NUMERICAL INVESTIGATION OF HEAT TRANSFER ENHANCEMENT USING AL_2O_3, CuO AND TiO_2 NANOFLUIDS IN A SHELL AND TUBE HEAT EXCHANGER

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OTOR OGHENEFEGOR JAHCARES	**ENG2002513**
EMIANTOR OMHEN DIVINE	**ENG2002443**
ABU UYIOSA LEO	**ENG2002408**

SUPERVISED BY : PROF OSAROBO IGHODARO

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CERTIFICATION

This is to certify that this research project titled: Numerical Investigation of Heat Transfer Enhancement using Al2O3, Cuo And Tio2 Nanofluids in a Shell and Tube Heat Exchanger, was carried out under the supervision of Prof. Osarobo Ighodaro.

…….. ……

Prof. Osarobo .O. Ighodaro **Date**

Project Supervisor

…….. ……

Engr. Martin Osikhuemhe **Date**

Project Coordinator

…….. ……

Prof. Osarobo .O. Ighodaro **Date**

Head of Department

DEDICATION

We dedicate this report to God Almighty, whose grace has granted us the strength to accomplish all that was necessary for the success of this project. To our families, Pioneer Otor, Helen Otor, Tejiri Otor, Christabel Otor, Ogheneyoma Precious Otor, Nyerovwo Otor, Abraham Emiantor, Joy Emiantor, Ivie Emiantor, Efua Emiantor, Ideh Emiantor, Victoria Osawaye, Osawaru Osawaye, Precious Olofinbiyi whose unwavering support and encouragement have been the foundation of our academic journey. To the Department of Mechanical Engineering, whose guidance and commitment to equipping us through extensive training and lectures have been pivotal in shaping us into who we are today. This work is also dedicated to all who have inspired and supported us along the way. Your faith in our potential has ignited our passion for learning and striving for excellence.

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ABSTRACT

Heat exchangers are fundamental components in thermal engineering, enabling efficient transfer of heat between fluids across various phase states. Their performance largely depends on the thermal characteristics of the working fluid, and improving these characteristics remains a central research focus. Nanofluids—base fluids enhanced with suspended nanoparticles—have emerged as promising candidates due to their potential to significantly improve heat transfer rates. This study investigates the viability of nanofluids as enhanced working fluids for heat exchanger applications, addressing the persistent challenge of increasing heat transfer efficiency in thermal systems.

The methodology involved selecting a shell-and-tube heat exchanger and performing detailed mathematical modelling, numerical simulations, and comparative analyses. Simulations were conducted using ANSYS Fluent, supported by theoretical models such as the Maxwell-Garnett relations, Pak and Cho density formulation, and Brinkman viscosity correlations. Mesh generation, boundary condition setup, and performance evaluation were carried out systematically between July and November 2025. Various nanofluid types and volume fractions were iteratively tested to identify the most thermally efficient fluid configuration for the system.

The results demonstrate a clear improvement in heat transfer characteristics when nanofluids are employed compared to conventional fluids. Significant enhancements were observed in thermal conductivity, convective heat transfer coefficients, and reduction in hot-air exit temperatures from the heat exchanger. The comparative outcomes confirm the strong potential of nanofluids to boost thermal energy recovery and overall system performance, highlighting their suitability for advanced industrial heat exchanger applications.

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ABBREVIATIONS AND KEYWORDS

CFD - Computational Fluid Dynamics

BC - Boundary Condition

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The demand for improved energy efficiency across global industrial systems has driven significant research into the recovery and utilization of waste heat. Industrial processes—such as power generation, chemical manufacturing, and refining —routinely lose a considerable portion of their energy input as unused thermal energy. According to Forman et al. (2016), between 20% and 50% of industrial energy is discharged as waste heat, depending on the process type and system efficiency. This energy, if recovered, could contribute substantially to lowering fuel consumption, operating costs, and greenhouse gas emissions.

Exhaust heat can, by far, best be captured through heat exchangers, which are devices designed to transfer heat from one medium to another at different temperatures without direct fluid contact. The thermal properties of the working fluid have a great influence on the effectiveness of the heat exchanger. Conventional heat transfer fluids like water, ethylene glycol, and engine oils are popular because of their chemical stability and ready availability. However, these fluids have low thermal conductivity, which is a disadvantage as it slows down the rate of heat transfer (Vajjha & Das., 2009).

The introduction of nanofluids has come of age in the last two decades as a breakthrough in thermal systems engineering. Nanofluids are manufactured by suspending nanosized solid particles (usually <100 nm) into a conventional base fluid. This concept was first introduced by Choi (1995), who noticed that even a small percentage of nanoparticles could significantly enhance the thermal performance of the fluid (Rahmatinejad et al., 2021).

From then on, nanofluids have been found to increase thermal conductivity by 40% or more, specifically about the kind of nanoparticles, concentration, method of preparation, and stability of dispersion (Vajjha et al., 2010; Singh et al., 2022).

Different types of nanoparticles have been explored for heat transfer applications, some of which have been considered for exploration are — aluminum oxide (Al_2O_3), copper oxide (CuO), and titanium dioxide (TiO_2) — because of their availability:

i. Al_2O_3 is known for its chemical stability and low cost.
ii. CuO is characterized by high thermal conductivity.
iii. TiO_2 is admired for its suspension stability and low toxicity (Kurhade et al., 2023)

Experimental and simulation works carried out recently have established the efficiency of these nanofluids in heat exchangers. For instance, Singh et al. (2022) reported that the use of CuO nanoparticles and Al_2O_3 nanofluids in copper tube heat exchangers improved heat transfer by up to 50%, while Kurhade et al. (2023) also reported an improvement in thermal efficiency. These findings suggest that nanofluids can be used to reduce temperature gradients and enhance the thermal performance of compact heat exchanger systems considerably.

Despite these positive advances, comparative studies for more than one nanofluid for the same boundary and flow conditions remain limited. Existing research diverges significantly in nanoparticle type, base fluid, volume fraction, and geometry, thus complicating the determination of the optimal nanofluid for real waste heat recovery systems. Further, experimental studies can be time-consuming and constrained by measurement limitations, leading to an increasing use of Computational Fluid Dynamics (CFD) as a versatile and affordable tool to predict nanofluid performance.

In this context, a simulation-based comparative analysis of commonly studied nanofluids can provide clearer guidance for engineers and researchers. This study is conducted on three commonly studied nanofluids— Al_2O_3–water, CuO–water, and TiO_2–water —using the same operating conditions in the double-pass shell-and-tube heat exchanger setup. This comparative analysis takes into consideration the

thermophysical properties, flow properties, and heat transfer ability of the nanofluid and determine the optimal nanofluid for waste heat recovery at maximum efficiency.

1.2 Statement of Problem

Industrial systems release a significant portion of their input energy as waste heat, reducing overall efficiency and increasing operational costs. Heat exchangers are commonly used to recover part of this energy, but their performance is strongly limited by the low thermal conductivity of conventional working fluids such as water, ethylene glycol, and oils. This limitation restricts the rate of heat extraction and results in substantial unrecovered heat losses.

Nanofluids have been proposed as an improved class of heat transfer fluids, but their performance varies widely depending on nanoparticle type, concentration, and flow conditions. As a result, engineering practice lacks clear guidance on which nanofluid provides the best enhancement for waste heat recovery applications, particularly in shell-and-tube heat exchangers commonly used in industry. This uncertainty makes selection difficult for designers seeking to improve heat exchanger efficiency.

There is therefore a practical need to evaluate and compare the performance of commonly used nanofluids under conditions representative of real waste heat recovery systems, to determine which option can provide reliable enhancement and improved thermal efficiency

1.3 Aim and Objectives

Aim:

To study, through CFD simulation, how Al_2O_3–water, CuO–water, and TiO_2–water nanofluids perform in a double-pass shell-and-tube heat exchanger, with the goal of identifying the most effective nanofluid for enhancing waste heat recovery.

Objectives:

1. Review: Summarise literature on Al_2O_3–water, CuO–water and TiO_2–water thermophysical properties and heat-exchanger performance.

2. Property modelling: Compute temperature- and concentration-dependent density, Cp, k, μ for each nanofluid at 0.2%, 0.5% and 1.0% using validated empirical correlations.

3. CFD model: Build a reduced-order double-pass shell-and-tube CFD model focusing on most heat-transfer-intensive section.

4. Simulation matrix: Run controlled CFD experiments with the same geometry and Boundary Conditions (BCs) across the three nanofluids and three volume fractions, recording outlet T, ΔP and pumping power.

5. Validation & sensitivity: Validate the baseline; pure water case vs published data, perform mesh-independence and BC sensitivity tests.

6. Compare & recommend: Compare thermal-hydraulic performance and recommend the most suitable nanofluid for waste heat recovery, reporting trade-offs.

1.3 Scope of the Study

This study focuses on the numerical investigation of heat transfer performance using mono nanofluids (Al_2O_3, CuO, and TiO_2) in waste heat recovery systems through a Computational Fluid Dynamics (CFD) simulation approach. It examines how variations in nanoparticle volume fractions influence thermophysical properties and heat exchanger efficiency. A comparative and analytical evaluation of the simulation results is conducted to establish the relative superiority of the nanofluids in promoting effective heat transfer.

The study is limited to steady-state, single-phase models under turbulent flow conditions, without considering chemical reactions or phase changes.

1.5 Significance of the Study

This study contributes to the literature on nanofluids as efficient heat transfer fluids for enhancing waste heat recovery system efficiency. By comparing Al_2O_3–water, CuO–water, and TiO_2–water nanofluids computationally in a double-pass shell-and-tube heat exchanger, this study offers practical information on their heat transfer characteristics and thermal efficiency at specified operating conditions of the simulation.

The significance of this study is as follows:

• It determines the most thermally efficient nanofluid among the selected ones, offering practical guidance to designers and engineers who aim to improve energy efficiency in industrial processes.

• It provides a cost-effective, simulation-based alternative to experimental testing, saving time and resources while still ensuring reliable results.

• The findings justify the practice of green engineering by promoting efficient use of waste heat, thereby conserving energy and reducing environmental degradation.

• It supports further optimization of heat exchanger systems, particularly in industries where the recovery of heat is key to energy management and process improvement.

• Finally, this study offers a valuable guide for future experimental research, nanofluid design, and system design optimization to achieve maximum thermal performance by making rational fluid choices.

1.6 Limitations of the Study

This project, although informative and concise, has its limitation:

1. Only three nanofluids (Al_2O_3–water, CuO–water, and TiO_2–water) were taken into consideration, thus a narrow field of comparison is involved, and other efficient nanofluid possibilities are not taken into consideration.

2. The simulations were based on empirical correlations for thermophysical properties, and this may not account for complex interactions at the nanoscale or under different environmental settings.

3. The study is limited to a double-pass shell-and-tube meaning that the results may not apply to other configurations and geometries.

4. Long-term stability, corrosion effects, and maintenance implications of nanofluids were not considered, which are crucial in real-world applications.

CHAPTER TWO

LITERATURE REVIEW

2.1 Preparation and Synthesis of Nanofluids

Nanofluids are suspensions of nanometer-sized particles in a base fluid, and so require a physically controlled preparation process to create good dispersion, thermal stability and a predictable performance across a range of engineering devices such as heat exchangers. The performance of nanofluid hinges on homogeneity and can only be predicted when a controlled means of synthesis, properties of the nanoparticles and the interaction with the base fluid is introduced into a complete and repeatable procedure of synthesis and preparation.

2.1.1 Nanofluid Preparation Strategies: Two-Step and Single-Step Methods

In general, there are two approaches (i.e., two-step and single-step methods) for preparing nanofluids, and they have advantages and disadvantages when it comes to particle dispersion, scalability, and nanofluid stability. The two-step method is primarily used in practice (especially in industrial applications), since it is easy and cheap to implement. The two-step method essentially includes the steps of synthesizing the nanostructures as discussed in the prior sections, with either chemical, mechanical, or physical techniques, and then mixing them with the base fluid via ultrasonication, mechanical stirring or high-shear mixing (Yu and Xie, 2012). Although the two-step method makes the mass production of nanofluids practical, it is often faced with challenges including agglomeration and sedimentation, requiring the addition of stabilizers and adjustments of pH for suspension (Razzaq et al., 2025).

By comparison, the single-step method using involved synthesis and dispersion of nanoparticles at the same time and is performed using laser ablation, thermal decomposition or chemical reduction (Jama et al., 2016). The single-step method decreases the chance of particle agglomeration and usually results in more homogenous nanofluid suspensions (Das et al., 2024). However, because of scalability, cost

constraints, and flexibility of materials, the single-step process is still just used for laboratory-scale works (Yu & Xie, 2012).

2.1.2 Surfactants and Stabilizers

Additives or surfactants/dispersants like cetyltrimethylammonium bromide (CTAB), sodium dodecyl sulfate (SDS), and oleic acid are often employed in nanofluids to suppress particle aggregation and achieve even dispersion in order to improve stability (Manimaran et al., 2022). The surfactants and dispertants reduce surface tension and allow repulsive forces between particles to be established so that they do not agglomerate or sediment (Razzaq et al., 2025). Nanofluid thermal conductivity can be detrimentally affected when surfactants are excessive, depending on how much heat is present in the system, therefore it is important to consider the surfactants when optimizing.

2.1.3 Factors Influencing Nanofluid Quality in Preparation

A number of parameters that are directly related to nanofluid quality and performance include:

1. Particle Size and Shape: Smaller nanoparticles increase the amount of heat transfer thanks to a larger surface area. Smaller particles have a tendency to agglomerate more readily, while spherical particles can make the process of dispersion easier, rod-like particles can create ways for thermally pathways, and platelets create some enhanced thermal conductivity (Yu and Xie, 2012)
2. Choice of Carrier Fluid: Nanofluids are typically intended to work with base fluids, including deionized water, ethylene glycol, and different types of oils, which are chosen based on the intended thermal application and their compatibility with the nanoparticles. The type of base fluid chosen will have a direct influence on the thermal and rheological properties of the final nanoparticle suspension (Jama et al., 2016)
3. Surfactant Concentration and pH: Nanoparticle stability can be strongly related to pH. When reaching or nearing the isoelectric point, the particles possess very little

charge, which can lead to groupings or settling clumps of nanoparticles. When changing pH to stray away from the isoelectric point there will be increased electrostatic repulsion helping to promote better dispersion and better stability of the particles. While there are also surfactants that can promote this, as well, they have to be in a fine concentration so as not to impact the viscosity or thermal conductivity of the fluid.

