Midpoint of the Heat Exchanger; (C) Temperature Distribution at the End of the Shell Side; (D) Temperature Distribution at the Tube Side Outlet.

4.2 SECOND CASAE STUDY RESULTS

4.2.1 Grid Test Results

A grid test will also be conducted for the second case study, due to the difference in fluid used here. In this scenario, the hot water will be replaced with hot water mixed with nanomaterial's, making the fluid in this case a 0.5% concentration of TiO_2. Its properties have been calculated and are presented in Table 3 above. The results are as shown in the figure and table below.

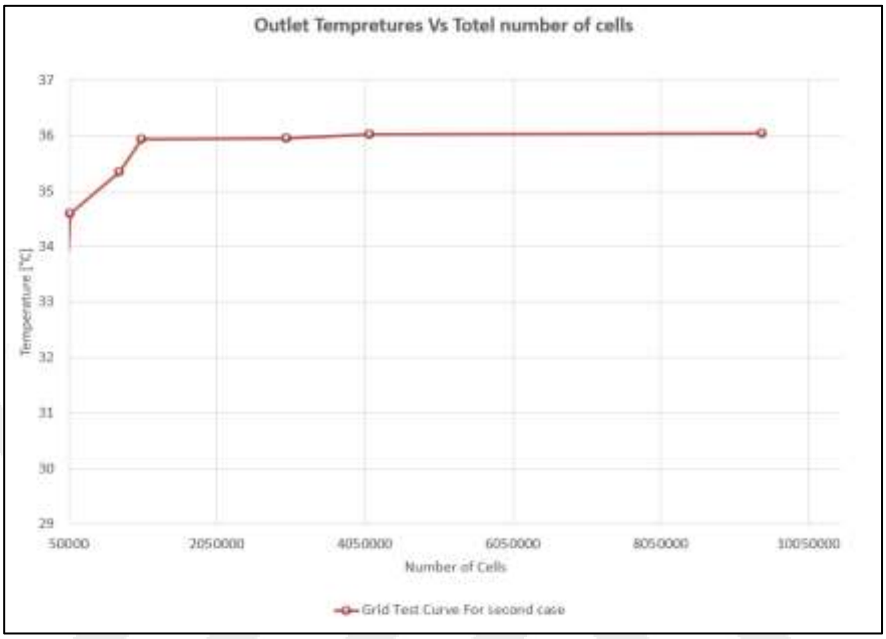

Figure 4.8: Outlet Temperatures for Cold Fluid at Different Numbers of Cells.

Table 4.2: Outlet Temperature Values for Different Numbers of Cells for the Second Case.

Refinement level	**Number of cells**	**Temperature**
1	45816	33.92498
2	71428	34.5929
3	734358	35.3448
4	1029859	35.9414
5	2989859	35.9602
6	4112679	36.04332
7	9419425	36.0509

It is observed from figure 4.9 above that the curve stabilized when the number of cells equaled 4,112,679, with a temperature at that point being 36.04°C, which is also detailed in the table below the figure. This indicates that this is the optimum mesh for the second case study, upon which the simulation will proceed.

4.2.2 Temperatures Results and Distribution

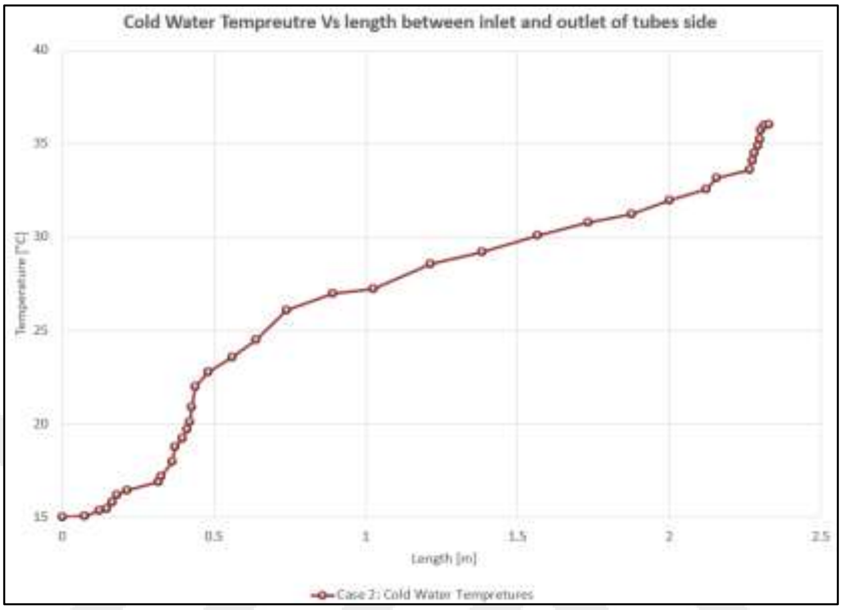

Figure 4.9: Temperatures Rise for Cold Fluid in the Tube Side Between the Inlet and Outlet in the Second Case Study.

