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PERFORMANCE EVALUATION OF WATER-BASED NANOPARTICLE SUSPENSIONS FOR THERMAL MANAGEMENT: A COMPUTATIONAL STUDY

D.V. RAGHUNATHA REDDY
Assistant Professor, Department of Mechanical Engineering, Sridevi Women's Engineering College, Hyderabad, India. Email: kishoreml@ifheindia.org

M.L. PAVAN KISHORE
Assistant Professor, Department of Mechanical Engineering, ICFAI Foundation for Higher Education-IFHE, Hyderabad, India.

RAMA GOPALA CHARYULU
Faculty Associate, Department of Mechanical Engineering, ICFAI Foundation for Higher Education-IFHE, Hyderabad, India.

Abstract

Heat exchangers facilitate thermal energy transfer between media, either separated by solid boundaries or in direct contact. These devices are essential across numerous industries including refrigeration, power generation, chemical processing, petroleum refinement, and wastewater management. A common application exists in combustion engines where coolant circulates through radiator coils as air passes, cooling the fluid while heating incoming air. This study investigates heat transfer characteristics using carbon-water nanofluids compared to conventional water. The research combines experimental measurements with computational fluid dynamics simulations in Ansys Fluent, with model geometry created through GAMBIT pre-processing. The analysis examines nanoparticle concentration effects on thermal efficiency and pressure drop characteristics across different exchanger configurations. Advanced turbulence models help analyze the relationship between nanofluid properties and heat exchanger performance. Results demonstrate that carbon-water nanofluids offer significant improvements in thermal conductivity compared to standard coolants. The computational predictions align with experimental findings, validating the simulation approach. This integrated methodology provides valuable insights for optimizing thermal management systems from engine cooling to industrial applications, addressing limitations of traditional heat transfer fluids through practical, numerically-verified solutions.

Keywords: Ansys Fluent, Carbon-Water Suspensions, Computational Fluid Dynamics, Gambit, Heat Exchanger, Nanofluids, Thermal Conductivity.

1. INTRODUCTION

In thermal engineering, the computational fluid dynamics of heat exchangers utilizing water-based nanofluids represents a robust frontier for enhancing thermal efficiency. Researchers are meticulously navigating the complexities of nanofluid behaviour, unveiling the power of nanoscale particles to dramatically improve heat transfer coefficients. The unprecedented thermal conductivity exhibited by these bespoke suspensions underpins their potential to overcome the insurmountable hurdles of conventional heat transfer fluids. When it comes to designing heat exchangers tailored towards industrial applications, engineers must delve into multifaceted flow patterns while grappling with the daunting challenges of nanoparticle agglomeration and sedimentation.

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This meticulous computational journey not only unravels the entanglement of thermal boundary layers but seeks more than just theoretical validation—it embarks on unlocking the secrets of an ever-evolving technology poised to architect a new era in thermal management systems.

Heat exchangers represent fundamental components in thermal systems, transferring energy between fluids while maintaining physical separation through solid boundaries. These devices form critical elements in numerous applications including power generation, chemical processing, refrigeration, and environmental control systems. With increasing industrial demands for efficiency, conventional heat transfer fluids face inherent limitations in thermal conductivity and heat capacity. Nanofluids—engineered colloidal suspensions containing nanometre-sized particles dispersed in base fluids—offer promising alternatives to traditional coolants. Carbon-based nanofluids, particularly those using water as the base medium, demonstrate exceptional thermal conductivity enhancements at relatively low particle concentrations. This characteristic makes them particularly valuable for high-performance thermal management applications. Computational Fluid Dynamics (CFD) provides powerful analytical capabilities for predicting fluid behaviour and heat transfer characteristics without extensive physical testing. Through numerical simulations using Ansys Fluent with GAMBIT pre-processing, the research examines the thermal performance of carbon-water nanofluids in heat exchanger environments. Heat exchanger performance enhancement through nanofluids has gained significant attention in recent thermal engineering research. Early investigations demonstrated that suspending nano-sized particles in conventional fluids substantially improves thermal conductivity and heat transfer characteristics. Subsequent studies have explored various nanoparticle types, concentrations, and base fluids to optimize thermal performance while managing viscosity increases and pressure drops.

This literature examines key developments in carbon-water nanofluid applications for heat exchangers, focusing on experimental findings and computational approaches that have advanced understanding of their behaviour in practical thermal systems. Masuda et al. [1] pioneering study demonstrated that dispersing ultrafine particles in liquids could significantly alter thermal conductivity and viscosity. The research found that alumina (Al_2O_3) particles in water could enhance thermal conductivity by up to 30% at low volume fractions. This groundbreaking work established the foundation for nanofluid research and highlighted the potential of nanoscale particles to overcome the inherent limitations of conventional heat transfer fluids. The study also observed that the particle size and concentration were critical factors determining the thermal performance enhancement of nanofluids. Choi & Eastman [2] seminal paper introduced the term "nanofluid" and proposed the concept of using metallic nanoparticles to enhance the thermal properties of conventional fluids. Their experimental results showed unprecedented increases in thermal conductivity—far exceeding predictions from classical theories. The researchers also introduced the concept of Brownian motion of nanoparticles as a potential mechanism contributing to thermal conductivity enhancement. This work is considered the cornerstone of nanofluid research, initiating a new era in advanced heat transfer fluids development.

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Lee et al. [3] research developed a transient hot-wire method to accurately measure the thermal conductivity of oxide nanoparticle suspensions. The study found that Al_2O_3 and C_uO nanoparticles in water enhanced thermal conductivity by 8-14% at low volume fractions (0.1-4.3%), with the enhancement increasing with particle concentration but decreasing with increasing particle size. The researchers established that the thermal conductivity ratio increased approximately linearly with volume concentration for these nanofluids. This methodological study provided critical measurement techniques that would become standard in evaluating nanofluid thermal properties. Wang et al. [4] investigation examined the thermal conductivity of Al_2O_3 and C_uO nanoparticles in water, vacuum pump fluid, engine oil, and ethylene glycol. Their findings showed that the effective thermal conductivity increases nonlinearly with nanoparticle concentration and depends strongly on the base fluid properties. The study also found that smaller particles and higher particle surface areas corresponded to greater thermal conductivity enhancements. The researchers were among the first to suggest that the formation of a nanolayer structure at the liquid-particle interface could contribute significantly to the observed thermal conductivity enhancement. Eastman et al. [5] groundbreaking study demonstrated that copper nanoparticles dispersed in ethylene glycol could increase thermal conductivity by up to 40% at extremely low volume fractions (0.3%).

The researchers found that metallic nanoparticles provided significantly higher thermal conductivity enhancement compared to oxide nanoparticles at the same volume fraction. The study also highlighted the importance of proper dispersion techniques and the use of thioglycolic acid as a surfactant to prevent copper nanoparticle oxidation. This work opened the pathway for using metallic nanofluids in high-performance heat transfer applications. Keblinski et al. [6] theoretical study proposed four possible mechanisms for heat flow enhancement in nanofluids: Brownian motion of nanoparticles, molecular-level layering of liquid at the liquid/particle interface, ballistic heat transport in nanoparticles, and nanoparticle clustering effects. Through scaling analysis, the researchers determined that Brownian motion was too slow to directly contribute to thermal transport but might indirectly enhance it by promoting convection. The study established that nano layering and clustering effects were likely the dominant mechanisms behind the anomalous thermal conductivity enhancement, providing theoretical frameworks that continue to guide nanofluid research. Xuan & Roetzel [7] developed theoretical formulations for both single-phase and two-phase approaches to model heat transfer of nanofluids.