2.1.4 Functionalization of the Surface

In order to further promote dispersion of nanoparticles, there is sometimes an additional step or process of surface functionalization. Functionalization of particles, particularly nanoparticles, refers to the process of modifying their surface to introduce new chemical or physical properties thereby improving dispersion stability and reducing agglomeration tendencies. For example, organic chains or hydroxyl groups can be added to the surface of the particles to increase hydrophilicity for use in water-based fluids (Yu and Xie, 2012). Functionalization can greatly improve the long-term stability of a nanoparticle suspension, but it may be an expensive or an involved step.

2.1.5 Hybrid Nanofluids and pH Adjustment

A newer approach in nanofluid research involves blending different types of nanoparticles such as Al_2O_3 with Cu or TiO_2 with SiO_2 into a single base fluid to form what is known as a hybrid nanofluid. The aim of hybrid systems, it is hoped, would be to produce a synergistic effect, where, in addition to thermal, solid content (related to solid phase), and dispersion stability (normally thought of as liquid phase), all of the basic properties of the different materials utilized will have optimal characteristics (Razzaq et al., 2025). The most recent synthesis methods also include electrochemical synthesis, spray pyrolysis, and microwave-assisted methods, all of which seem to aid in dispersion and reduce processing time (Jama et al., 2016). Nanofluid stability can be enhanced by modifying the pH level of the base fluid to promote electrostatic repulsion among suspended nanoparticles. When the pH is adjusted away from the isoelectric point, nanoparticles tend to repel one another due to increased surface charge, which

reduces the likelihood of clustering or sedimentation (Yu and Xie, 2012). This approach is particularly useful in formulations where no surfactants or chemical surface treatments are applied.

2.1.6 Recent Advancements and Choices in Nanofluid Preparation

Recent advancements in nanofluid preparation often aim to improve the cost effectiveness, commercialization capacity and other aspects of relevant metric development. For example, recent work has also discovered plant extracts or bio-compatible agents that could allow for "green synthesis routes" which lessen the amount of dangerous chemicals needed (Razzaq et al., 2025). Other works have shown that a combination of magnetic stirring and probe sonication create homogenous suspensions much more than conventional methods.

When preparing nanofluids, we have to be very aware of trade-offs with thermal performance, stability, cost and environmental impact. For example, smaller particles may provide better heat transfer, but they tend to agglomerate and sediment much better. Even if we use a surfactant to stabilize the nanofluid preparations, it may also impact the heat transfer effectiveness, or break down under elevated temperature applications. As can be noted, dealing with these trade-offs, appropriate preparation will involve trade-offs (Yu and Xie, 2012).

2.2 Thermophysical Properties of Nanofluids

Nanofluids which are suspensions of engineered colloidal nanoparticles (with typical nanoparticle sizes smaller than 100 nm) in traditional base fluids such as water, ethylene glycol, or oils, have been generating a great deal of interest due to favourable thermophysical properties and the potential to change thermal management systems. Since Choi's original work in 1995, nanofluids have been identified as viable materials for improving heat transfer performance in various energy systems or industrial applications.

Nanofluids have improved thermal conductivity, specific heat, viscosity, and density, as well as these properties affecting convective heat transfer and currents (Jama et al., 2016). The enhanced thermal behaviour of nanofluids is attributed to several mechanisms at the nanoscale level: Brownian motion, interfacial layering, particle clustering, and thermophoresis. These nanoscale processes allow for a better exchange of energy between the suspended particles and the fluid than can be observed for traditional fluids.

Ebrahimnia-Bajestan et al. (2023) also pointed out that nanofluids may increase thermal conductivity by 10–40% depending on particle type, shape, concentration and temperature. The authors mention that particle morphology and stability of dispersions are important; especially because poorly dispersed nanoparticles can agglomerate, which degrades heat transfer performance.

In a review article, Harikrishnan et al. (2023) offered empirical and modelled data for the most common types of nanofluid formulations, Al_2O_3–water, CuO–water, SiO_2–water, and TiO_2–water, and determined Al_2O_3–water nanofluids have significant benefits in terms of suspension stability and preparation effort, CuO–water nanofluids have the greatest thermal conductivity, and TiO_2-water nanofluids are used more frequently in biomedical applications because of their low toxicity relative to other nanoparticles. This relates to suspension stability and inertness.

The fundamental thermophysical properties of nanofluids that affect their performance are thermal conductivity, dynamic viscosity, specific heat capacity, and density, which together define their applicability for heat transfer (Sharifpur et al., 2023). All four thermophysical properties of fluids are salient input data for computational fluid dynamics (CFD) and experimental modelling. Most of the literature relies on empirical or semi-empirical relationships to establish the thermophysical properties of nanofluids. They are known to depend on factors such as volume fraction, temperature, and nanoparticle characteristics including shape and size (Timofeeva et al., 2011). In their article, Harikrishnan et al. (2023) referred to a dilemma where absolutely most classical models (Maxwell, Hamilton-Crosser, etc.) will often underestimate the nonlinear

characteristics of nanofluids if experimentation and testing is conducted at different operating points. Additionally, Jama et al., (2016) are also highlighting where a shift towards hybrid nanofluids, incorporating two or more nanoparticles, would yield synergistic properties, for example, thermal conductivity and viscosity.

The literature review highlighted above has indicated the promise of nanofluids, particularly Al_2O_3–water, CuO–water, and TiO_2–water, to enhance thermal conductivity and specific heat capacity, which can ultimately improve heat exchanger performance. The study of these three nanofluids has gained considerable attention due to availability, the thermally stable material and thermal characteristics best suited for promoting heat transfer, additional consideration of their use may be warranted for industrial thermal applications. The results support their inclusion in this study and validates a real comparison under controlled conditions. Previous studies have shown that mono nanofluids such as Al_2O_3–water, CuO–water, and TiO_2–water are widely examined for their potential in heat exchanger and waste heat recovery systems. These studies commonly focus on how variations in nanoparticle concentration and thermophysical properties influence thermal performance under different operating conditions.

In summary, while there have been many studies on nanofluids and confirmation of superior performance compared to conventional heat transfer fluids, their performance depends on multiple interacting factors including particle type, particle concentration, temperature, and method of dispersion. This discussion provides a strong basis for the current study of simulating Al_2O_3–water, CuO–water, and TiO_2–water nanofluids with identical operating conditions for the purposes of determining heat exchanger effectiveness performance.

2.3 Influence of Volume Fraction on Heat Transfer

It is worth considering the volume fraction of the different nanoparticles and how they affect effective heat transfer in heat exchangers.

2.3.1 Effect of Volume Fraction on Heat Transfer Efficiency

The volumetric fraction (ϕ) determines how nanoparticles are distributed in a base fluid and significantly influences thermophysical properties such as thermal conductivity, viscosity, and specific heat capacity. These parameters directly affect the heat transfer capability of nanofluids.

Hussein and Alaiwi (2023) experimentally evaluated the effect of TiO_2–water nanofluid volume fraction (0.1%, 0.3%, and 0.5%) in a double-pipe counterflow heat exchanger. They reported an increase in overall heat transfer effectiveness, with a maximum enhancement of 23% at 0.3% volume fraction, followed by a slight decline at 0.5% due to increased viscosity and particle agglomeration.

Similarly, Akshay Kumar Surana et al. (2017) numerically investigated a shell-and-tube heat exchanger using Al_2O_3–water nanofluid. Their findings revealed that increasing nanoparticle concentration from 0.1% to 1% improved the convective heat transfer coefficient and overall effectiveness by approximately 18–25%, though higher concentrations led to increased pumping power requirements.

In another study, Thakur and Singh (2017) experimentally analysed Al_2O_3–water nanofluid with air bubble injection in a shell-and-tube heat exchanger. They observed that adding nanoparticles at 0.2–0.5% volume fraction improved the heat transfer rate by up to 28%, with air bubble injection further enhancing turbulence and thermal dispersion.

Ajeeb and Murshed (2022) compared both numerical and experimental investigations of Al_2O_3 and TiO_2 nanofluids in a compact plate heat exchanger. Their results confirmed that thermal performance improved with volume fraction up to 0.4%, beyond which viscosity effects became dominant. Al_2O_3 nanofluid achieved a higher Nusselt number enhancement (≈21%) compared to TiO_2 (≈17%) at the same loading.

In another related work, Bendaraa et al. (2021) conducted both numerical and experimental studies on alumina-based nanofluids in a double-pipe heat exchanger.

Their results showed that increasing the nanoparticle concentration from 0.1% to 1% enhanced the overall heat transfer coefficient by up to 30%, attributed to improved energy transport at the fluid–solid interface.

Boukerma et al. (2017) also examined Al_2O_3 and CuO nanofluids with water–ethylene glycol mixtures and found that the optimal enhancement occurred at ϕ = 0.3–0.5%, depending on the base fluid composition. Beyond these concentrations, the heat transfer benefit decreased due to rising viscosity and instability of nanoparticle suspension.

Overall, findings across studies demonstrate a consistent trend: nanofluid heat transfer efficiency initially increases with nanoparticle volume fraction, peaks within the range of 0.2–0.5%, and declines at higher concentrations. The decline is mainly due to viscosity increase, nanoparticle clustering, and reduced effective convection. These insights provide essential guidance for optimizing nanofluid concentration in CFD-based thermal system designs.

2.3.2 Influence of Particle Size and Shape

Nanoparticle volume fraction, shape, and size all play significant roles in determining the thermophysical properties of nanofluids. A reduction in particle size increases the surface-to-volume ratio, leading to a larger surface area for heat conduction. Consequently, the thermal conductivity gain is attributed to enhanced surface contact at the solid–liquid interface, which improves interfacial heat transport. A phase change may also occur at the interface, which can significantly influence the effective thermal conductivity of the nanofluid (Rahman et al., 2024).

However, this improvement in thermal conductivity comes with a trade-off. As nanoparticle size decreases, viscosity tends to increase, thereby impeding fluid flow and raising pumping power requirements. Ravisankar et al. (2022) reported that nanofluids with smaller particle diameters exhibited up to a 15–25% increase in thermal conductivity but also a 10–18% rise in viscosity, suggesting that optimization between size and flow resistance is essential for efficient heat transfer systems.

Similarly, the shape of nanoparticles plays a critical role. Non-spherical geometries such as rods, platelets, or flakes create more efficient conductive pathways due to their elongated or layered structures, which facilitate directional heat transfer. However, these shapes also restrict fluid motion and may lead to aggregation or sedimentation under certain flow conditions (Alqaed, 2021; Rashid et al., 2020). Alqaed's numerical study on micro heat sinks revealed that rod-shaped nanoparticles enhanced thermal performance by approximately 12% compared to spherical ones, albeit with a corresponding 7% increase in pressure drop.

Rahman et al. (2024) and Yu and Xie (2012) further highlighted that nanoparticle geometry and size not only influence thermal conductivity but also affect nanofluid stability and specific heat. Their findings emphasize that optimizing particle morphology is key to balancing conductivity gains with manageable viscosity. Supporting this, molecular-scale simulations by Topal and Servantie (2018) demonstrate that while smaller or elongated nanoparticles promote higher thermal conductivity, excessive size reduction or irregular shape can reduce fluid mobility and increase pumping losses.

Additionally, Louis (2023) reviewed various nanofluid applications in double-pipe heat exchangers and concluded that selecting nanoparticles of optimal size (typically between 20–50 nm) and moderate aspect ratio yields the best balance between heat transfer enhancement and flow efficiency.

2.3.3 Volume Fraction Trade-offs and Optimal Range

There has been ample evidence that thermal conductivity increases as the volume fraction of nanoparticles increase, which has a proportional change in viscosity, which does have flow resistance, thereby raising pumping power. For example, Liu et al. (2011) observed the thermal conductivity of a 5 vol% CuO–ethylene glycol nanofluid was about 12.4% greater than pure ethylene glycol; in general, higher mass fractions of nanoparticles produced improved nanofluid performance. Although viscosity was not

measured, it is important to highlight that an increase in thermal performance is generally coincident with an increase in fluid resistance, this observation draws attention to a practical decision one has to make when improving performance through nanofluid options; while thermal conductivity can improve, often this is accompanied with the potential or actual increase in pressure and the cost of pumping the nanofluid.

As an additional note, comprehensive work conducted by Yang et al. (2022) found there exists an optimum concentration of nanoparticles, specifically for CuO, the maximum thermal performance occurs around 1.0 vol %, providing basically no gain in heat transfer beyond this concentration with an associated increase in pumping power required.

2.3.4 Effect of Nanoparticle Type

Moreover, Rahman et al. (2024) reported that thermal conductivity enhancement typically occurs in the volume fraction range of 0.1 to 1%, but the type of nanoparticles was showed to be quite crucial in controlling the results. Kumar and Sonawane (2016) also conducted a study to compare the thermal conductivity and heat transfer performance of CuO and TiO_2 nanofluids in water and ethylene glycol. They showed that CuO nanofluids were superior to the TiO_2 nanofluids in terms of both thermal conductivity and overall heat transfer coefficient for the same volume fractions. This suggests that if the nanoparticles are to improve thermal performance of a liquid, it will be better able to achieve this when the nanoparticles have higher intrinsic thermal conductivity.

2.3.5 Non-linear Effects and Higher Concentrations

Palabiyik et al. (2012) reported a non-linear relationship between thermal conductivity and volume fraction, due to the fact that performance is a non-linear function of concentration which could arise between nanoscale phenomena such as Brownian motion, agglomeration, and nanolayering. They also suggested that simulating nanofluids without experimentally evaluating the number and concentration ratios may

yield inaccurate results. Furthermore, in discussing higher nanoparticle concentrations they showed that agglomeration and sedimentation increased which decreased dispersion stability and potentially reduced heat transfer efficiency. Therefore, they pointed out that since the loading of the nanoparticles must be optimized to achieve effective performance of the nanofluid, nanoparticle loading merits careful consideration.

2.4 Effect of Nanoparticle Material on Thermal Performance

When examining the thermal performance of nanofluids, specifically thermal conductivity and convective heat transfer characteristics, the thermal properties of the nanoparticles comprising the dispersion must be considered. Many experimental studies and review papers have reported that the particle type such as oxide, metal, carbon-based, and hybrid significantly affects the heat transfer and its gains under specific flows and temperatures.