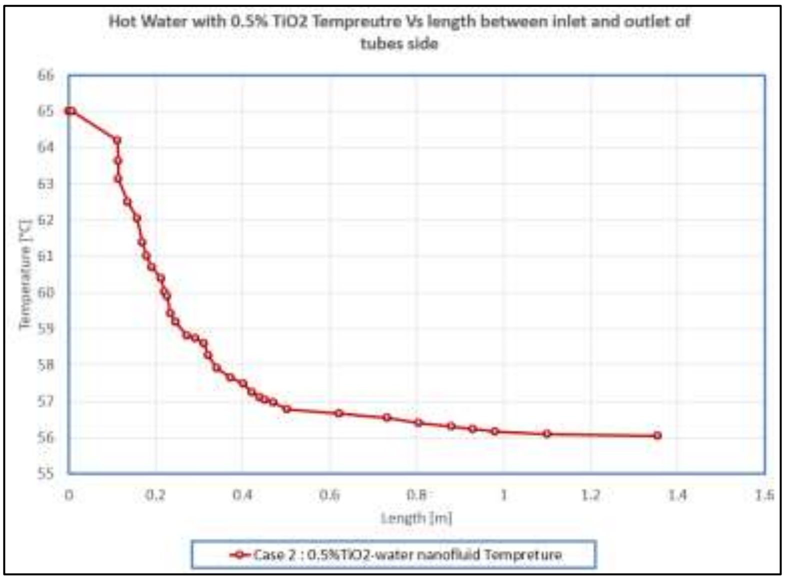

Figure 4.10: Temperatures Decrease for Hot Fluid in the Shell Side Between the Inlet and Outlet in a Second Case Study.

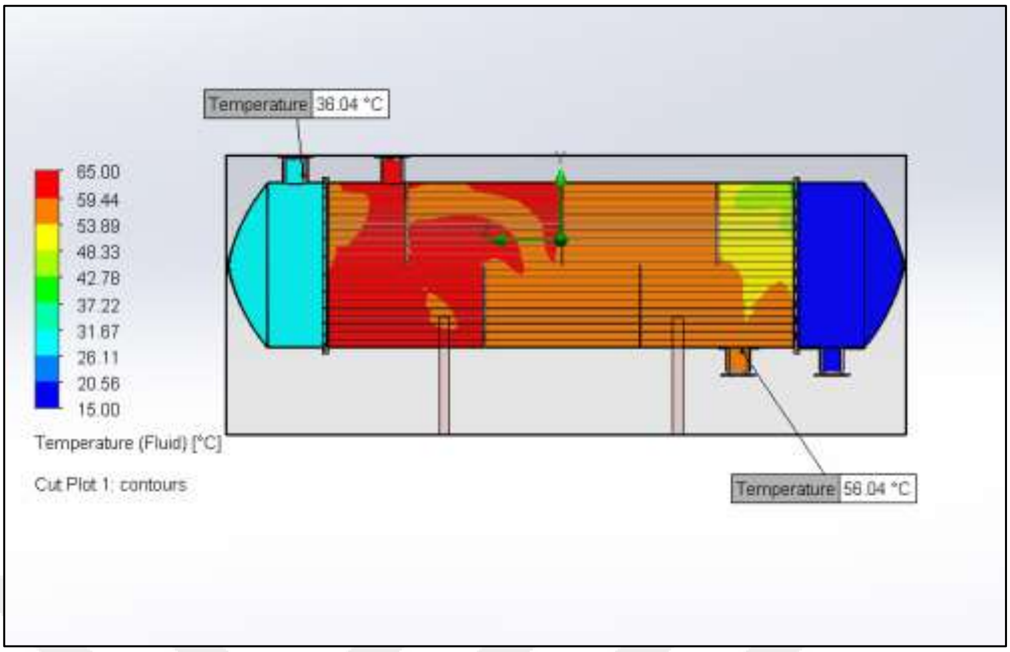

Figure 4.11: Temperature Contour Results and Outlet Temperatures for Both Fluids for the Second Case Study..