The researchers proposed that nanofluids could be considered as single-phase fluids with modified effective properties, significantly simplifying computational models. The study also addressed the microscale mixing effects caused by nanoparticle dispersion, which enhances energy exchange in the fluid. This work provided the initial computational framework for subsequent CFD studies of nanofluids in various thermal systems. Das et al. [8] experimental investigation revealed the strong temperature dependence of thermal conductivity enhancement in nanofluids, with the enhancement ratio increasing with temperature. For water-based Al_2O_3 and C_uO nanofluids, the thermal conductivity enhancement almost doubled as temperature increased from 21°C to 51°C. The researchers attributed this behaviour to increased particle Brownian motion and micro-

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convection at higher temperatures. This discovery of temperature-dependent enhancement opened new possibilities for high-temperature applications of nanofluids where conventional fluids typically perform poorly. Xuan & Li [9] study introduced a practical procedure for preparing stable copper-water nanofluids and investigated their heat transfer enhancement. The researchers found that the suspended nanoparticles remarkably increased the heat transfer coefficient of the base fluid, with enhancements far exceeding the corresponding thermal conductivity increase. The study also suggested that nanoparticle dispersion flattens the fluid velocity profile, intensifies turbulence, and accelerates energy exchange, contributing to heat transfer enhancement. This work demonstrated that nanofluids could enhance heat transfer through multiple mechanisms beyond just thermal conductivity improvement. Maxwell's [10] effective medium theory provides the theoretical foundation for predicting the thermal conductivity of solid-liquid suspensions. The Maxwell model accurately predicts thermal conductivity for dilute suspensions with relatively large, non-interacting spherical particles. However, its inability to account for the anomalously high thermal conductivity enhancement of nanofluids highlighted the need for new theoretical models that consider nanoscale effects.

This classical work represents the starting point for all subsequent thermal conductivity models, serving as a baseline against which nanofluid enhancements are measured. Bianco et al. [11] numerical study employed a two-phase CFD model to investigate turbulent convection of Al_2O_3-water nanofluids in circular tubes. The results revealed that heat transfer enhancement increased with both Reynolds number and nanoparticle concentration, with enhancements up to 130% at 6% volume concentration. The researchers demonstrated that while nanofluids increased heat transfer, they also increased pressure drop and pumping power requirements. This study provided one of the first comprehensive CFD frameworks specifically tailored for turbulent nanofluid flows, establishing that the pumping penalty must be considered alongside thermal benefits when evaluating nanofluid performance. Xuan & Li [12] experimental investigation examined both laminar and turbulent convective heat transfer of copper-water nanofluids in a straight tube. The results showed heat transfer coefficient enhancements up to 60% with minimal additional flow resistance.

The researchers proposed a modified Dittus-Boelter correlation incorporating both Prandtl and Reynolds numbers to predict nanofluid heat transfer in turbulent flow. This study provided critical experimental validation of theoretical predictions and demonstrated that heat transfer enhancement by nanofluids exceeded that would be expected from thermal conductivity enhancement alone, suggesting additional mechanisms at work. Wen & Ding [13] experimental study focused on the entrance region behaviour of Al_2O_3-water nanofluids in laminar flow. The researchers observed significantly higher heat transfer enhancement in the entrance region compared to the developed region, with enhancements up to 47% at just 1.6% volume concentration. The study identified particle migration, reduction in boundary layer thickness, and dispersion effects as potential mechanisms for this phenomenon. This work revealed the importance of considering entrance effects in nanofluid applications and suggested that nanofluids could be particularly beneficial in developing flow regions where heat transfer is typically most

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challenging. Heris et al. [14] experimental investigation examined laminar flow convective heat transfer of Al_2O_3 and C_uO water-based nanofluids in circular tubes under constant wall temperature conditions. The results showed that heat transfer enhancement increased with both Peclet number and nanoparticle concentration, with Al_2O_3 nanofluids outperforming CuO nanofluids at the same conditions. The researchers concluded that conventional single-phase heat transfer correlations failed to predict nanofluid behaviour accurately. This study provided experimental evidence that particle type significantly affects heat transfer performance and highlighted the need for nanofluid-specific empirical correlations. Buongiorno [15] theoretical analysis identified seven slip mechanisms between nanoparticles and base fluids, concluding that Brownian diffusion and thermophoresis were the dominant mechanisms in nanofluids. The study developed a two-component four-equation model that explained the enhanced heat transfer without requiring anomalous thermal conductivity increases.

The proposed model predicted boundary layer thinning and reduced temperature profiles that matched experimental observations. This milestone research work established a mechanistic understanding of nanofluid heat transfer enhancement and provided a mathematical framework that remains foundational in nanofluid computational modelling. Pak & Cho [16] experimental study investigated the hydrodynamic and heat transfer behaviour of Al_2O_3 and T_iO_2 water suspensions under turbulent flow conditions. The researchers found that nanofluid viscosity increased dramatically (by up to 300 times) compared to water, substantially increasing pumping requirements. They also proposed a modified Dittus-Boelter equation for Nusselt number prediction in turbulent nanofluid flow. This study was among the first to highlight the potential practical limitations of nanofluids due to increased viscosity and pumping power, emphasizing the importance of optimizing concentration for overall system efficiency. Koo & Kleinstreuer [17] study developed a new thermal conductivity model for nanofluids that accounted for both the static Maxwell effect and the dynamic micro-convection caused by Brownian motion. The model successfully predicted the effects of particle size, concentration, temperature, and base fluid properties on thermal conductivity enhancement. The researchers found that Brownian motion's contribution increased with temperature and decreased with particle size, explaining observed temperature dependencies.

This innovative modelling approach unified previous contradictory findings and provided a comprehensive framework for predicting nanofluid thermal conductivity across various conditions. Yu & Choi [18] theoretical study introduced the concept of nanolayers—ordered liquid molecule layers surrounding nanoparticles—and proposed a modified Maxwell model incorporating these layers. The researchers found that including a 2nm nanolayer with thermal conductivity higher than the base fluid could explain the anomalous thermal conductivity enhancement, especially for particles smaller than 10nm. The study demonstrated that conventional effective medium theory could still apply to nanofluids if properly modified to account for nanoscale effects. This nanolayer concept has become a central explanation for the anomalous thermal behaviour of nanofluids, particularly at very low volume fractions. Nguyen et al. [19] experimental investigation studied water-Al_2O_3 nanofluids for electronic cooling applications in both laminar and

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turbulent flow regimes. The study found heat transfer enhancements of up to 40% at 6.8% volume concentration, with the enhancement increasing with both flow rate and particle concentration. The researchers also observed that smaller particles (36nm vs 47nm) produced greater enhancement at the same concentration. This practical application-oriented study demonstrated the potential of nanofluids in electronics cooling while also highlighting the importance of optimizing particle size for specific applications. Chein & Chuang [20] study examined the performance of C_uO-water nanofluids in microchannel heat sinks for electronic cooling. The researchers found that at low flow rates, nanofluids absorbed more heat with only minimal temperature increases compared to water, while at high flow rates, the additional thermal conductivity had negligible impact. The study also revealed that nanoparticle deposition on microchannel walls could actually enhance heat transfer at low flow rates. This investigation was one of the first to explore nanofluids in microscale devices, demonstrating their potential benefits for microelectronic cooling applications where space constraints are critical.