2.4.1 Metal Oxide Nanoparticles (Al_2O_3, CuO, TiO_2)

Metal oxide nanoparticles are the most researched nanoparticles due largely to their cheap and reasonable availability, stability, and dispersible properties. Metal oxide nanoparticles typically enhance heat transfer in both laminar and turbulent regimes by an average of 5-20% as compared to base fluids depending on the loading, size of particles and pH adjustments (Alami et al., 2023). In their comparison in microchannels, Al_2O_3 showed the greatest heat transfer performance, followed by CuO and TiO_2, with the more dispersive long term performance of TiO_2 in higher loading concentrations (Zahmani et al., 2024). Studies on Al_2O_3/water nanofluids in minichannel heat sinks have reported convective heat transfer enhancements in the range of 10–15% at moderate particle concentrations, with only minimal increases in pressure drop compared to water (Zahmani et al., 2024; Manimaran et al., 2025)

2.4.2 Metal Nanoparticles

Metal nanoparticles like copper and silver have larger intrinsic thermal conductivities than oxides, and in many cases, are higher than those larger micro particles leading to better enhancement potential using a metal. However, metals can permeate more quickly, loosen from attachment, and oxidize or agglomerate which compromises the long-term performance of the composite unless properly stabilized (Yang et al., 2022). This water performance limits metal nanoparticles as an application for large-scale systems, even though they have obvious laboratory-scale applications.

2.4.3 Carbon-Based Nanoparticles (Graphene, Graphene Oxide)

Carbon allotropes, especially graphene and graphene oxide (GO), are obtaining interest based off their impressive thermal properties. Experiments with GO nanofluids have demonstrated increases in thermal conductivity of approximately 25 - 40% at concentrations less than 0.1 vol% using GO dispersion of flakes. This is mostly possible due to the high intrinsic conductivity of flakes, as well as the large surface area of the flakes (Mei et al., 2022). However, viscosity penalties are higher similar to the findings of metal oxide nanofluids due to the increased viscosity penalties of these allotropes also being higher, meaning care must be taken on the loading of these materials as well as the types of surfactants that may be used. Review articles that compare different graphene-based systems stated that, provided proper dispersion can be accomplished, carbon-based nanoparticles outperform metal oxides in both conduction and convection heat transfer (Razzaq et al., 2025).

2.4.4 Hybrid Nanoparticles (oxide + oxide, oxide + carbon)

Hybrid nanofluids take advantage of complementary characteristics of different materials with distinct particles. An example is the use of Al_2O_3–TiO_2 hybrids, which obtained up to ~30% greater convective heat transfer coefficients and less entropy generation than a single component fluid (Kanti et al., 2025). The gain can be attributed to two pathways for heat transport as a results of accessing different conduction channels. Reviews performed previously also indicated that hybrids tend to perform

better overall than single material nanofluids, but stability and production costs of different materials must be addressed (Manimaran et al., 2025; Mirahmad et al., 2025).

2.4.5 Performance Trade-Offs

With regards to nanoparticle materials used for thermal applications, engineers also consider trade-offs associated with competing components.

1. **Stability**: One of the most significant issues: oxide nanofluids such as Al_2O_3 and TiO_2 remain dispersed in water longer than metallic and carbon-based nanoparticle materials, with oxide nanofluids requiring more special chemical treatment. Metallic and carbon-based nanoparticle materials tend to aggregate or settle out of the dispersion and require dispersants or surface functionalization to keep is suspended in the nanofluid (Zahmani et al, 2024; Razzaq et al, 2025).

2. **Viscosity and Conductivity**: It is also well known that increases in thermal conductivity correspond with an increase in viscosity, which ultimately requires more pumping-power (Mei et al, 2022; Yang et al, 2022).

3. **Cost and Scale**: Overall, oxide nanofluids, have the highest scalability and the lowest cost, whereas carbon and hybrid systems potentially have superior performance but are also more expensive (Mirahmad et al., 2025).

2.5 Nanofluids in Shell-and-Tube Heat Exchangers

Due to its mechanical strength, flexibility and compatibility with various liquid and heat requirements, shell and tube heat exchangers remain one of the most common heat exchange systems in various industries. In recent years, growing interest has been observed in exploring the use of nanofluids in shell-and-tube configurations simply because they have high potential in enhancing heat transfer performance, especially in waste heat recovery systems.

There are studies that show the benefits of nanofluid application in shell-and-tube heat exchangers.

2.5.1 Evidence from Previous Studies

Nogueira (2020) analytically explored the performance of a shell-and-tube heat exchanger using CuO nanoparticles dispersed in an ethylene glycol–water mixture on the shell side. The study results showed that heat transfer and outlet temperatures were improved for the CuO nanofluids as CuO concentration increased from 0.1-0.5% when compared to base fluid parameters. The parameters that were calculated including the effectiveness calculated using the ε-NTU method confirmed improved performance with the nanofluid option. Lima et al. (2023) demonstrated a mix of experimental and CFD analyses of GNP/water nanofluids in a double tube heat exchanger with the GNP/water nanofluid temperature gain maximum for the GNP/water 28% with model's results matching well with experimental results. Likewise Nivedini et al. (2020) showed using ANSYS Fluent modelling that silica/water nanofluids improved cooling in a double pipe exchanger by as much as 10 °C under the correct operating conditions. These results support the premise that geometric changes coupled with the use of nanofluids can improve temperature uniformity and thermal resistance for systems based on a shell-and-tube type system. This complements the present study's focus on inexpensive yet effective designs, i.e., the double-pass configuration, which facilitates longer residence times and enhanced thermal mixing.

Also Albadr et al. (2013) carried out experiments on a horizontal shell-and-tube heat exchanger using Al_2O_3–water nanofluids at concentrations ranging from 0.3% to 2% by volume under turbulent flow. Their results showed that higher nanoparticle loading and mass flow rate enhanced the convective heat transfer coefficient compared to pure water. However, these gains were accompanied by increased viscosity and a corresponding rise in friction losses. In all, these works confirm that shell-and-tube heat exchangers are the most suitable for nanofluid simulation comparison owing to their significant practical importance and flexibility. Furthermore, they convey the thermophysical improvement

nanofluids render, especially in turbulent or transitional flow regimes, which predestines them for applications with changing waste heat.

2.5.2 Rationale for the Present Simulation Design

Previous CFD and experimental studies (Surana et al., 2020; Thakur et al., 2021; Ajeeb et al., 2022; Bendaraa et al., 2021; Boukerma et al., 2020) have demonstrated the viability of nanofluids for improving heat exchanger efficiency. However, most of these investigations were limited in scope. For instance, Surana et al. (2020) considered only Al_2O_3–water nanofluid under laminar flow, while Bendaraa et al. (2021) examined alumina nanofluid in a double-pipe configuration without turbulence validation. Thakur et al. (2021) focused on air-assisted enhancement techniques, which do not isolate nanofluid effects. Similarly, Ajeeb et al. (2022) and Boukerma et al. (2020) restricted their analyses to plate-type exchangers or variable base fluids, limiting generalization to shell-and-tube systems.

These gaps highlight the need for a comparative CFD-based assessment across multiple mono nanofluids—Al_2O_3, CuO, and TiO_2—under consistent geometric and flow conditions. This ensures a fair evaluation of their thermal performance while maintaining computational simplicity and industrial relevance.

2.6 Computational Fluid Dynamics in Nanofluid Heat Transfer Studies

Computational Fluid Dynamics (CFD) has become an essential tool for thermal engineers to evaluate fluid motion and heat transfer in systems involving nanofluids. In many instances, engineers find it difficult to evaluate these systems analytically or experimentally due to their complex geometries, multi-phase flow characteristics, and microscale interactions that cannot be easily captured in closed-form equations or laboratory setups. As noted by Surana (2020) and Najim (2019), analytical solutions often fail to accommodate the intricate shell-side flow behaviour and nanoparticle dispersion effects observed in nanofluid heat exchangers. Experimental approaches, though insightful, are frequently constrained by cost, measurement accuracy, and

difficulty in maintaining uniform nanoparticle suspension (Tiari & Rezende, 2018; Oflaz, 2022).

CFD therefore provides a viable alternative for examining these systems under varied conditions and complex geometries that are otherwise challenging to replicate physically. Using CFD, engineers can predict detailed parameters such as local temperature distribution, velocity fields, and pressure drops, allowing them to refine heat exchanger designs and minimize the number of experimental prototypes required (Deka, 2021).

However, while CFD offers flexibility and predictive power, limitations still exist in its ability to fully replicate real-world nanofluid behaviour. For instance, Najim (2019) and Surana (2020) employed single-phase models that assume homogeneous nanoparticle dispersion—an assumption that simplifies computation but overlooks potential agglomeration effects. Similarly, Tiari and Rezende (2018) conducted steady-state simulations that ignored transient thermal fluctuations, while Oflaz (2022) restricted analysis to single-tube configurations, omitting shell-side influences. Deka (2021) compared different nanofluids but reported limited validation with experimental data, highlighting a common challenge in ensuring CFD results align with practical outcomes.

Hence, while CFD remains a powerful approach for exploring nanofluid heat transfer performance, its predictive accuracy depends strongly on model selection, boundary condition fidelity, and validation against experimental evidence. These studies collectively demonstrate both the strength and limitations of CFD in nanofluid research, thereby justifying the use of numerical simulation in this work to achieve controlled, comparative, and computationally feasible analysis of nanofluids in a double-pass shell-and-tube heat exchanger.

2.6.1 CFD in Nanofluid Analysis

The importance of Computational Fluid Dynamics (CFD) in nanofluid analysis was first established by Ravikanth et al. (2010), who performed a three-dimensional steady-state

laminar flow simulation of Al_2O_3–water and CuO–water nanofluids through flat tubes designed to mimic automotive radiator channels. Their numerical framework was based on the continuity, momentum, and energy equations, solved using the finite volume method (FVM) under constant heat flux boundary conditions. Temperature-dependent correlations for viscosity and thermal conductivity were implemented, following the classical Maxwell–Garnett and Brinkman models. The simulation results were validated against experimental data for Nusselt number (Nu) and friction factor (f) in the Reynolds number range of 500–1800, showing deviations below ±8%, thus affirming CFD's credibility in nanofluid prediction. The authors reported that increasing nanoparticle concentration (ϕ = 0.01–0.04) enhanced convective heat transfer coefficients by up to 22%, but also increased pressure drop by approximately 15–20%, highlighting the fundamental trade-off between heat transfer enhancement and hydraulic penalty.

Subsequent studies extended CFD analysis into the turbulent regime to capture non-linear effects more accurately. Akshay Kumar Surana (2020) employed the RNG k–ε turbulence model to investigate Al_2O_3–water nanofluid flow in a shell-and-tube heat exchanger at Re = 10,000–25,000, using ANSYS Fluent with SIMPLE pressure–velocity coupling. The results revealed that for ϕ = 0.03, the overall heat transfer coefficient improved by 28%, while the friction factor rose by about 14% relative to pure water. Similarly, Fatma Oflaz (2022) evaluated the thermo-hydraulic performance of hybrid Al_2O_3–graphene nanofluids in a circular tube, incorporating temperature-dependent nanoparticle transport properties and employing wall-function treatment for near-wall turbulence. Her findings confirmed that hybrid nanoparticles outperform single-component ones but suffer higher viscosity, which demands optimization of concentration and particle composition.

Tiari and Rezende (2018) focused on a plate heat exchanger using CuO–water nanofluid, where they simulated conjugate heat transfer with transient boundary conditions to study thermal response under dynamic loading. Their study revealed that particle Brownian motion and thermophoresis effects could not be neglected when the

characteristic length scale dropped below 2 mm, a condition often ignored in steady-state analyses.

Kaustabh Deka (2021) performed a comparative CFD study on several nanofluids (Al_2O_3, TiO_2, CuO) under identical conditions, using the realizable k–ε model and second-order upwind discretization schemes. The results indicated that Al_2O_3–water exhibited the best compromise between thermal and hydraulic performance, but noted that most available models assumed single-phase homogeneity, neglecting particle–particle interactions and settling effects, which limits real-world applicability.

Critically, most existing CFD analyses adopt single-phase approaches, where the nanofluid is treated as a homogeneous mixture with effective thermophysical properties. While this approach simplifies computation, it fails to represent microscale phenomena such as Brownian motion, thermophoresis, and agglomeration dynamics, which influence local heat transfer rates. The two-phase Eulerian–Lagrangian models that capture these effects are rarely used due to their high computational cost.

In summary, CFD studies such as those by Ravikanth et al. (2010), Surana (2020), Rezende (2018), Oflaz (2022), and Deka (2021) demonstrate CFD's strength in predicting nanofluid flow and heat transfer characteristics, but they also expose its inherent limitations. These limitations—particularly assumptions of steady-state flow, homogeneity, and ideal dispersion—justify the need for controlled CFD-based parametric studies, such as this one, to bridge the gap between simplified simulations and physically representative nanofluid behaviour in heat exchangers.

2.6.2 Improvements in CFD Modelling

CFD modelling has advanced to accommodate more intricate geometries and the simulation of hybrid nanofluid combinations. Relatedly, Ahamed et al. (2024) conducted similar CFD simulations to address hybrid nanofluids, involving CuO–Al_2O_3 polymer mixtures in a double-pipe heat exchanger model with helical coil inserts and altered designs. The data of the current research illustrates the significant increase in the

heat transfer ability of hybrid nanofluids, given from the influence of modifying the nanofluid behaviour and modifying the internal designs. The CFD data produced by the other authors was validated against experimental data, demonstrated the ability of CFD modelling to assess enhanced heat exchanger scenarios.

Likewise, Bellahcene et al. (2024) carried out a computational study using CFD to study the performance of shell-and-tube heat exchangers with baffles and Al_2O_3-water nanofluids. Their extensive assessment examined how the number of baffles and a varying volume fraction of nanofluid affected heat transfer and flow resistance. Their results showed that increasing the number of baffles facilitated mixing and turbulence intensity, which increased the Nusselt number and total thermal performance, but ultimately did come with an associated increase in pressure drop. The study highlights CFD's utility not only in simulating nanofluid behaviour but also in evaluating geometric modifications that can optimize exchanger design for better thermal efficiency.