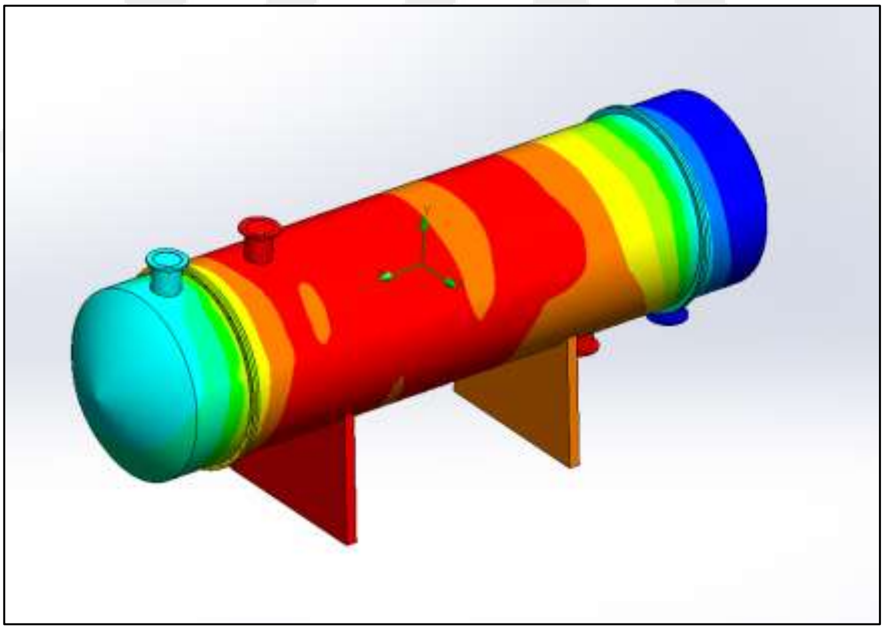

Figure 4.12: Surface Temperature Distribution on the Shell and Tube Heat Exchanger for the Second Case Study.

The figure below shows the temperature distribution along different sections at several locations along the z direction for the second case study.

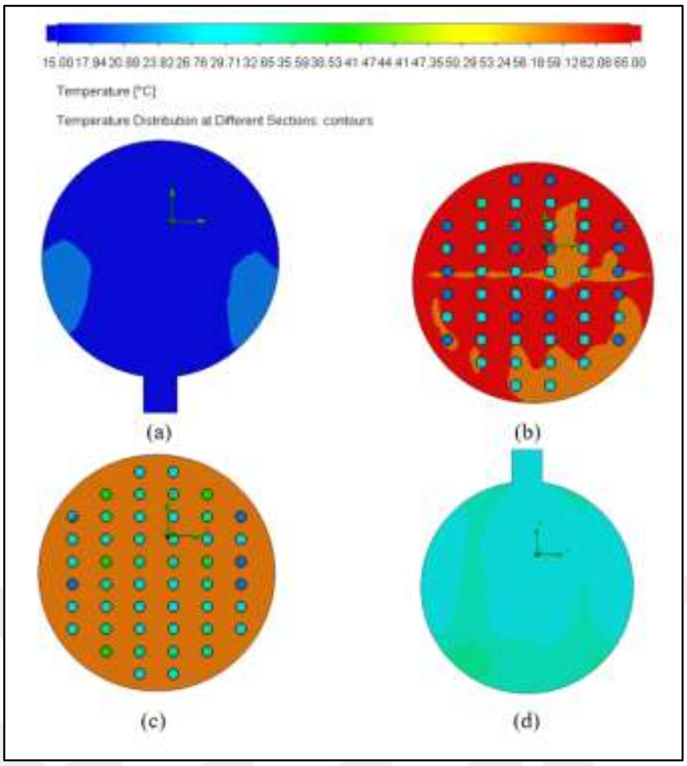

Figure 4.13: (A) Temperature Distribution at the Tube Side Inlet; (B) Temperature Distribution at the Midpoint of the Heat Exchanger; (C) Temperature Distribution at the End of the Shell Side; (D) Temperature Distribution at the Tube Side Outlet.