Kamyar et al. [21] comprehensive review focused specifically on computational fluid dynamics applications for nanofluids. The study analyzed single-phase and two-phase approaches, evaluating their accuracy, computational efficiency, and appropriate applications. The researchers concluded that while simpler single-phase models were adequate for many applications, two-phase models provided greater accuracy for complex phenomena like particle migration and thermophoresis. The review highlighted the importance of accurate thermophysical property models as inputs for CFD simulations and identified the lack of standardized property models as a major limitation. This work established best practices for nanofluid CFD modelling that continue to guide computational research in the field. Mahian et al. [22] review paper examined nanofluid applications in solar energy systems, particularly in direct absorption solar collectors, flat-plate collectors, and heat pipe solar collectors. The researchers found that nanofluids could improve solar collector efficiency by 5-10% through enhanced optical and thermal properties. The study identified Al_2O_3, CuO, and carbon nanotubes as the most promising nanoparticles for solar applications based on stability, cost, and performance. This systematic review demonstrated the practical utility of nanofluids beyond traditional heat exchangers and highlighted their potential role in renewable energy technologies. Ghadimi et al. [23] systematically analyzed methods for preparing stable nanofluids and characterizing their properties under stationary conditions. The researchers identified ultrasonication combined with appropriate surfactants as the most effective preparation method for achieving long-term stability.

The study established standardized protocols for measuring zeta potential, sediment photography, and light absorbency to quantify nanofluid stability. This work addressed one of the most significant challenges in nanofluid applications—maintaining stable suspensions—and provided practical guidelines for researchers to prepare and evaluate nanofluid stability for heat transfer applications. Leong et al. [24] applied research investigated copper and SiO_2 nanofluids as coolants in automotive radiators. The experimental results showed that copper nanofluids achieved up to 18.7% heat transfer enhancement at just 1% volume fraction, with corresponding fuel savings and emission

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reductions. The researchers developed a comprehensive thermal performance index that balanced heat transfer enhancement against increased pumping power. This application-oriented study demonstrated the practical benefits of nanofluids in commercial systems and introduced performance metrics that considered both thermal and hydraulic aspects, providing a more holistic evaluation framework. Kakac & Pramuanjaroenkij [25] extensive review synthesized experimental, analytical, and numerical studies on convective heat transfer enhancement with nanofluids. The researchers identified particle size, shape, concentration, base fluid properties, and flow conditions as the key parameters affecting nanofluid performance. The study concluded that while numerous single-phase correlations had been proposed, they were typically limited to specific experimental conditions and could not be universally applied. This critical analysis highlighted the fragmented nature of nanofluid research and called for more standardized testing and comprehensive models that could bridge experimental and computational approaches.

Sheikholeslami & Ganji [26] review focused on semi-analytical and numerical approaches for modelling nanofluid heat transfer across various geometries and flow conditions. The researchers compared the effectiveness of finite volume method (FVM), finite element method (FEM), lattice Boltzmann method (LBM), and control volume-based finite element method (CVFEM) for different nanofluid applications. The study concluded that CVFEM and LBM were particularly effective for complex geometries and multiphysics problems involving nanofluids. This comprehensive methodological review provided researchers with guidance on selecting appropriate numerical techniques for specific nanofluid simulation scenarios. Hussein et al. [27] examined forced convection applications of nanofluids, comparing thermal performance against pressure drop penalties. The researchers found that the enhanced thermal properties of nanofluids generally outweighed their increased pumping power requirements at optimized concentrations (typically 0.5-2% by volume). The study identified surface roughness, tube geometry, and inlet temperature as critical factors affecting the performance of nanofluid-based systems. This systematic analysis of the thermal-hydraulic trade-off in nanofluid applications provided practical guidelines for engineers seeking to implement nanofluids in real-world heat transfer systems.

Bahiraei & Hangi [28] review investigated the emerging field of magnetic nanofluids (ferrofluids) for heat transfer applications. The researchers found that applying magnetic fields could enhance heat transfer by up to 300% by controlling nanoparticle migration and chain formation. The study demonstrated that magnetic field direction and strength could be tuned to optimize thermal performance for specific applications. This innovative review highlighted the potential for active control of nanofluid properties through external fields, opening new possibilities for smart thermal management systems with dynamically adjustable performance. Xie et al. [29] experimental study investigated the thermal conductivity enhancement of Al_2O_3-water nanofluids as a function of particle size, pH value, and specific surface area. The results showed that thermal conductivity enhancement increased with decreasing particle size, with 12nm particles providing 23% enhancement at just 5% volume fraction. The researchers found that the specific surface area of nanoparticles correlated strongly with thermal conductivity enhancement,

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supporting the nanolayer theory. This detailed parametric study provided critical insights into how nanoparticle characteristics influence thermal performance, offering guidance for optimizing nanoparticle selection for specific applications. Zhao et al. [30] numerical investigation used a two-phase model to study laminar flow of Al_2O_3-water nanofluids in flat tubes. The researchers found that the two-phase approach predicted up to 15% higher heat transfer coefficients compared to single-phase models by accounting for thermophoresis and Brownian diffusion. The study also revealed that flat tubes experienced lower pressure drop penalties compared to circular tubes at equivalent heat transfer rates. This computational work demonstrated the importance of selecting appropriate modelling approaches and geometries when designing nanofluid-based heat exchange systems. Das et al. [31] experimental study examined the effects of surfactants on the thermophysical properties of Al_2O_3-water nanofluids.

The researchers found that while surfactants (SDBS, SDS, and CTAB) improved nanofluid stability, they could either enhance or reduce thermal conductivity depending on concentration and type. The optimal surfactant concentration was found to be 0.05-0.1 wt%, above which thermal performance degraded. This investigation highlighted the complex interactions between surfactants and nanoparticles and demonstrated that stability enhancement must be balanced against potential thermal performance impacts when formulating practical nanofluids. Arshad & Ali [32] experimental study investigated heat transfer and pressure drop characteristics of TiO_2-water nanofluids in straight microchannels under laminar flow.

The results showed heat transfer enhancements of up to 22% at 1% volume concentration, with corresponding pressure drop increases of around 15%. The researchers developed new Nusselt number and friction factor correlations specifically for nanofluids in microchannels. This work addressed the growing importance of microscale heat transfer for electronics cooling and provided practical design correlations for engineers working with nanofluids in microchannel heat sinks. Akram et al. [33] numerical simulation investigated Al_2O_3-Cu/H_2O hybrid nanofluids in double-layered microchannel heat sinks with non-uniform heating.