In addition, Khalid et al. (2024) conducted an open-access CFD investigation into the thermal performance of nanofluids in high-temperature cooling applications, simulating the behavior of four different nanofluids—Al_2O_3–water, ZrO_2–water, Ag–water, and Si–water—under reactor-like conditions. Their results showed that nanofluids consistently outperformed pure water in terms of heat transfer coefficient and critical heat flux. The study pointed out that CFD is not only useful for assessing traditional nanofluid characteristics, but can also capture the effects of nanoparticle material on thermal efficiency and system safety influenced by real operating conditions. This shows the valuable role CFD can play to facilitate analyses of optimized fluid-thermal systems and also the possibility of achieving increased reliability and cost savings. With more computing power available to the general population, it is likely that CFD will play an even bigger role in the optimization and design of the thermal systems of the future.

2.6.3 Key Advantages of CFD in Nanofluid Research

CFD is popularly used for nanofluids simulations because of several key advantages:

Computational Fluid Dynamics provides an in-depth understanding of the different nanofluid types using visualizations of temperature, pressure, and flow characteristics throughout the entirety of the heat exchanger component. These visualizations provide useful details on flow dynamics and occurrences of recirculation or flow separation.

1. **Control of Boundary Conditions:** Unlike an experimental setup, CFD allows for exact control of inlet velocities, wall conditions, and properties of nanoparticles, etc.; allowing for repeatability and ease of comparative analysis.

2. **Material and Geometric Flexibility:** CFD allows for the simulation of innumerous nanofluid types and geometries of heat exchangers without fabrication, while also allowing for parametric studies, where volume fraction, flow rate, or geometry, can be changed with very little effort.

3. **Cost Effectiveness:** In research environments restricted by budget and resources, CFD provides a low-cost alternative to characterize heat exchanger performance. CFD does not require physical fabrication or prototyping to repeat an experiment, especially in the early stages of the design process.

4. **Feasibility for Optimization:** CFD allows for performance analysis for many conditions; enabling optimization studies for many conditions as well, including looking at both thermal efficiency and pressure drop (pumping power) to meet Multiple Objectives.

2.6.4 Limitations and Challenges

Despite the significant insights CFD provides into nanofluid behaviour, several limitations and challenges still affect the reliability and interpretation of simulation outcomes.

1. **Dependence on Input Accuracy:**

Nanofluid thermophysical properties such as viscosity, specific heat, and thermal conductivity are often derived from empirical or semi-empirical correlations (e.g., Maxwell–Garnett, Pak & Cho). These models may oversimplify the real interfacial dynamics between nanoparticles and the base fluid, especially at high concentrations or under non-isothermal conditions. This limitation can lead to deviations between predicted and actual thermal performance.

In this study, this challenge is addressed by using temperature-dependent property correlations reported in validated literature for Al_2O_3–water, CuO–water, and TiO_2–water nanofluids. Concentrations are kept within dilute regimes (≤4%) to remain within the validity range of these correlations.

2. Validation Requirements:

The predictive capability of CFD models is only as credible as their validation against experimental or benchmark data. Without such verification, critical parameters such as Nusselt number, friction factor, or pressure loss may be over- or under-predicted.

Accordingly, the numerical framework in this study is cross-referenced with published experimental results from Surana (2020), Oflaz (2022), and Thakur (2019), to ensure that the baseline case (pure water) and nanofluid-enhanced cases align with established literature trends.

3. Meshing and Solver Sensitivity:

The curved and narrow passages within shell-and-tube heat exchangers make the numerical results highly sensitive to mesh quality, near-wall treatment, and solver settings. Coarse meshes may fail to capture boundary-layer effects, while excessive refinement increases computational cost without significant accuracy gains.

This challenge is mitigated by performing a mesh-independence test, adopting a hybrid meshing strategy (hexahedral core and prism layers near walls), and applying second-order discretization schemes for both momentum and energy equations to ensure numerical stability.

4. Computational Demand:

High-fidelity CFD simulations particularly those involving turbulent flow and multi-phase modelling—can be computationally intensive. The inclusion of nanoparticle transport mechanisms (Brownian motion, thermophoresis) significantly increases runtime and memory requirements.

This study addresses the issue by employing a steady-state, single-phase approach that maintains physical relevance while reducing computational complexity. The adopted double-pass shell-and-tube configuration focuses on the most heat-transfer-intensive region, allowing for efficiency without compromising thermal accuracy.

In summary, while CFD-based nanofluid analysis faces inherent challenges in property estimation, validation, meshing, and computational demand, this study incorporates best practices from literature and controlled simplifications to minimize these limitations. This approach ensures a balance between model realism, computational efficiency, and physical interpretability.

2.6.5 Relevance to this study

The present study applies Computational Fluid Dynamics (CFD) as a core analytical tool to comparatively evaluate three mono nanofluids—Al_2O_3–water, CuO–water, and TiO_2–water within a double-pass shell-and-tube heat exchanger configuration. The modelling framework adopts consistent boundary conditions, operating parameters, and geometric dimensions across all test cases to ensure that variations in the results arise solely from changes in nanoparticle type and concentration.

Each nanofluid is analyzed at three volume fractions (0.2%, 0.5%, and 1.0%), with thermophysical properties estimated using validated empirical correlations that are both

temperature- and concentration-dependent. This enables an accurate assessment of how each nanofluid influences heat transfer enhancement and flow resistance.

Unlike most previous studies that altered geometry, flow conditions, or nanofluid type independently (e.g., Surana, 2020; Oflaz, 2022; Thakur, 2019), this study adopts a standardized simulation procedure to allow for a direct and unbiased comparison of performance parameters such as outlet temperature, pressure drop, velocity field, and temperature distribution.

Furthermore, the CFD domain is reduced to the most heat-transfer-intensive section of the exchanger. This reduced-order modelling approach retains the essential physics of the problem while minimizing computational cost—an approach that aligns with current optimization trends in numerical thermal system design.

By addressing the inconsistency and fragmentation observed in many previous nanofluid simulation studies, this work contributes a systematic and comparative perspective that enhances methodological uniformity and practical interpretability. The study therefore advances CFD-based understanding of nanofluid performance in waste heat recovery systems and helps bridge the gap between theoretical potential and industrial application..

CHAPTER THREE

METHODOLOGY

3.1 Approach to Computational Fluid Dynamics Simulation

In ANSYS Fluent, Computational Fluid Dynamics (CFD) follows a systematic workflow that ensures accuracy, consistency, and ease of troubleshooting during model development. This sequential approach not only provides a clear structure for model development but also allows for efficient correction, since any issues can be traced to specific stages such as geometry, meshing, or boundary conditions. By maintaining this methodology, ANSYS Fluent guarantees a rigorous and repeatable process for fluid flow simulation and design.

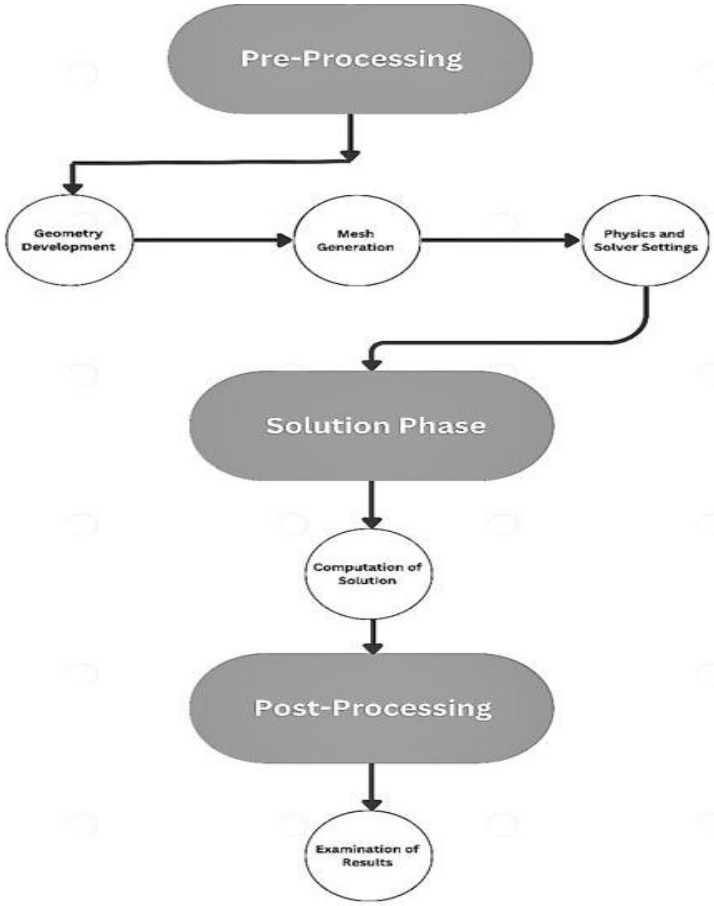

Figure 3.1: Illustrative workflow chart of this study

3.1.1 Pre-processing

Pre-processing serves as the foundation for accurate and efficient simulations. It involves creating the computational model and preparing it for numerical solution. The main tasks under preprocessing include geometry development, mesh generation, and physics and solver settings.

1. Geometry Development

Geometry development defines the physical structure of the system to be analyzed. It involves creating a three-dimensional representation of the computational domain, which may include ducts, pipes, chambers, or heat exchangers through which the fluid flows. In ANSYS, geometry can be created directly using DesignModeler or SpaceClaim, or imported from external CAD software. Simplification of geometry is often performed at this stage to remove unnecessary details that do not influence the flow or heat transfer, thereby reducing computational cost.

For this project, the geometry represents the section of the system where flue gases transfer heat to the selected nanofluid. A simplified model is used to capture the essential flow and thermal behavior while maintaining computational efficiency. The model used here was the WU63-66 U-tube heat exchanger, initially modeled in solidworks and imported as geometry into the fluent design modeler. Defeaturing was done to the model to remove geometric features that do not significantly influence geometric results. This parts include bolts, nuts, small holes, text engravings, seals e.t.c. This allows for a simpler mesh, faster solution and easier analysis.

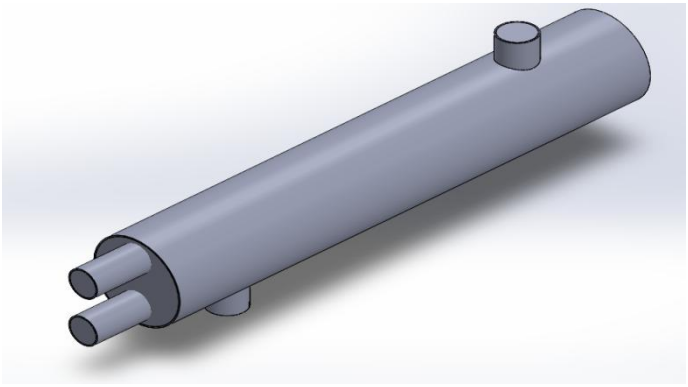

Figure 3.2: Defeatured WU63-23 Bell and Gossett heat exchanger.

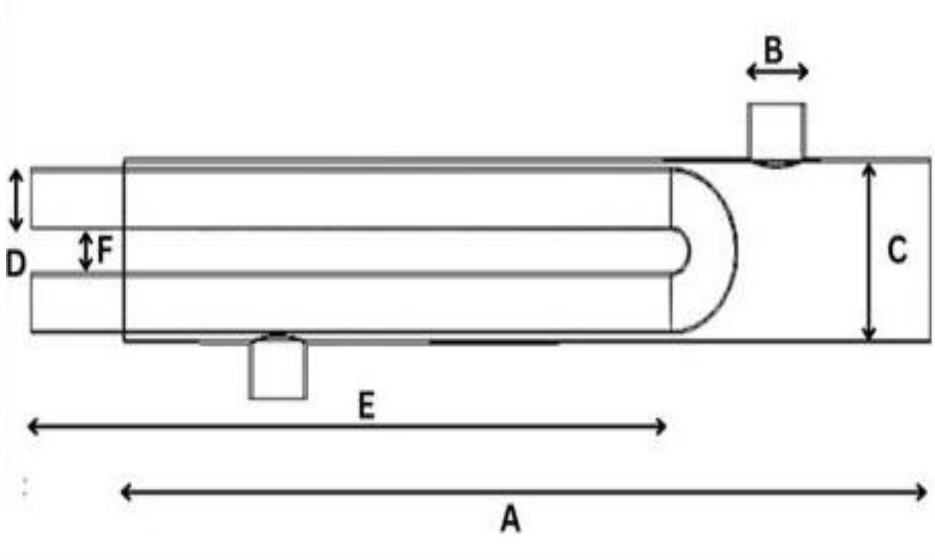

Figure 3.3: Dimensioned WU63-23

Table 3.1: All Dimensions (mm)

Type	A	B	C	D	E	F
WU63-23	914	58.5	168	50.8	724	22.1

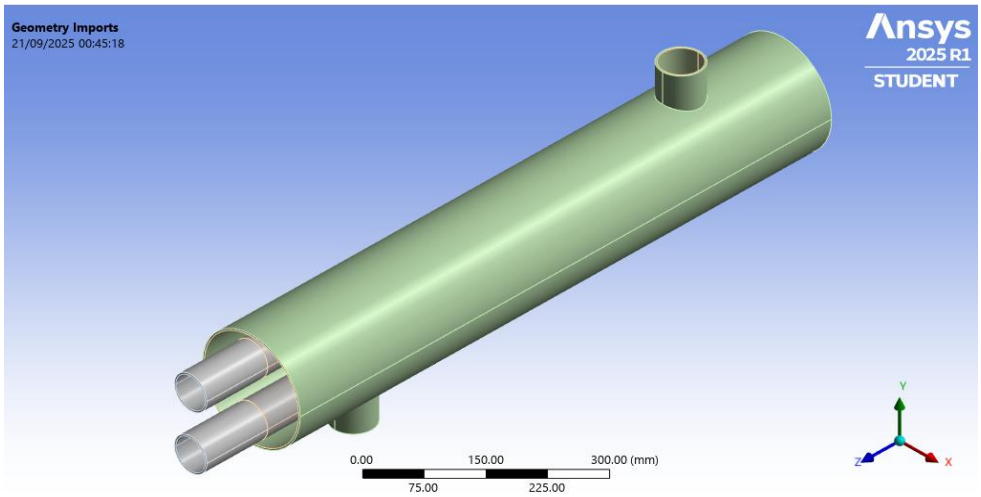

Figure 3.4 Imported geomerty of heat exchanger in design modeler

2. Mesh Generation

Mesh generation involves dividing the geometry into small, discrete elements where the governing equations of fluid flow and heat transfer are numerically solved. The quality of the mesh significantly affects both the accuracy and stability of the simulation results.