Table 4.3: Results for Both Case Studies.

Fluid	**Fluid**	**Outlet Temperature**
Case Study 1	Hot fluid: Water	56.88 C
	Cold fluid: Water	33.63 C
Case study 2	Hot fluid (TiO_2 with ϕ 0.5%)	56.04 C
	Cold fluid: Water	36.04 C

To calculate the percentage improvement in heat transfer, the formula used is:

$$\text{Improvement Percentage} = \frac{(\Delta T_{second\ case} - \Delta T_{first\ case})}{\Delta T_{first\ case}} \times 100\% \quad (4.1)$$

$$\text{Improvement Percentage} = \frac{((36.04 - 15) - (33.63 - 15))}{(33.63 - 15)} \times 100\% = \mathbf{11.44\%}$$

The results demonstrate enhanced heat transfer performance using Nano fluid compared to pure water as the working fluid. The 0.5% TiO_2 Nano fluid on the shell side yielded an 11.44% improvement in the cold fluid temperature rise over the baseline case, highlighting the benefits of nanoparticles. The precise CFD model proves effective in predicting local heat transfer coefficients, fluid bulk temperatures, and surface heat fluxes, matched reasonably with experimental correlations. Comparing multiple meshes ensured grid-independent solutions. Further, the detailed temperature contours and profiles elucidate the variations along the exchanger length and nested fluid passages. This advanced comprehension of the prevailing thermal-hydraulic behavior will aid evaluating the viability of nanofluids for specific heat exchange applications, considering the trade-off between improved capacity and greater pumping requirements from heightened viscosity. Additional parametric analyses can help optimize these systems. Pending further field validation, the accurate simulations demonstrate a powerful tool for analysis and development of Nano fluid heat exchangers, thanks to the precise physics captured. The gains shown motivate additional exploration into novel geometry tailoring and nanoparticle type/concentration customization for heat transfer intensification according to service needs.

5. CONCLUSIONS AND FUTURE WORK

5.1 CONCLUSIONS

This comprehensive computational study has successfully demonstrated the significant value of using computer-aided design and modeling techniques for developing optimized heat exchanger systems with enhanced performance. Leveraging CAD software and powerful CFD simulations, this work has enabled exploring and tailoring novel heat exchanger configurations tailored to precise requirements and thermal duties.

A key highlight of this research is providing rigorous validation on the efficacy of nanofluids for appreciably intensifying the heat transfer capacity and thermal efficiency of shell-and-tube heat exchangers compared to conventional fluids. The 3D modeling and detailed parametric analysis has revealed that the addition of tiny concentrations of nanoparticles can lead to major heat transfer improvements, concurring with established experimental trends. This confirmation of nanofluids providing sizable heat transfer augmentations could stimulate their greater adoption.

Furthermore, the accuracy of the advanced numerical techniques has been quantified through rigorous grid independence testing, lending full credibility to the computational predictions. The reasonable match between simulated performance parameters like heat transfer coefficients, fluid temperatures and experimental correlations affirms the high-fidelity physics captured by the CFD approach. Hence, the modeling methodology can serve as a powerful virtual prototyping tool for exploring and optimizing heat exchanger designs, significantly reducing experimental testing overheads.

5.2 FUTURE RECOMMENDATIONS

i. Fabricate a prototype heat exchanger and conduct experimental testing to validate the simulation findings

ii. Investigate novel types of Nano fluids such as graphene, carbon nanotubes, metal nanoparticles in various base fluids and concentrations

iii. Evaluate the performance of Nano fluid-enhanced heat exchangers in real-world applications like power plants, chemical industries, electronics cooling, etc.

iv. Develop more advanced computational models for heat exchanger analysis using artificial intelligence and machine learning techniques

v. Perform studies to improve the stability and component compatibility of nanofluids in heat transfer systems

vi. Explore the effects of nanoparticle surface functionalization on thermal performance

vii. Analyze integrating external fields like magnetics or thermal gradients to further intensify heat transfer rates of nanofluids

viii. Conduct techno-economic assessments and life cycle analyses to determine the feasibility of scaling up nanofluid-based heat exchangers

ix. Investigate methods like ultrasonic vibration, surfactant addition, pH control to obtain uniform and durable nanoparticle suspensions.

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