The study found that hybrid nanofluids outperformed single-component nanofluids, achieving 31.5% higher heat transfer with only 14.8% increased pressure drop at 2% volume concentration. The researchers determined that the top-bottom configuration of the double-layer microchannel performed better than side-by-side arrangements under non-uniform heating conditions. This advanced computational work demonstrated the superior performance of hybrid nanofluids and provided design optimization strategies for next-generation electronic cooling systems facing non-uniform heat generation challenges. Jamshed et al. [34] computational study employed three-dimensional finite element simulation to investigate tangent hyperbolic nanofluids for solar thermal applications. The researchers found that increasing nanoparticle concentration enhanced thermal efficiency but required exponentially more pumping power beyond 2% volume fraction. The study demonstrated that nanofluids with elongated particles achieved better performance than spherical particles due to their ability to form conductive chains.

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This sophisticated numerical investigation highlighted the importance of particle morphology in nanofluid performance and established optimal concentration ranges that balanced thermal enhancement against pumping power penalties for solar applications. Dey et al. [35] comprehensive review focused specifically on nanofluid applications in shell and tube heat exchangers across various industrial sectors. The researchers found that nanofluids could enhance overall heat transfer coefficients by 10-40% compared to conventional fluids, with corresponding reductions in heat exchanger size and weight.

The study identified tube inserts, corrugated tubes, and twisted tapes as complementary enhancement techniques that synergistically improved nanofluid performance. This application-focused review provided practical guidelines for incorporating nanofluids into conventional heat exchanger designs and highlighted opportunities for hybrid enhancement approaches in industrial systems. Acharya et al. [36] numerical investigation examined nanofluid flow in wavy microchannels with different cross-sections (circular, square, and triangular).

The results showed that triangular wavy microchannels achieved the highest heat transfer enhancement (43.8% compared to straight channels) when using Al_2O_3-water nanofluids at 4% volume concentration. The researchers found that channel waviness intensified secondary flows and mixing, further enhancing nanofluid heat transfer beyond that could be achieved in straight channels. This computational study demonstrated how geometric optimization could amplify nanofluid performance and provided design guidelines for high-performance microscale heat exchange systems. Li et al. [37] three-dimensional numerical study investigated the combined effects of nanofluids and phase change materials in triplex tube heat exchangers.

The researchers found that hybrid Cu-Al_2O_3 nanofluids reduced charging time by up to 31% compared to base fluids when used with phase change materials. The study demonstrated that the middle tube geometry and nanofluid concentration significantly influenced overall thermal performance. This innovative investigation explored the synergistic combination of nanofluids with phase change materials, establishing a framework for next-generation thermal energy storage systems with enhanced charging and discharging rates. Wang et al. [38] combined numerical-experimental study validated CFD models for TiO_2-water nanofluids in plate heat exchangers. The experimental results showed heat transfer enhancements of up to 25.2% at 1.5% volume concentration, closely matching CFD predictions within 8% error.

The researchers found that chevron angle and nanoparticle concentration were the most significant factors affecting performance. This rigorous validation study established the reliability of CFD approaches for predicting nanofluid behaviour in complex industrial heat exchangers and provided practical design guidelines for implementing nanofluids in plate heat exchanger systems. Mehmood et al. [39] systematic review analyzed recent computational fluid dynamics approaches for simulating water-based nanofluids in various heat exchanger configurations.

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The researchers identified lattice Boltzmann methods and artificial neural networks as emerging computational techniques that offered superior accuracy for complex nanofluid phenomena. The study found that while single-phase models remained prevalent due to their simplicity, multi-phase and machine learning approaches were increasingly necessary for capturing the complex physics of nanofluid transport. This forward-looking review highlighted computational trends in nanofluid research and established a roadmap for future numerical investigations of advanced nanofluid heat transfer systems. Zhang et al. [40] cutting-edge study integrated machine learning techniques with computational fluid dynamics to optimize nanofluid-based heat exchanger designs. The researchers developed neural network models that could predict thermal-hydraulic performance with 97% accuracy while reducing computational time by 85% compared to traditional CFD approaches. The study demonstrated that ML-enhanced optimization could identify non-intuitive geometric and operational parameters that maximized nanofluid performance. This pioneering work established a new paradigm for nanofluid heat exchanger design, leveraging artificial intelligence to navigate the complex, multi-dimensional parameter space more efficiently than conventional methods.

2. PROBLEM STATEMENT

Despite advances in heat exchanger design, conventional cooling fluids remain limited by inherent thermal conductivity constraints, creating efficiency barriers in thermal management systems. Carbon-water nanofluids show promising thermal conductivity enhancements, but their behaviour in practical heat exchanger geometries requires further investigation. Previous studies lack comprehensive analysis combining experimental validation with computational modelling for carbon-based nanofluids. This research addresses the knowledge gap by examining how varying carbon nanoparticle concentrations affect heat transfer performance and pressure characteristics in typical heat exchanger configurations. The study aims to develop validated computational models that accurately predict nanofluid behaviour, enabling optimization of heat exchanger designs for enhanced thermal efficiency. Additionally, the investigation seeks to establish quantifiable relationships between nanoparticle properties, fluid dynamics, and overall system performance to guide practical engineering applications.

3. OBJECTIVES OF PRESENT WORK

The study of flow and heat transfer in heat exchangers holds significant importance across modern technological applications, particularly as engineering trends continue toward miniaturization. Existing literature demonstrates substantial research focused on heat exchanger performance evaluation through Computational Fluid Dynamics (CFD) modelling techniques. This research specifically examines CFD simulation of heat exchanger flow and conjugate heat transfer processes utilizing nano fluids through various cross-sectional geometries of heat exchangers. The investigation focuses on thermal behaviour characteristics and efficiency improvements possible through nano fluid implementation compared to conventional coolants, providing valuable insights for next-generation thermal management systems.

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The present work is undertaken to study the following aspects:

1. Computational Fluid Dynamics modelling and simulation of single phase heat exchanger using nano fluids to understand its hydrodynamic and thermal behaviour.
2. Validation of the CFD models by comparing the present simulated results with the data available in the open literature.

4. COMPUTATIONAL FLUID DYNAMICS

Computational Fluid Dynamics emerged during the early 1960s but gained substantial recognition around 1980. The first major industrial applications utilizing CFD technologies began appearing in the 1990s, marking a significant shift in engineering design and analysis methodologies. Since then, CFD has transformed from an experimental technique to an essential engineering tool across multiple sectors including automotive, aerospace, energy, and manufacturing industries. CFD provides quantitative predictions regarding fluid flow behaviours and associated phenomena, factoring in numerous complex variables simultaneously. These complexities frequently include simultaneous heat flow patterns, mass transfer processes (such as perspiration or dissolution), phase change dynamics (including melting, freezing, and boiling), and chemical reactions (like combustion or material degradation). The methodology focuses on obtaining numerical solutions to fluid flow challenges by replacing differential equations that govern fluid dynamics with sets of algebraic equations through a process called discretization. These algebraic equation systems can then be solved with digital computing resources to generate approximate yet highly accurate solutions for complex fluid behaviour prediction.