To ensure mesh independence, a mesh sensitivity test was conducted on the geometry using element sizes of 15 mm, 10 mm, 7 mm, 6 mm, and 5 mm. These meshes were evaluated and compared based on specific quantities of interest, including mass flow rate, velocity, mass imbalance residuals, and boundary temperature. Water was used as the base fluid for all simulations.

Table 3.2: Mesh for 15mm

Mesh 1 (Element size : 15mm)							
	Velocity		Mass Flow Rate		Residuals	Temperature	
	Cold Domain	Hot Domain	Cold Domain	Hot Domain	Mass Imbalance	Cold Domain	Hot Domain
Inlet	0.5	1	0.99502522	0.0032386757	$-2.362987e^{-10}$	25.000004	518.95036
Outlet	0.50430217	1.3805056	-0.99502522	0.003231702		25.137664	318.7044

Table 3.3: Mesh for 10mm

Mesh 2 (Element size : 10mm)							
	Velocity		Mass Flow Rate		Residuals	Temperature	
	Cold Domain	Hot Domain	Cold Domain	Hot Domain	Mass Imbalance	Cold Domain	Hot Domain
Inlet	0.5	1	0.99502522	0.0032386757	$-2.362987e^{-10}$	25.000004	518.95036
Outlet	0.50430217	1.3805056	-0.99502522	-0.003231702		25.137664	318.7044

Table 3.4: Mesh for 7mm

Mesh 3 (Element size : 7mm)							
	Velocity		Mass Flow Rate		Residuals	Temperature	
	Cold Domain	Hot Domain	Cold Domain	Hot Domain	Mass Imbalance	Cold Domain	Hot Domain
Inlet	0.5	1	0.99789001	0.0032606292	$-9.816574e^{-13}$	25.000001	518.9583
Outlet	0.50573016	1.4770367	-0.99788986	-0.0032562128		25.136883	314.7072

Table 3.5: Mesh for 6mm

Mesh 4 (Element size : 6mm)							
	Velocity		Mass Flow Rate		Residuals	Temperature	
	Cold Domain	Hot Domain	Cold Domain	Hot Domain	Mass Imbalance	Cold Domain	Hot Domain
Inlet	0.5	1	1.0017713	0.0032685682	$1.7114549e^{-11}$	25.000003	518.96978
Outlet	0.50640108	1.4977255	-1.0017713	-0.0032660217		25.136037	319.63899

Table 3.6: Mesh for 5mm

Mesh 5 (Element size : 5mm)							
	Velocity		Mass Flow Rate		Residuals	Temperature	
	Cold Domain	Hot Domain	Cold Domain	Hot Domain	Mass Imbalance	Cold Domain	Hot Domain
Inlet	0.5	1	1.0051026	0.0032758981	$-2.2807875e^{-12}$	25	518.98108
Outlet	0.50790731	1.5326395	-1.0051026	-0.0032777174		25.136306	307.70759

From the comparative analysis, Mesh 4 was selected as the most suitable mesh for the project. It exhibited an acceptable mass imbalance and produced steady average temperature values at both the inlet and outlet compared to the other mesh sizes. Additionally, its mass flow rate remained consistent at the outlet for both the cold and hot domains. Moreover, Mesh 4 provided a good balance between accuracy and computational efficiency, requiring less simulation time than the finer 5 mm mesh.

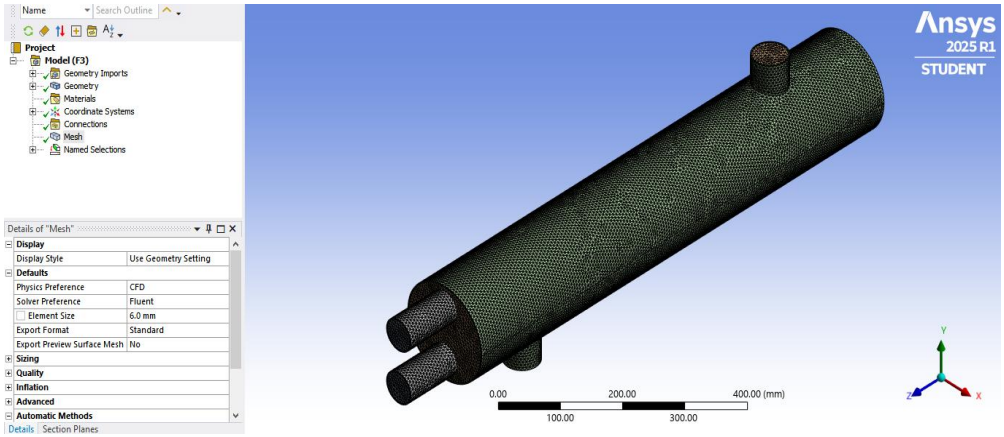

Figure 3.5 Example of a generated mesh (6mm)

The governing equations can now be solved on the 6mm mesh chosen. These equations are discussed below.

3.1.1.1 Governing Principles in the Computational Fluid Dynamics

Computational Fluid Dynamics is the science of predicting fluid flow, heat and mass transfer, chemical reactions and related phenomena. ANSYS Fluent is one of the most widely used Computational Fluid Dynamics (CFD) solvers. To predict these phenomena ANSYS Fluent makes use of the Finite Volume Method (FVM) of analysis to solve equations for conservation of mass, Newtons second law of motion (F = ma), and the conservation of energy. ANSYS fluent makes use of the FVM to solve the governing conservation equations of fluid flow namely:

$$\frac{\partial}{\partial t}\int \rho\phi dV + \oint \rho\phi \vec{u}.\vec{n}dA = \oint \Gamma\nabla\phi.\vec{n}\,dA + \int S_\phi dV \qquad (3.1)$$

where

V = volume

A = control surface (boundary of the volume)

ρ = fluid density

ϕ = transported variable

$\vec{u}$ = velocity vector

Γ = diffusion coefficient

S_ϕ = source term

$\vec{n}$ = unit normal vector to the surface

ANSYS fluent uses the FVM to solve the governing conservation equations of fluid flow namely:

- Conservation of mass (Continuity equation)
- Conservation of momentum (Navier–Stokes equations)
- Conservation of energy

These equations would be discussed breiefly:

1. **Conservation of Mass**

The conservation of mass principle is simply a statement that mass cannot be created or destroyed during a process and all the mass must be accounted for during an analysis. In

steady flow, the amount of mass within the control volume remains constant, and thus the conservation of mass can be expressed as:

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho . \vec{u}) = 0 \qquad (3.2)$$

where

ρ = density

$\vec{u}$ = velocity vector

In differential form, in two dimensional form, it is represented as

$$\frac{du}{dx} + \frac{dv}{dy} = 0 \qquad (3.3)$$

where

u = average velocity in the x-direction

v = average velocity in the y-direction

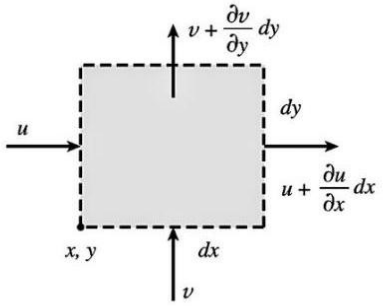

Figure 3.6: Differential control volume used in the derivation of mass balance in velocity boundary layer in two-dimensional flow over a surface.

2. **Conservation of Momentum (Navier-Stokes Equations)**

The momentum balance equation, commonly referred to as the Navier–Stokes equations, follows directly from Newton's second law of motion which can be written as expression for momentum balance in and can be stated as "*the net force acting on the control volume is equal to the mass times the acceleration of the fluid element within the control volume, which is also equal to the net rate of momentum outflow from the control volume"* (Çengel, Y. A., & Ghajar, A. J. 2015).

In a fluid, two categories of forces act on a finite control volume:

1. Surface forces which are forces exerted across the surfaces of the volume, primarily represented as pressure forces resulting in normal stresses and viscous forces which induce shear stresses due to velocity gradients.
2. Body forces, comprising of forces that act throughout the volume of the fluid element, such as gravitational forces centrifugal, inertial forces e.t.c.

The conservation of momentum can thus be written as

$$\frac{\partial}{\partial t}(\rho\vec{u}) + \nabla.(\rho\vec{u}\vec{u}) = -\nabla p + \nabla.\tau + \rho\vec{g} \qquad (3.4)$$

where

p = pressure

τ = viscous stress tensor (dependent on viscosity and velocity gradients)

$\rho\vec{g}$ = body forces

In one dimensional differential form, it is represented as

$$\rho(u\frac{du}{dx} + v\frac{du}{dy}) = \mu\frac{\partial u}{\partial y^2} - \frac{\partial P}{\partial x^2} \qquad (3.5)$$

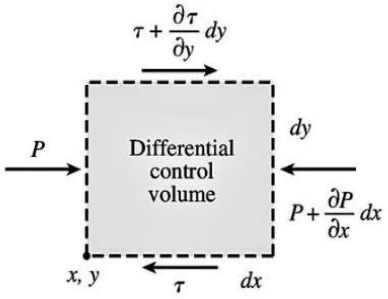

Figure 3.7: Differential control volume used in the derivation of x-momentum equation in velocity boundary layer in two- dimensional flow over a surface.

3. **Conservation of Energy**

The energy balance for any system undergoing any process is expressed as the amount of energy leaving the system subtracted from the energy entering the system is equal to the amount of energy used by the system. It can be stated as the change in the energy content of a system during a process is equal to the difference between the energy input and the energy output.

Considering a steady-flow process, the total energy content of a control volume remains constant, and the amount of energy entering a control volume in all forms must be equal to the amount of energy leaving it. This is a crucial aspect of CFD analysis as discrepancies can occur where energy E_{in} differs from E_{out} (e.g heat transferred from a hot fluid being less than the heat gained from the cold fluid). The energy conservation equation is written as

$$\frac{\partial}{\partial t}(\rho E) + \nabla . (\vec{u}(\rho E + p)) - \nabla . (k\nabla T) + \phi + S_E \qquad (3.6)$$

where

E = total energy per unit mass

T = temperature

k = thermal conductivity

ϕ = viscous dissipation

S_E = energy source term

In differential form, in one dimensional form, it is represented as

$$\rho c_p(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}) = k(\frac{\partial T}{\partial x^2} + \frac{\partial T}{\partial y^2}) \text{.....} 3.1.1.1.7$$

where

c_p = specific heat capacity at constant pressure

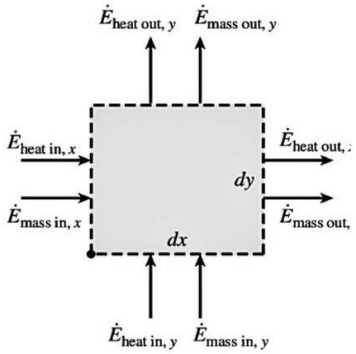

Figure 3.8: The energy transfers by heat and mass flow associated with a differential control volume in the thermal boundary layer in steady two- dimensional flow.

4. Physics and Solver Settings

Once the geometry and mesh were prepared, the next preprocessing stage involved defining the physics of the problem and configuring the solver settings. This step included the following:

1. Material Properties:

The solver uese four properties are required to fully define the flow properties of a fluid. These are density, specific heat capacity, thermal conductivity, and viscosity.

The thermophysical properties of aluminum oxide (Al_2O_3) nanoparticles used in this study—density of 3970 kg/m³, specific heat capacity of 765 J/kg·K, and thermal conductivity of 36 W/m·K—were adopted from H. Togun et al. (2021). These values were reported in their study on hybrid Al_2O_3–Cu–water nanofluids, where the authors experimentally and numerically analyzed heat transfer behavior and validated the thermophysical parameters against existing literature. The data provide a reliable baseline for simulating nanofluid behavior under thermal and flow conditions, ensuring consistency with experimentally verified models.

The thermophysical properties of CuO nanoparticles—namely a density of 6500 kg/m³, specific heat capacity of 540 J/kg·K, and thermal conductivity of 20 W/m·K—were reported by Kanayo K. Asogwa et al. (2022) in their comparative study on Al_2O_3–water and CuO–water nanofluids over an exponentially accelerated radiative Riga plate surface. These values form the basis for assessing the superior thermal performance of CuO-based nanofluids due to the metal oxide's relatively high density and conductivity compared to Al_2O_3, which enhances convective heat transfer in hybrid or single-phase nanofluid applications.

The thermophysical properties of TiO_2 nanoparticles — with a density of 4250 kg/m³, specific heat capacity of 686.2 J/kg·K, and thermal conductivity of 8.4 W/m·K — were reported by Rashid et al. (2021). These values are widely used in nanofluid simulations and analytical models to predict heat transfer enhancement. The relatively high density of TiO_2 contributes to better heat storage capacity per unit volume, while its moderate

thermal conductivity supports effective thermal energy transport without excessive rise in viscosity. The specific heat capacity indicates its ability to absorb and retain heat efficiently, making TiO_2–water nanofluids suitable for stable, low-cost heat transfer applications where both thermal stability and dispersion uniformity are essential.

Determination of Density

The determination of the different density of the nanofluids was based on the law of mixtures and the Pak and Cho relation.

The theory of mixtures is a classical approach in thermodynamics and fluid mechanics used to estimate the effective properties of a mixture from those of its constituents. For density, the mixture is assumed to behave as a homogeneous single-phase fluid with properties that are the volume-fraction-weighted average of its components.

Pak and Cho applied the mixture theory approach in determining the density of different nanofluids. Hence if:

ρ_{nf} = density of nanofluid

ρ_{bf} = density of the base fluid

ρ_{np} = density of nanoparticles

ϕ = nanoparticle volume fraction

Then the mixture density is:

$$\rho_{nf} = (1 - \phi)\rho_{bf} + \phi\rho_{np} \qquad (3.8)$$

This equation is in good agreement in predicting the density of nanofluids assuming that:

1. Nanoparticles are uniformly dispersed.
2. No agglomeration, slip, or interaction between phases.
3. Volume fraction ϕ is small.

Pak and Cho's relation is essentially the rule of mixtures for density of nanofluid.

Specific Heat Capacity

The Maxwell–Garnett effective medium theory which is originally from electromagnetism has been adapted for estimating the specific heat capacity of

nanofluids. The law of mixtures for composite fluids is used to estimate this property by treating the nanofluid as a composite material made up of host fluid (base fluid) and dispersed phase (nanoparticles).