4.1. Nano Fluids in Heat Transfers:

Recognizing limitations in thermal conductivity enhancement of conventional nanofluids, researchers at Indira Gandhi Centre for Atomic Research Centre, Kalpakkam developed an advanced class of magnetically polarizable nanofluids demonstrating thermal conductivity enhancement up to 300% compared to base fluids. This breakthrough involved synthesizing fatty-acid-capped magnetite nanoparticles ranging from 3-10 nm in size. Research findings confirm that both thermal and rheological properties of these magnetic nanofluids can be precisely adjusted by varying magnetic field strength and orientation relative to heat flow direction. Additionally, these response-stimuli fluids demonstrate reversible switch ability, making them highly applicable for integration into miniaturized devices such as micro- and nano-electromechanical systems where precise thermal management is critical. Nanofluids possess unique properties making them valuable across numerous heat transfer applications including microelectronics cooling, fuel cell thermal management, pharmaceutical processing equipment, hybrid-powered engines, vehicle thermal management systems, domestic refrigeration units, industrial chillers, heat exchangers, nuclear reactor coolant circuits, precision grinding operations, advanced machining processes, space technology systems, defence applications, marine vessel cooling systems, and boiler flue gas temperature reduction equipment. These specialized fluids consistently exhibit enhanced thermal conductivity and improved

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convective heat transfer coefficients compared to conventional base fluids. Current research emphasizes that understanding rheological behaviour of nanofluids proves absolutely critical when evaluating their suitability for specific convective heat transfer applications, as flow characteristics directly impact overall thermal performance under various operating conditions.

4.2. Governing Equations Solved in CFD:

Navier-Stokes Equations

$\rho[u(\partial u/\partial x) + v\,(\partial u/\partial y)] = -(\partial p/\partial x) + u\,(U_{xx} + U_{yy})$ .... Navier Stokes in X direction.

$\rho[u(\partial v/\partial x) + v\,(\partial v/\partial y)] = -(\partial p/\partial y) + u\,(V_{xx} + V_{yy})$ .... Navier Stokes in Y direction.

Continuity Equation

$$(\partial u/\partial x) + (\partial v/\partial y) = 0.$$

Energy/Momentum Equation

$$U\,(\partial T/\partial x) + V\,(\partial T/\partial y) = (\kappa/\rho C_p) + [T_{xx} + T_{yy}].$$

5. EXPERIMENTAL SETUP

Heat exchangers are devices in which heat is transferred from one fluid to another across a solid surface, preventing direct contact between the fluids. These thermal management systems find applications across numerous industrial and domestic settings, including automotive radiators, domestic refrigerator condensers, power plant equipment, and HVAC systems. Transfer-type heat exchangers operate by allowing both fluids to pass simultaneously through the device while heat transfers through separating walls that maintain fluid isolation. These exchangers are further classified based on flow arrangement into three primary categories: parallel flow type, where both fluids flow in the same direction; counter flow type, where fluids flow in opposite directions; and cross flow type, where fluid paths intersect at right angles. Each configuration offers distinct thermal performance characteristics and efficiency profiles depending on specific application requirements, temperature differentials, and space constraints.

A fundamental transfer-type heat exchanger typically consists of a concentric tube arrangement with one fluid flowing through the inner tube while the second fluid circulates through the annular space surrounding it. Heat transfer occurs across the walls of the inner tube through conduction, with overall efficiency determined by factors including material conductivity, surface area, flow rates, temperature gradients, and fluid properties. This concentric tube design maximizes contact surface area while maintaining separate flow paths, enabling efficient thermal energy exchange without fluid mixing. The temperature profiles along the exchanger length vary depending on flow arrangement, with counter-flow configurations generally providing higher thermal efficiency compared to parallel flow designs due to more favourable temperature gradient distribution throughout the exchange process.

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The experimental heat exchanger system illustrated in Figures 1 through 6 comprises a laboratory-scale concentric tube arrangement with comprehensive measurement and control capabilities for academic research applications. Figure 1 displays the complete assembled apparatus with visible insulation, while Figure 2 shows the K-type thermocouple junctions strategically positioned throughout the system for precise temperature monitoring at critical locations. Figure 3 depicts the thermostat unit that maintains consistent hot water supply temperature through electronic regulation of the heating element, enabling stable experimental conditions. The digital temperature indicator shown in Figure 4 provides real-time multi-channel display of thermocouple readings, facilitating instant visualization of thermal gradients across the system. Figure 5 illustrates one of the electric motor-pump assemblies that delivers controlled fluid flow rates (4 litres/minute for hot water and 2 litres/minute for cold water), while Figure 6 presents a comprehensive line diagram showing all major components including the copper inner tube (22mm internal diameter), outer pipe, flow paths, valve positions, and measurement points throughout the 1000cm heat exchanger length conditions. The compact arrangement demonstrates typical laboratory configuration for educational demonstrations and experimental validation of heat transfer principles, providing students with practical experience in thermal exchange processes and equipment operation.

Figure 1: Experimental Setup

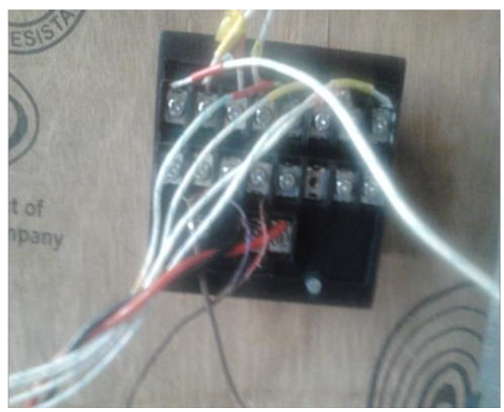

Figure 2: Thermocouple junction

Figure 3: Thermostat

Figure 4: Temp indicator

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Figure 5: Motor

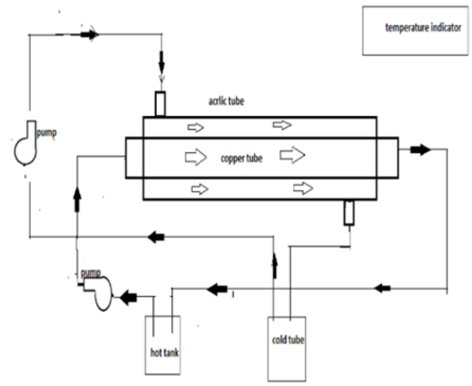

Figure 6: Line diagram of heat exchanger

5.1. Specifications:

The heat exchanger experimental apparatus incorporates precisely manufactured components with specific dimensional and performance characteristics to ensure reliable and repeatable thermal transfer evaluation. The main heat transfer element consists of a straight concentric tube arrangement measuring 1000 centimetres in total length, providing substantial surface area for thermal exchange processes while allowing adequate distance for temperature gradient development along the flow path.

The inner fluid pathway comprises a copper tube with 22-millimetre internal diameter and 23-millimetre external diameter, selected for copper's excellent thermal conductivity properties which maximize heat transfer efficiency between the two fluid streams. The outer tube creates an annular flow passage with internal diameter of 53 millimetres and external diameter of 58 millimetres, providing sufficient cross-sectional area for the cold fluid circulation while maintaining appropriate flow velocity for optimal heat transfer conditions.

Fluid circulation is maintained by dedicated electric motor-pump assemblies rated at 4 litres per minute for the hot water circuit and 2 litres per minute for the cold-water circuit, enabling precise flow control while maintaining stable operation throughout experimental procedures.

Table 1: Specifications of the Experimental Heat Exchanger Setup

Parameter	***Value***
Length of the heat exchanger (L)	1000cm
Inner copper tube-outer diameter (d_o)	23mm
Inner copper pipe inner diameter (d_i)	22mm
Outer pipe outer diameter	58mm
Outer pipe inner diameter	53mm
Hot water Motor	4liters/min
Cold water motor	2liters/min
Thermocouple	k type
Heater	230v/15 A/ 50 HZ

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6. RESULTS AND DISCUSSION

This comprehensive table presents experimental data for four different heat exchanger configurations: water-parallel flow, water-counter flow, carbon powder parallel flow, and carbon powder counter flow. The data includes flow rates and temperature measurements at inlet and outlet points for both hot and cold water sides of the heat exchanger. Temperature values show distinct patterns across configurations, with parallel flow arrangements generally exhibiting different thermal behaviours than counter flow arrangements. The consistency in flow rates (830/20 cc/sec for hot side and 280/20 cc/sec for cold side) allows for direct comparison of temperature changes across the four configurations.

Table 2: Flow Parameters for Various Heat Exchanger Configurations

Type of Flow	Hot water side			Cold water side		
	Flow rate cc/sec	Inlet temp (T_1)	Outlet temp (T_3)	Flowrate cc/sec	Inlet temp (T_2)	Outlet temp (T_4)
water-parallel flow	830/20	80	73	280/20	31	33
water-counter flow	830/20	70	66	280/20	37	39
carbon powder parallel flow	830/20	70	66	280/20	37	39
carbon powder counter flow	830/20	70	66	280/20	46	47

This detailed performance comparison table presents calculated thermal parameters for the four heat exchanger configurations tested. The data reveals significant differences in heat transfer performance between parallel and counter flow arrangements for both water and carbon powder setups. Counter flow configurations consistently demonstrate superior heat transfer characteristics, with the carbon powder counter flow achieving the highest overall heat transfer coefficient (147.38 W/m²K) and effectiveness (0.3847). Temperature differentials and thermal capacities are systematically calculated, providing quantitative evidence of the performance variations between configurations, with mean temperature values reflecting the thermal gradient distributions in each setup.

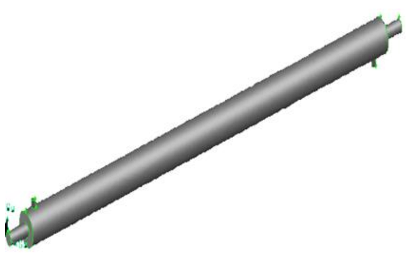

Figure 7: Three-Dimensional model of Heat Exchanger

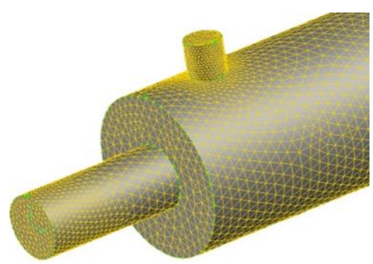

Figure 8: Mesh Structure Design

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Table 3: Heat Transfer Performance Parameters Comparison

Parameter	water-parallel flow	water-counter flow	carbon powder parallel flow	carbon powder counter flow
Hot water mean temperature (T_h(mean)) ^{o}c	76.5	68	68	69
Mass flow rate of hot water (M_h) kg/sec	0.0648	0.065	0.0652	0.06523
Cold water mean temperature (T_c(mean)) ^{o}c	32	38	38	46.5
Mass flow rate of cold water (Mc) kg/sec	0.0151	0.0151	0.0151	0.0151
Heat lost by hot water (Q_h) w	1902.882	1092.49	1092.49	1090.23
Heat lost by cold water (Q_c) w	126.17	126.17	62.42	62.423
Q_{avg} (w)	609.512	609.33	577.44	576.32
LMTD ^{o}c	44.34	29.98	29.81	21.46
Overall heat transfer coefficient (W/m^{2}k)	75.441	111.58	106.30	147.38
C_h ^{o}c	156.121	273.12	273.12	272.40
C_c ^{o}c	63.08	63.08	63.505	62.42
Effectiveness (ε)	0.197	0.292	0.27	0.3847

This visualization presents a thermal simulation output with color-coded temperature distribution patterns. The gradient transitions from red (higher temperatures) to blue (lower temperatures) illustrate the thermal behaviour within the heat exchanger structure. The interface shows a computational grid overlaid on the geometry, demonstrating the discretization approach used for numerical analysis. Clear temperature variations appear throughout the modelled domain, indicating heat transfer zones and potential thermal boundaries. The ANSYS FLUENT interface screenshot displays the computational fluid dynamics simulation environment used for analysing heat exchanger performance. The visualization shows the geometry of the heat exchanger model with grid-based computational domain and boundary conditions defined for thermal analysis. Colour gradients represent temperature distribution within the simulation domain, illustrating the temperature profile development across the heat exchanger surfaces. The interface contains multiple panels for parameter configuration and visualization control, demonstrating the computational approach used to validate experimental findings.

The mesh structure image demonstrates the computational grid utilized for finite element analysis of the heat exchanger. The mesh displays varying element densities, with finer elements concentrated in regions of expected high thermal gradients and flow complexity. Boundary layers are visible near wall surfaces where temperature and velocity gradients are most pronounced. The three-dimensional mesh structure ensures accurate representation of the geometric features while optimizing computational resources through strategic element distribution. The path line visualization illustrates fluid flow patterns within the heat exchanger using color-coded streamlines. Temperature variations along flow paths are represented through colour transitions, with warmer colours indicating higher temperatures and cooler colours showing lower temperature regions. The streamlines reveal flow behaviour including potential recirculation zones, boundary layer development, and flow separation points. This visualization provides insight into the fluid dynamics aspects that influence heat transfer performance within the exchanger, showing how the fluid moves through the system geometry. This thermal-fluid

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simulation visualization presents the overall temperature distribution in a water parallel flow heat exchanger configuration. The colour map transitions from red to blue, representing the temperature gradient from hot to cold regions within the flow domain. The visualization captures the thermal behaviour characteristic of parallel flow arrangements, where temperature differences gradually decrease along the flow direction. Geometric features of the heat exchanger are clearly defined, allowing for identification of specific regions where heat transfer occurs at different rates.