The effective specific heat capacity of a nanofluid is usually expressed on a volumetric basis as:

$$c_{pnf} = \frac{(1-\phi)\rho_{bf} \, . \, c_{pbf} + \phi\rho_{np}c_{pnp}}{\rho_{nf}} \qquad (3.9)$$

where:

c_{pnf} = heat capacity of nanofluid

c_{pbf} = heat capacity of base fluid

c_{pnp} = heat capacity of particle

$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np}$ (from Pak and Cho / mixture theory).

Thermal Conductivity

The model used for estimating the thermal conductivity of the nanofluid is that of the Maxwell-Garnett. "The Maxwell-Garnett effective medium theory" which originally developed for dielectric materials in 1904 has been widely adapted to estimate effective thermal conductivity of composite materials, including nanofluids. It is a modified model of the Maxwell equation, the most elementary in describing the thermal conductivity of nanofluids and it is in par with the experimental data. The equation thus:

$$K_{nf} = K_{bf}\frac{K_{np}+2K_{bf}-2\phi(K_{bf}-K_{np})}{K_{np}+2K_{bf}-\phi(K_{bf}-K_{np})} \qquad (3.10)$$

where:

K_{nf} = thermal conductivity of nanofluid

K_{bf} = thermal conductivity of base fluid

K_{np} = thermal conductivity of particles

Viscosity

When nanoparticles are added to a base fluid, the viscosity of the mixture increases. The Brinkman equation was originally developed for suspensions of rigid spheres in a

Newtonian fluid. It extends Einstein's equation which is valid only for very dilute suspensions (Rahmatinejad, B et al. 2021).

The effective viscosity of a nanofluid is given by:

$$\mu_{nf} = \mu_{bf}(1-\phi)^{-2.5} \qquad (3.11)$$

where:

μ_{nf} = effective viscosity of the nanofluid

μ_{bf} = viscosity of base fluid

This equation holds good in predicting the viscocity of nanofluids provided these assumptions are verified:

1. Rigid spherical particles.
2. Uniform dispersion (no clustering/agglomeration).
3. Negligible particle–particle and particle–fluid slip effect.

Table 3.7 shows the thermodynamic properties of metallic compounds which are used as nanoparticles and table 3.8 shows derived properties of the nanofluids using the aforementioned numerical models. Here the nanoparticles as stated in other preceeding chapters are Al_2O_3, CuO, and TiO_2. The base fluid chosen is water.

Table 3.7: Thermodynamic properties of the nanoparticles Al_2O_3, CuO, TiO_2 and base fluid, H_2O.

Properties	**Al_2O_3**	**CuO**	**TiO_2**	**Water**
Density (kg/m^3)	3970	6500	4250	998.2
Specific Heat Capacity (J/(Kg.K))	765	540	686.2	4182
Thermal Conductivity (W/(m.K))	36	20	8.4	0.6
Viscosity (Pa.s)	-	-	-	0.001003

Table 3.8: Thermodynamic properties of the selected nanofluids at various percentage concentrations by mass of the nanoparticles.

Properties	**% by mass of nanoparticle**	**Al_2O_3-water**	**CuO-water**	**TiO_2-water**
Density(kg/m^3)3	0.2	1004.144	1009.204	1004.704
	0.5	1013.059	1025.709	1014.459
	1.0	1027.918	1053.218	1030.718
Specific Heat Capacity(J/Kg.K)	0.2	4154.979	4135.084	4152.423
	0.5	4115.047	4066.602	4108.773
	1.0	4050.029	3957.232	4037.850
Thermal Conductivity(W/m.K)	0.2	0.603	0.603	0.603
	0.5	0.609	0.608	0.607
	1.0	0.617	0.617	0.615
Viscosity(Kg/m.s) or (Pa.s)	0.2	0.001008	0.001016	0.001029
	0.5			
	1.0			

2. **Boundary Conditions:**

Boundary conditions were established to represent the real physical constraints of the system. The water inlet temperature was set at 25 °C, while the air (flue gas) inlet was modeled at 519 °C which is the average temperature of the SGT5-2000E heavy duty gas turbine used in Azura. Inlet velocities of 0.5 m/s for fluid in the tubes and 1m/s for air in the shell, outlet pressures of 1 atm was used, wall conditions, and symmetry planes were also defined to accurately describe the flow and thermal boundaries.

Table 3.9 Reactive power and respective temperature of turbine outlet

Reactive Power (MVAR)	Turbine Temperature Outlet °C
25	521
26	517
22	520
24	521
27	518
27	520
23	517

3. **Solver Selection:**

   Since the flow was assumed to be incompressible, a pressure-based solver was selected. Consequently, ANSYS Fluent solved the governing equations using pressure-based boundary conditions while neglecting compressibility effects.

4. **Turbulence and Heat Transfer Models:**

   Appropriate turbulence and heat transfer models were chosen to accurately capture the flow and thermal behavior. The k–ω SST model was adopted, as it is widely recommended for heat exchanger simulations (Hrutuj Raut, 2021), due to its ability to resolve boundary layer effects efficiently. In this study, the solver settings were configured to simulate forced convection between flue gases and nanofluids, ensuring that turbulence and thermal transport phenomena were properly represented to assess the system's heat recovery performance.

3.1.2 Solution Phase

The solution phase is the stage where ANSYS Fluent performs the actual numerical calculations to solve the governing equations of fluid flow and heat transfer within the computational domain. This step translates the problem definition, geometry, mesh, and physical models specified during preprocessing into meaningful numerical results.

5. Computation of Solution

In this stage, the solver applies the Finite Volume Method (FVM) to discretize and solve the governing conservation equations for mass, momentum, energy, and turbulence across the mesh elements. These equations are discussed below.

In the process of computing the solution of the project particular settings are inputed. The computation process involves the following key tasks:

- **Initialization:**

  The solution process begins with initializing the flow variables such as velocity, pressure, and temperature to provide the solver with suitable starting values. Initialization can be performed using either a uniform (standard) approach or more physically realistic flow estimates (hybrid initialization). For this project, hybrid initialization was employed to ensure better numerical stability and faster convergence.

- **Iteration:**

  A steady-state simulation was adopted, where the solver iteratively updates the solution variables until convergence is achieved. The SIMPLE solution method was selected. Default solver controls were maintained, and 500 iterations were performed to obtain stable and reliable results.

- **Convergence Monitoring:**

  Throughout the computation, residuals were continuously monitored to assess convergence behavior. In addition to residual plots, physical parameters such as outlet temperature, inlet and outlet mass flow rates, pressure drop, and heat transfer rate were tracked to ensure that the solution remained physically meaningful and consistent.

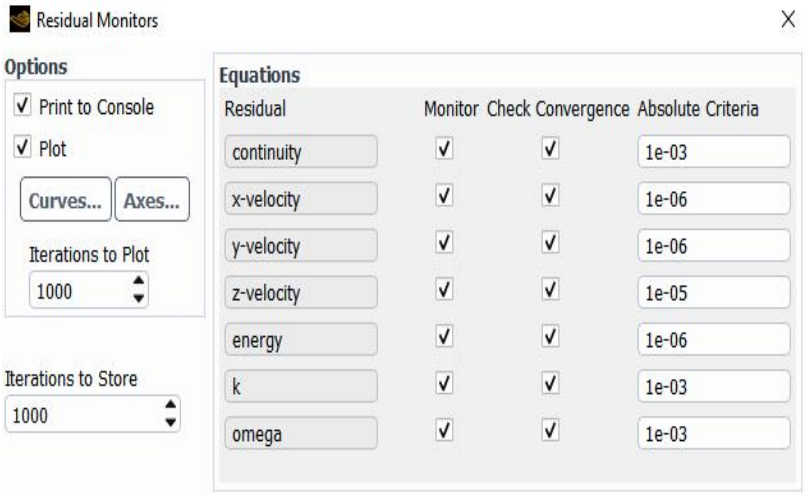

Figure 3.9 Residuals values for convergence

In this project, the computation phase focused on accurately resolving the coupled fluid flow and heat transfer interactions between the flue gases and nanofluids. Iterations were continued until the residuals fell below acceptable convergence criteria, confirming the stability and accuracy of the solution.

3.1.3 Post-processing

6. Examination of Results

The examination of results in ANSYS Fluent involves both graphical visualization and numerical analysis of the computed flow and thermal fields. This process includes generating temperature and pressure contours, velocity streamlines, and vector plots to illustrate the direction, magnitude, and distribution of flow within the computational domain.

By integrating contour plots, and streamline visualizations, the post-processing stage provides a comprehensive understanding of the system's overall thermal and flow behavior. This detailed analysis supports informed decision-making regarding the heat transfer performance and effectiveness of the nanofluids employed in the study.

3.2 Comparative Quantities for Analysis

To evaluate and compare the thermal performance of the nanofluids against each other and that of water, several key quantities were analyzed. These parameters provide insights into the heat transfer characteristics, flow behaviour, and overall efficiency of the heat exchanger system. The quantities considered include:

3.2.1 Temperature of the Hot Air (Flue Gas) Leaving the Heat Exchanger

The outlet temperature of the hot air (flue gas) serves as an initial indicator of the waste heat recovery capability of each working fluid. By comparing the outlet temperatures, it becomes possible to determine how effectively each nanofluid absorbs heat from the flue gas. A lower outlet temperature indicates a higher rate of heat transfer and, consequently, better thermal performance.

3.2.2 Heat Transfer Rate of the Heat Exchanger

The heat transfer rate provides a direct measure of the total amount of heat absorbed by the nanofluid and the corresponding heat released by the flue gas. This parameter is essential for evaluating the thermal efficiency and capacity of the heat exchanger. The maximum heat transfer rate is computed to assess the system's performance and the comparative effectiveness of different nanofluids.

$$Q_{actual} = \dot{m}c_p(T_{out} - T_{in}) \ = \dot{m}(h_{out} - h_{in}) \qquad (3.12)$$

$$Q_{max} = \dot{m}c_p(T_{h,in} - T_{h,out}) \qquad (3.13)$$

3.2.3 Effectiveness

Effectiveness is a dimensionless quantity used to evaluate the performance of a heat exchanger relative to its ideal operation. It represents the ratio of the actual heat transfer to the maximum possible heat transfer. A higher effectiveness value indicates a more efficient heat exchanger and improved utilization of thermal energy.

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} \qquad (3.13)$$

3.4.4 Pressure Drop

The pressure drop across the heat exchanger is calculated to determine the flow resistance encountered by each nanofluid. From this, the required pumping power is derived to maintain a constant flow velocity. These parameters are vital for assessing the trade-off between enhanced heat transfer and the additional energy required to circulate the fluid.

$$\Delta p = p_{in} - p_{out} \qquad (3.14)$$

$$W = \Delta p.V = \Delta p\,.\,\frac{\dot{m}}{\rho} \qquad (3.15)$$

3.2.5 Overall Heat Transfer Coefficient

The overall heat transfer coefficient reflects the combined effect of convection and conduction on the total heat transfer performance of the system. It serves as a key indicator of the heat exchanger's efficiency and the ability of each nanofluid to conduct and transfer heat effectively.

$$U = \frac{Q_{actual}}{A.\Delta T_{lm}} \qquad (3.17)$$

Where

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln\{\frac{\Delta T_1}{\Delta T_2}\}} \qquad (3.18)$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Comparative Quantities for Analysis

This chapter presents the results obtained from the simulations based on data and methodologies outlined in the previous chapter. Several simulations were conducted to arrive at the selected thermophysical properties we are going to be discussing in this chapter. By these results, we can determine the best conditions under which our nanofluids can perform optimally.

4.2 Heat Lost by the Air (Flue Gas)

The Heat transfer rates provided in this study have been derived based on heat gain in the fluid. The heat transfer rates are grossly dependent on the inlet and exit properties of the fluid and air in the pipe. With each concentration by mass (0.2%, 0.5% & 1%) we get a varying value for the heat transfer rate(Q).

For our study, the highest heat transfer rate recorded is in 1% CuO (658.211645W), 1% TiO_2 (656.375114W) and 0.5% TiO_2 (656.189493W) this means that nanofluid, 1% CuO showed the best heat transfer rate of air. The lowest heat transfer rates were observed in 1% Al_2O_3, 0.2% CuO, and 0.2% TiO_2.

Table 4.1: Heat lossed by air in watts

Nanofluid	0.2%	0.5%	1%
Al_2O_3	665.301316	655.793469	652.258810
CuO	653.184244	655.701131	658.211645
TiO_2	655.049961	656.189493	656.375117

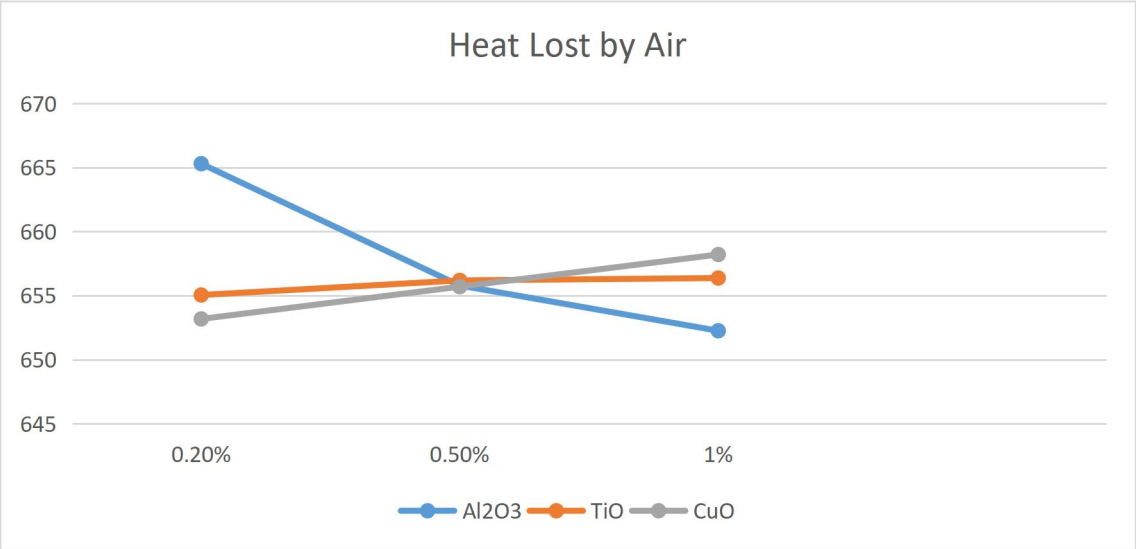

Figure 4.1: Comparative analysis of all nanofluids based on heat lost air by each nanofluid in watts

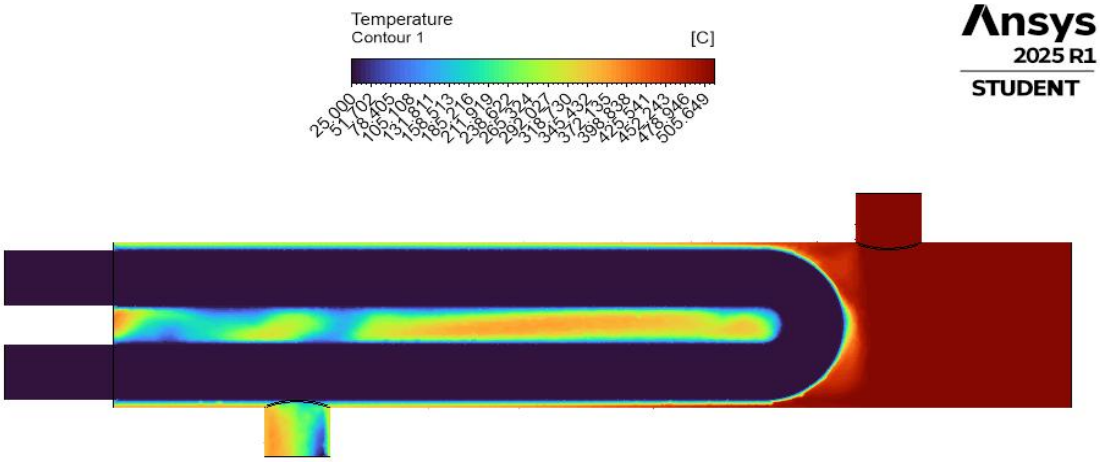

Figure 4.2: Temperature Contour for CuO 1%

4.3 Heat Gained by the Nanofluid

The rate of heat transfer by the fluid indicates the overall ability of the working fluid to absorb and convey thermal energy through the heat exchange. A higher heat transfer value reflects a better capacity of the fluid to extract heat from the hot gas and transfer it to the cold side, thereby improving the system's thermal efficiency.