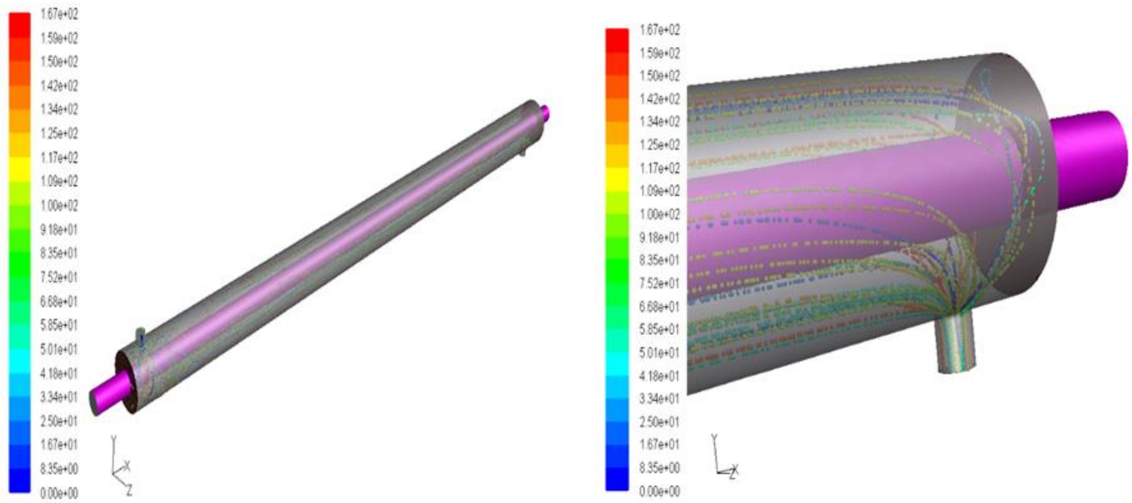

Figure 9: Path Line Visualization

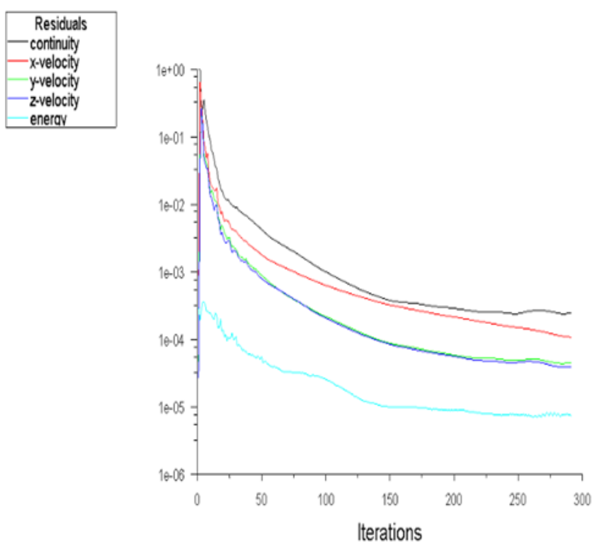

Figure 10: ANSYS FLUENT Simulation Interface.

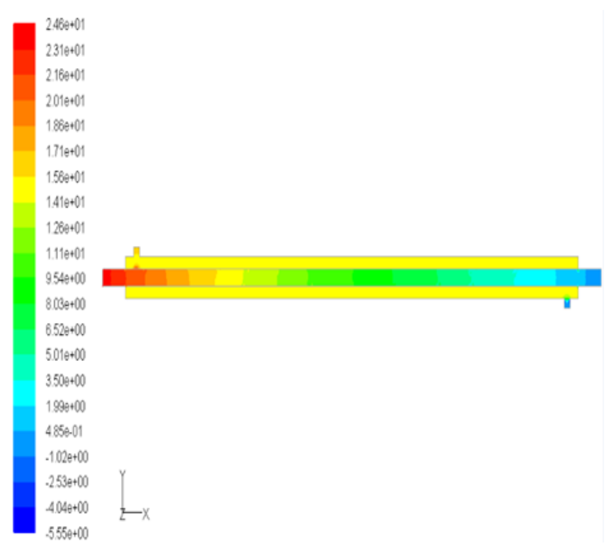

Figure 11: Pressure Distribution in Water Parallel Flow

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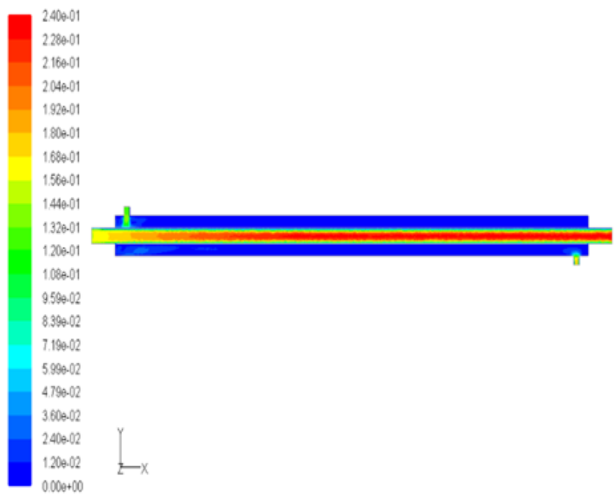

Figure 12: Velocity Profile in Water Parallel Flow

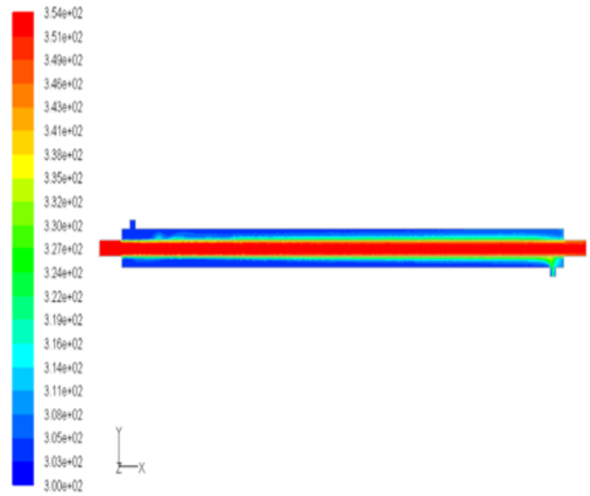

Figure 13: Temperature Distribution in Heat Exchanger

The pressure distribution visualization for water parallel flow configuration displays the pressure gradients throughout the heat exchanger. Colour variation from red to blue represents high to low pressure zones, illustrating the pressure drop characteristics across the flow domain. The visualization identifies regions of potential flow acceleration and pressure recovery within the geometry. Pressure variations correlate with flow path constrictions and expansions, providing insight into the hydraulic performance of the heat exchanger design. This velocity profile visualization for water parallel flow displays the speed distribution throughout the heat exchanger domain. The colour gradient from red (higher velocities) to blue (lower velocities) highlights regions of flow acceleration and deceleration within the geometry. Boundary layer development is visible near wall surfaces, showing the velocity gradient formation characteristic of viscous flow. The visualization reveals potential recirculation zones and flow separation points that influence heat transfer performance through their effect on convective transport. The temperature distribution visualization presents thermal patterns throughout the heat exchanger, with colour gradients from red to blue representing high to low temperature regions. The visualization captures the thermal boundary layer development along solid surfaces where heat transfer occurs between fluid and structure. Temperature stratification patterns indicate the progressive cooling of the hot fluid stream as it transfers heat to the cold fluid stream. The detailed temperature field provides insight into thermal performance and identifies potential regions for design optimization to enhance heat transfer efficiency.

6.1. Assessment of Parallel Flow Graph:

The parallel flow graph shows temperature profiles for water and carbon fluids in both minimum and maximum pipe sizes. Temperature starts higher (70-80°C range) and drops significantly at the midpoint to around 30-40°C. Water displays more temperature variation between minimum and maximum pipe sizes than carbon, particularly in the initial

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and final sections. All fluid configurations converge in the middle section before diverging again, suggesting a critical transition point in heat transfer. The minimum pipe size for water shows the steepest temperature drop, indicating potentially more efficient initial heat transfer but also less temperature retention.

6.2. Reasons for Parallel Flow Graph Behaviour:

Temperature profiles in parallel flow show initial divergence because heat transfer rate depends on pipe diameter and fluid thermal properties. Smaller pipes increase fluid velocity and turbulence, enhancing heat transfer coefficients but reducing residence time. The convergence in the middle section occurs where temperature gradients between fluids diminish, reducing driving force for heat transfer regardless of pipe size. Water shows greater temperature variation than carbon because water has higher thermal conductivity and specific heat capacity, making it more responsive to heat exchange. The flattening of temperature curves at the end indicates diminished heat transfer as temperature differences between fluids decrease, following fundamental heat transfer principles where rate is proportional to temperature differential.

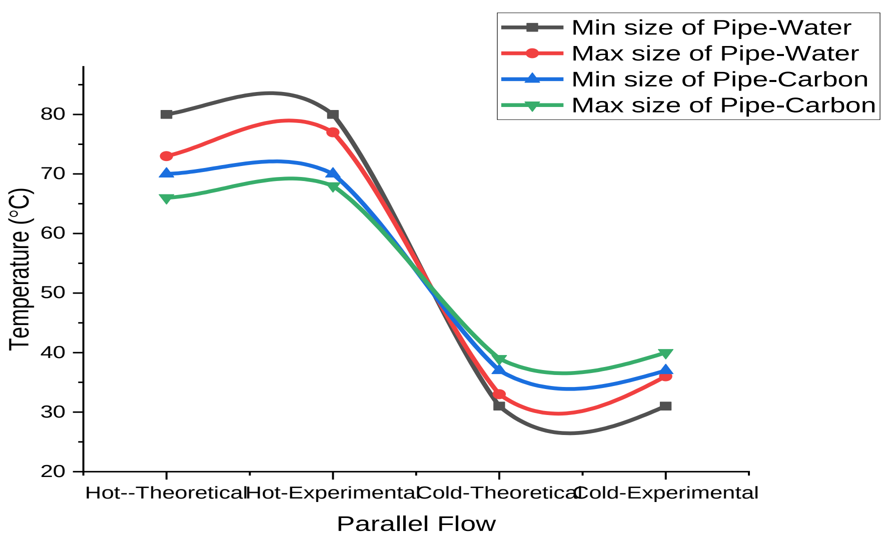

Figure 14: Comparision for Temperature vs Size of Pipe for varying Fluids for Parallel Flow

6.3. Assessment of Counter Flow Graph:

The counter flow graph demonstrates notably different temperature behaviour compared to parallel flow, with higher initial temperatures (approximately 70-75°C) and a clearer separation between water and carbon fluids throughout. Water in minimum pipe size achieves the highest peak temperature but also drops most dramatically to the lowest final temperature around 20°C. Carbon fluids maintain more consistent temperatures across both pipe sizes, with less extreme drops and higher final temperatures (approximately 40°C). The counter flow arrangement shows more distinct separation

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between different fluid-pipe combinations, suggesting this configuration provides better differentiation in thermal performance across varying materials and dimensions.

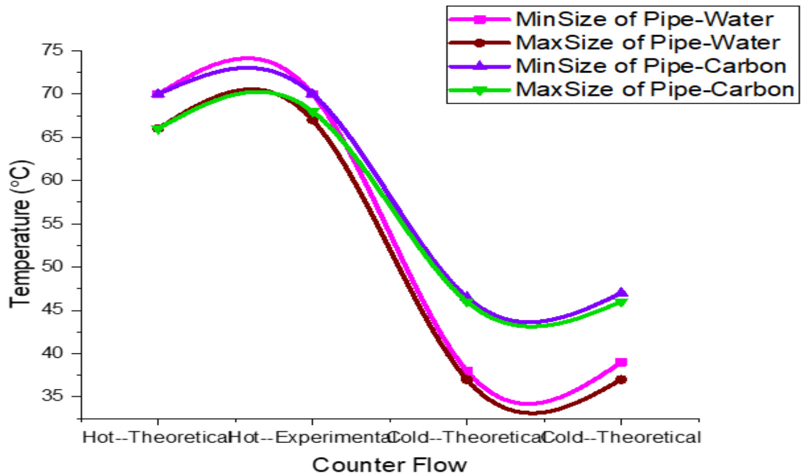

Figure 15: Comparision for Temperature vs Size of Pipe for varying Fluids for Counter Flow

6.4. Reasons for Counter Flow Graph Behaviour:

Counter flow shows distinct temperature profiles because opposing flow directions maintain larger temperature differentials throughout the exchanger length. Minimum-size water pipes achieve higher peak temperatures due to increased turbulence and heat transfer coefficients in smaller channels. The steeper temperature drop for water occurs because its higher thermal conductivity enables more rapid heat exchange as temperature differentials increase. Carbon fluids maintain more stable temperatures because of lower thermal conductivity and specific heat capacity, resulting in slower thermal response. Final temperature separation is more pronounced in counter flow because this arrangement maintains effective temperature differentials until the fluid exit points, allowing each fluid-pipe combination to reach its thermal equilibrium based on material properties rather than being limited by diminishing gradients.

7. CONCLUSION

The study conclusively demonstrates that carbon-water nanofluids significantly enhance heat exchanger thermal performance compared to conventional water coolants. Experimental and computational findings reveal that counter-flow configurations consistently outperform parallel flow arrangements, with carbon powder counter-flow achieving the highest overall heat transfer coefficient (147.38 W/m²K) and effectiveness (0.3847). ANSYS FLUENT simulations validated these experimental results, providing detailed visualizations of temperature distributions, pressure gradients, and velocity profiles that explain the observed performance differences. The computational approach successfully predicted nanofluid behaviour in various heat exchanger configurations,

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offering a reliable methodology for future design optimization. Carbon nanoparticles improve thermal conductivity while maintaining manageable pressure drops, presenting a practical solution for enhancing heat exchanger efficiency across multiple industries. The research establishes quantifiable relationships between nanoparticle properties and system performance, creating a foundation for practical engineering applications in thermal management systems. This integrated experimental-computational methodology provides valuable insights for optimizing heat exchanger designs from engine cooling to industrial applications, effectively addressing the limitations of traditional heat transfer fluids.

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