For the base fluid, water achieved a heat transfer rate of 569.907132 W. The highest heat transfer values were recorded for 0.2% CuO (570.700095 W), 0.5% CuO (569.143563 W), and 0.2% TiO_2 (569.143563 W). These results show that introducing nanoparticles especially CuO at lower concentrations enhances the fluid's thermal conductivity and improves heat absorption.

In contrast, the lowest heat transfer values were obtained with 1% CuO (564.295387 W), 1% TiO_2 (565.758356 W), and 0.2% Al_2O_3 (565.870270 W). The decline at higher concentrations may be attributed to increased viscosity and particle agglomeration, which hinder fluid motion and reduce the effective surface area available for heat exchange.

Table 4.2: Heat gained by nanofluid in watts

Nanofluid	0.2%	0.5%	1%
Al_2O_3	565.870270	566.815378	568.018793
CuO	570.700095	569.581356	564.295387
TiO_2	569.143563	566.845280	565.758356

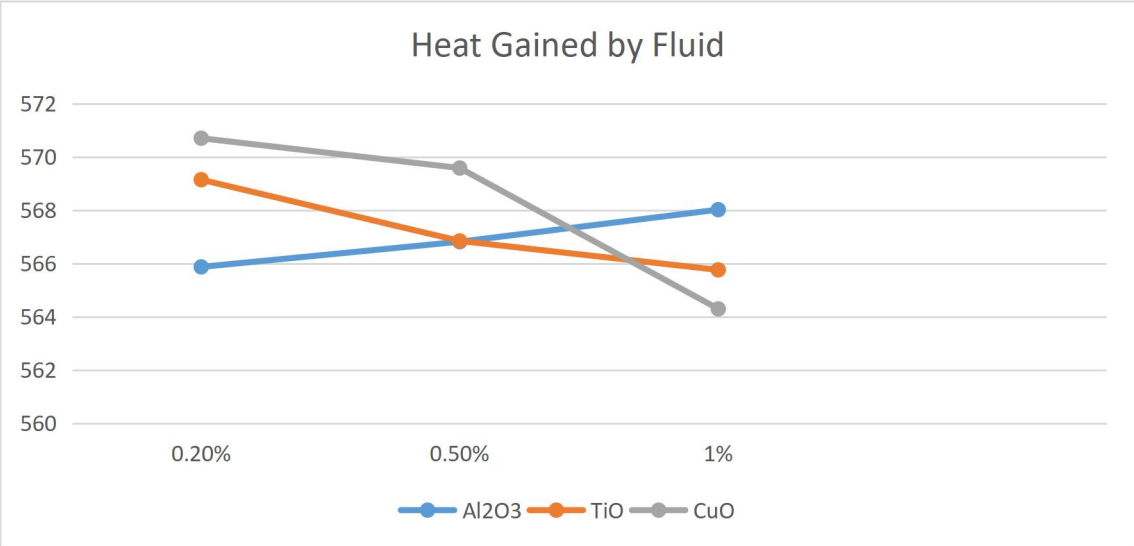

Figure 4.3: Comparative analysis of all nanofluids based on heat gained by each nanofluid in watts

4.4 Pressure Drop

The pressure drop of the fluid is as a result of the change in density. This causes resistance encountered by each nanofluid. In the comparison of the nanofluids, the highest pressure drop was registered as 1% CuO which registered 4.2% increase to that of water. Following up was that of 1% TiO_2 which registered 2.51% increase in the overall pressure drop in the tube and that of 1% Al_2O_3. If the person's concern is to maximize heat transfer but to lower pressure drop, his choice would be between 0.2% Al_2O_3, TiO2, CuO which registered values of 157.73624, 157.8025, 158.33895 respectively to that of water which was 157.73624.

Table 4.3: Pressure drop by nanofluid in pascals

Nanofluid	0.2%	0.5%	1%
Al_2O_3	157.736240	159.101600	161.363370
CuO	158.338950	160.603590	164.362420
TiO_2	157.802500	159.267790	159.267790

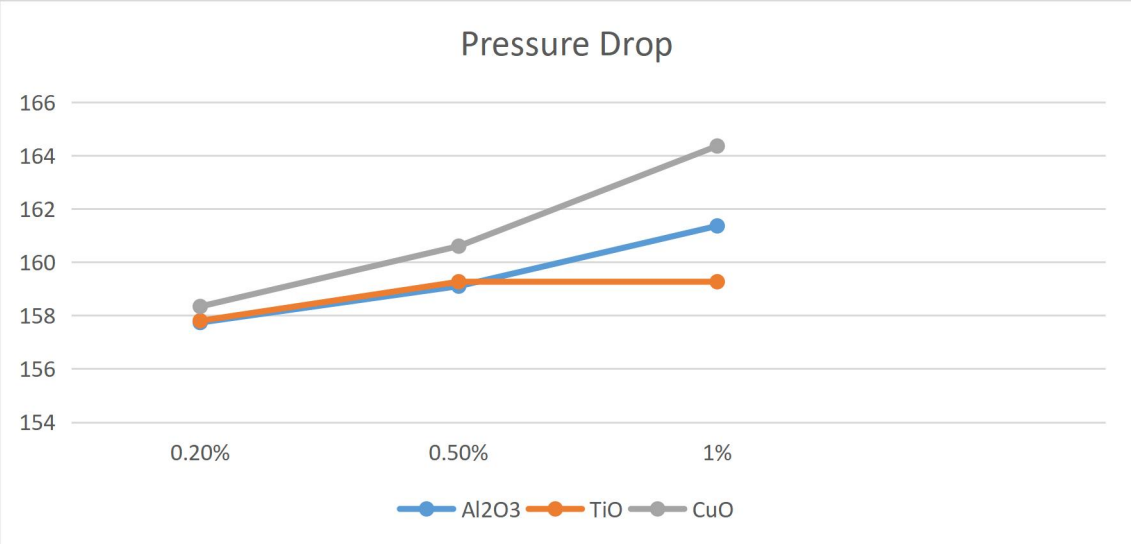

Figure 4.4: Comparative analysis of all nanofluids based on pressure drop by each nanofluid in watts

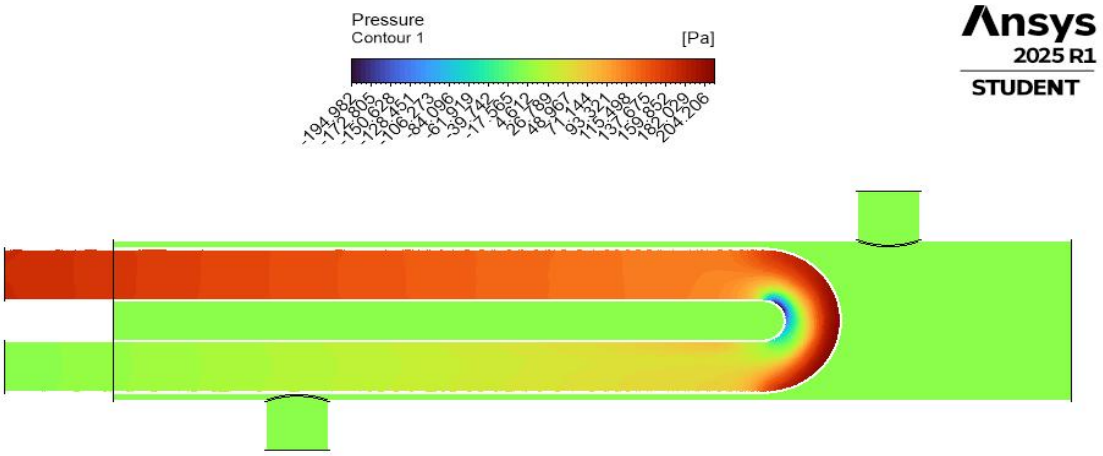

Figure 4.5: Pressure Contour for CuO 1%

4.5 Effectiveness

The effectiveness of the heat exchanger represents the ability of each working fluid to transfer heat between the hot and cold streams. A higher effectiveness value indicates better thermal performance and heat transfer.

For the base fluid, water recorded an effectiveness of 0.35016. Among the nanofluids tested, the highest effectiveness values were obtained with 0.2% CuO (0.351185), followed by 0.5% CuO (0.350496) and 0.2% TiO_2 (0.350227). These slight increases in effectiveness compared to water suggest that introducing nanoparticles enhances heat transfer capability, particularly at lower concentrations.

On the other hand, the lowest effectiveness values were recorded for 1% CuO (0.33244), 1% TiO_2 (0.348144), and 0.2% Al_2O_3 (0.348213). The decline at higher nanoparticle concentrations could be attributed to increased viscosity, which impedes fluid motion and reduces convective heat transfer efficiency.

Table 4.4: Effectiveness by nanofluid

Nanofluid	0.2%	0.5%	1%
Al_2O_3	0.348213	0.348794	0.349535
CuO	0.351185	0.350496	0.347244
TiO_2	0.350227	0.348813	0.348813

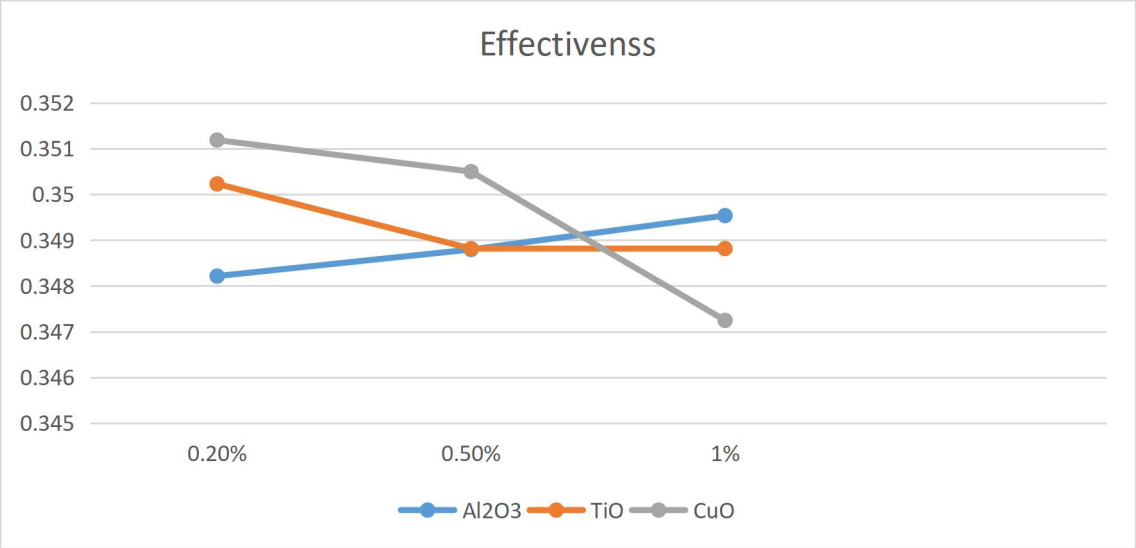

Figure 4.6: Comparative analysis of all nanofluids based on effectiveness by each nanofluid in watts

4.6 Overall Heat Transfer

The overall heat transfer coefficient represents the combined effects of convection and conduction in a heat exchanger. It indicates how effectively the system transfers heat between fluids and reflects the influence of nanoparticle concentration on thermal performance. A higher U-value means better heat transfer performance, showing that the nanofluid is more effective at conducting and transferring heat.

For Cu nanofluid, the highest U-value (5.891946 W/m^2K) was observed at 0.2% concentration, indicating optimal performance at low concentration. For TiO2 nanofluid, the highest U-value (5.881050 W/m^2K) occurred at 0.2% concentration. Generally, Cu nanofluid performed slightly better than TiO2 nanofluid in terms of overall heat transfer efficiency.

The U-value of water is 5.890857 W/m^2K. The Cu nanofluid at 0.2% concentration shows only a 0.0185% improvement in overall heat transfer coefficient compared to water (a very slight enhancement, almost negligible in practical terms.)

Table 4.6: Overall heat transfer coefficient by nanofluid

Nanofluid	0.2%	0.5%	1%
Al_2O_3	5.847900	5.866532	5.878323
CuO	5.891946	5.887379	5.670792
TiO_2	5.881050	5.860470	5.849747

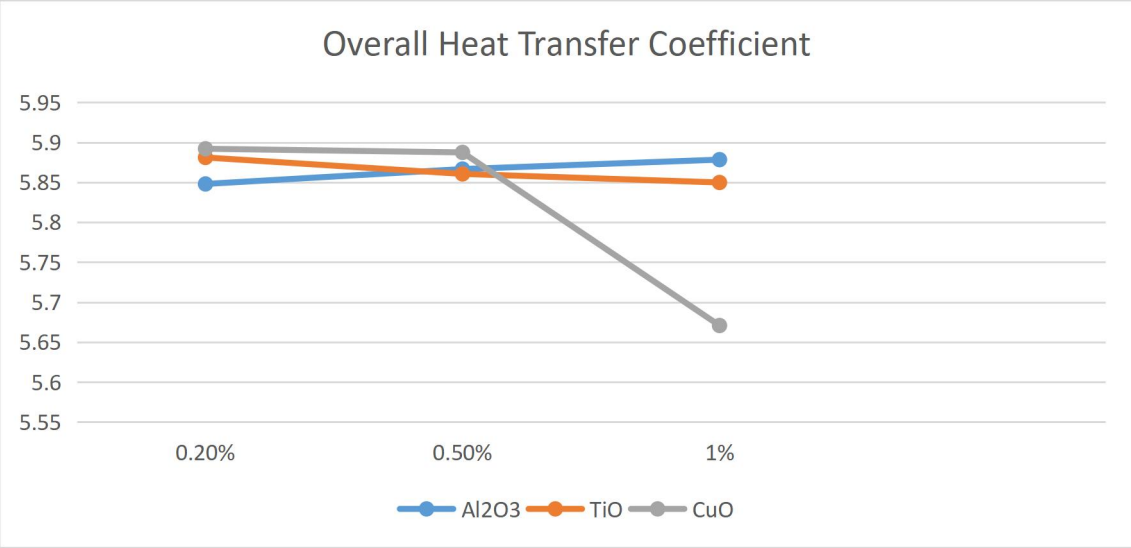

Figure 4.7: Comparative analysis of all nanofluids based on overall heat transfer coefficient by each nanofluid in watts

4.7 Temperature of the hot air leaving the shell

The outlet temperature of the hot air (flue gas) provides an important indication of the waste heat recovery efficiency of each working fluid. A lower outlet temperature signifies that the nanofluid has absorbed more heat from the flue gas, demonstrating beter thermal performance.

In this study, the outlet temperature for water (base fluid) was 319.63899 °C. Among the nanofluids tested, 1% Al2O3 nanofluid recorded the lowesr outlet temperature of 318.86642 °C, representing a 0.242% reduction compared to water. This indicates that Al2O3 nanofluid absorbed the most heat from the flue gas, making it the most effective fluid in enhancing heat transfer performance.

The 1% CuO nanofluid followed closely, with an outlet tenperature of 318.87937 °C, which is 0.238% lower than that of water. This also signifies an improved heattransfer rate, though slightly less effective than Al2O3. Next is the 1% TiO2 nanofluid, which had an outlet temperature of 319.43727 °C, showing a 0.063% reduction compared to water. While TiO2 nanofluid compared to water. While TiO2 nanofluid still performed better than water, its improvement in heat absorption was relatively modest.

The 0.2% CuO nanofluid recorded the highest outlet temperature of 320.4053 °C, which is 0.76631 °C (0.240%) higher than that of water. This indicates that it absorbed the least amount of heat from the flue gas, and therfore exhibited the poorest heat transfer performance among the tested fluids. The 0.2% TiO2 nanofluid had an outlet temperature of 319.8417 °C, slightly 0.20272 °C (0.063%) higher than water, showing a small reduction in heat recovery efficiency. However, the 0.5% CuO nanofluid recorded the lowest outlet temperature of 319.64394 °C, which is very close to that of water (only 0.00495 °C higher).

Table 4.7: Air outlet temperature by nanofluid

% conc. of nanoparticle	Al_2O_3	TiO_2	CuO
0.20%	319.7641	319.8417	320.4095
0.50%	319.6153	319.4939	319.6439
1%	318.8664	319.4373	318.8794

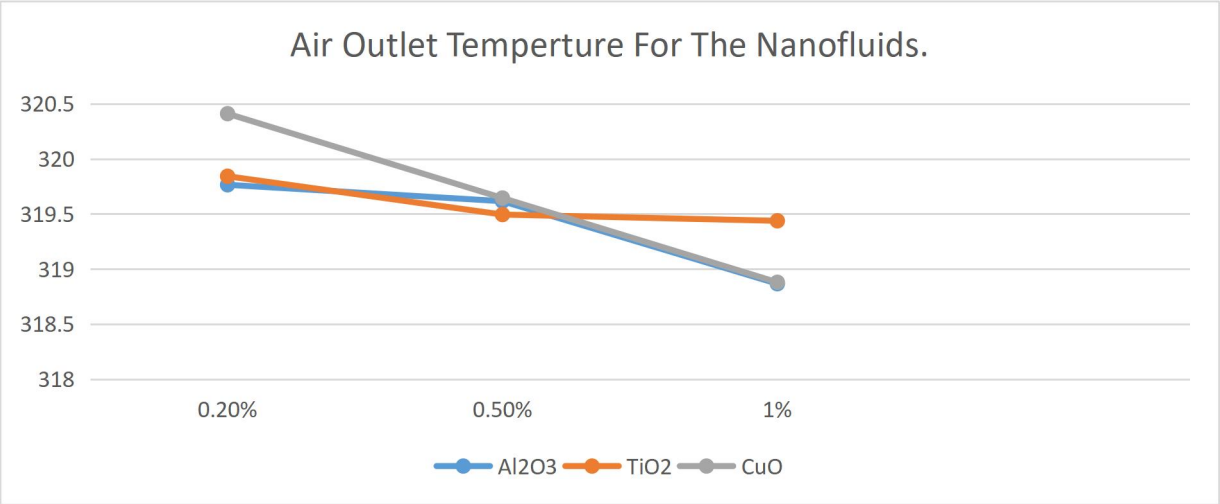

Figure 4.8: Comparative analysis of all nanofluids based on outlet temperature of the air by each nanofluid in degrees celcius

4.8 Comparison Based on Optimum Performance

The computational analysis provided quantitative insights into the performance of different nanofluid configurations in the waste heat recovery heat exchanger. Each nanofluid exhibited unique strengths, demonstrating that the suitability of a fluid depends on the intended operational priority—thermal enhancement, hydraulic efficiency, or system stability.

Table 4.8: Optimum value of quantities by nanofluids

Quantities	Value	Nanofluid
Air Outlet Temperature (°C)	318.8664	1% Al_2O_3
Heat Gained by Fluid	570.7000095	0.2% CuO
Heat Lossed by Air	658.211645	1% CuO
Pressure Drop (Pa)	157.73624	0.2% Al_2O_3
Effectiveness	0.351185	0.2% CuO
Pumping Power (W)	0.157085	0.2% Al_2O_3
Overall Heat Transfer Coefficient (W/m^2K)	5.891946	0.2% CuO

4.9.1 The 1% Al_2O_3-Water Nanofluid

The 1% Al_2O_3 nanofluid achieved the lowest outlet air temperature of 318.87 °C, indicating the highest rate of heat extraction from the hot air stream. This reflects its strong convective heat transfer ability and high capacity for energy absorption within the exchanger. The aluminium oxide nanoparticles, due to their high specific surface area and stability in aqueous suspension, improved the interaction between the fluid and the heated surface, thereby lowering the flue gas exit temperature.

However, while its cooling effectiveness was impressive, this fluid was associated with a moderate increase in pressure drop and did not record the highest overall heat transfer coefficient or system effectiveness.

4.9.2 The 1% CuO-Water Nanofluid

The 1% CuO nanofluid demonstrated excellent heat exchange consistency between the hot and cold sides, with the highest heat loss by air (658.21 W). This suggests superior energy transfer from the gas stream into the working fluid, confirming the effectiveness of CuO nanoparticles in enhancing conductive heat transfer.

However, despite this strong performance, 1% CuO exhibited relatively higher viscosity and potential for particle agglomeration, which led to elevated pumping power requirements. Consequently, while the 1% CuO formulation performs effectively under controlled simulation conditions, it may not maintain the same stability under extended or turbulent industrial operations with the added disadvantage of high pressure drop.

4.9.3 The 0.2% Al_2O_3-Water Nanofluid

The 0.2% Al_2O_3 nanofluid offered the lowest pressure drop (157.74 Pa) and the lowest pumping power (0.157 W), marking it as the most hydraulically efficient configuration. The reduced nanoparticle concentration resulted in lower viscosity, ensuring smoother flow with minimal energy loss due to frictional resistance.

Although its thermal enhancement was lower compared to CuO nanofluids, this variant provides an optimal solution where energy-saving and operational stability are critical. Therefore, 0.2% Al_2O_3 is best suited for long-duration processes or systems with limited pumping capacity.

4.9.4 The 0.2% CuO-Water Nanofluid

The 0.2% CuO nanofluid consistently outperformed other variants in several key parameters: it achieved the highest overall heat transfer coefficient (5.89 W/m^2K) and the highest effectiveness (0.351), while also recording one of the highest heat gains by fluid (570.7 W). These results confirm that CuO nanoparticles, even at lower concentrations, significantly enhance energy exchange due to their superior thermal conductivity and effective Brownian motion at moderate volume fractions.

However, despite being the best overall performer in most categories, the 0.2% CuO nanofluid cannot be considered the absolute best because it does not achieve the lowest outlet air temperature or the minimum pressure drop. This highlights a performance trade-off in that while thermally dominant, it may impose slightly higher hydraulic penalties compared to the Al_2O_3 nanofluids.

Hence, 0.2% CuO–water emerges as the most balanced configuration, providing the best compromise between high thermal efficiency, reasonable pressure drop, and manageable pumping power. Its performance balance makes it an excellent candidate for industrial waste heat recovery applications where both thermal output and operational stability are vital.

Therefore, the selection of a "best" nanofluid depends on the design objective. If the goal is maximum heat recovery efficiency, 0.2% CuO–water is the most appropriate. However, if the system prioritizes low energy consumption and stable flow, 0.2% Al_2O_3–water remains the preferred choice.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The computational fluid dynamics (CFD) investigation conducted on the waste heat recovery performance of nanofluids within a heat exchanger system has provided detailed insights into their thermal behaviour, flow characteristics, and comparative advantages over conventional fluids such as water. Using ANSYS Fluent, the study analyzed the heat transfer processes and flow fields of single nanofluids, with specific attention to parameters such as temperature distribution, outlet flue gas temperature, and pressure drop.

The simulation results revealed that the introduction of nanoparticles such as Al_2O_3, CuO, and TiO_2 into the base fluid significantly enhanced thermal conductivity of the working fluid. This improvement was attributed to the high surface area of nanoparticles, which promoted better energy exchange between the solid and fluid phases. As a result, the nanofluid demonstrated a more uniform temperature profile and improved heat absorption efficiency compared to water.

The study also confirmed the reliability of CFD as a predictive tool for optimizing thermal systems. The simulation outcomes aligned with established empirical correlations, validating the use of models such as Brinkman's viscosity, Pak and Cho's density relation, and Maxwell-Garnett's thermal conductivity and specific heat models for nanofluid property estimation.

A key finding from the steady state simulations showed that the outlet flue gas temperature decreased more when nanofluids were used, indicating more efficient recovery of waste heat. Consequently, the thermal energy that would otherwise be lost to the environment could be effectively captured and transferred, improving the heat exchanger's performance. This supports the suitability of nanofluids as next-generation working fluids for industrial heat recovery applications, particularly in oil and gas

process systems, where large temperature gradients and fluid mass flow variations are common.

In summary, each nanofluid demonstrated distinctive strengths: Al_2O_3 provided efficient cooling and flow stability, while CuO offered superior thermal conductivity and overall heat transfer performance. Among all tested fluids, 0.2% CuO–water emerged as the optimal compromise between thermal enhancement and hydraulic efficiency, making it the most suitable for waste heat recovery systems where both performance and energy economy are critical.

Overall, the findings underscore that nanofluid integration into waste heat recovery systems can lead to increased energy efficiency, reduced thermal losses, and improved sustainability. The combination of numerical modeling and parametric analysis provided a comprehensive understanding of how fluid type, nanoparticle concentration, and flow conditions interact to affect system performance. This research thus contributes to ongoing advancements in thermal management and process energy optimization in the oil and gas industry.

5.2 Recommendations

Based on the findings from the CFD simulations and nanofluid heat transfer analysis, the following recommendations are proposed to enhance waste heat recovery system design and performance in industrial applications:

1. **Adoption of Nanofluids for Enhanced Thermal Efficiency:**
   Industries, particularly in oil and gas operations, should consider replacing conventional heat transfer fluids with well-characterized nanofluids to improve heat exchanger performance. Nanofluids containing metallic oxide nanoparticles such as Al_2O_3 or CuO are especially effective in capturing and transferring waste heat from flue gases.
2. **Optimization of Nanoparticle Concentration:**
   To balance between thermal conductivity enhancement and increased viscosity,

optimal nanoparticle concentrations (typically between 0.5–3% by volume) should be maintained. Excessive particle loading may lead to higher pumping power requirements and possible particle agglomeration.

3. **Continuous Monitoring and Maintenance:**
   To ensure long-term performance, system operators should implement monitoring of nanofluid stability and flow conditions. Filtration systems and anti-agglomeration additives can help maintain uniform dispersion of nanoparticles during prolonged operation.

4. **Experimental Validation and Model Refinement:**
   Further experimental investigations should be conducted to validate the numerical results obtained in this study. Empirical data would allow refinement of the CFD models and better correlation between simulation predictions and real-world performance, especially under turbulent and multiphase conditions.

5. **Integration into Energy Recovery Systems:**
   The use of nanofluids should be extended beyond standalone heat exchangers to integrated energy recovery systems such as combined heat and power (CHP) units and flue gas recuperators to maximize overall plant energy efficiency.

6. **Economic and Environmental Assessment:**
   Future work should incorporate life-cycle cost analysis and environmental impact assessment of nanofluid deployment in industrial processes. Understanding both economic viability and ecological benefits will support large-scale adoption of nanofluid-based waste heat recovery technologies.

7. **Collaboration Between Research and Industry:**
   Continuous collaboration between CFD researchers, process engineers, and nanotechnology experts is recommended to advance modeling precision, improve nanofluid stability, and develop standardized design frameworks for thermal systems in oil and gas applications.

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