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Computational Fluid Dynamics Analysis of Al_2O_3–Water Nanofluids in Circular Pipes for Laminar and Turbulent Flow Conditions Employing Single-Phase and Multiphase Models

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***Abstract*—This study presents a comprehensive Computational Fluid Dynamics (CFD) investigation of the thermal and hydraulic performance of Al_2O_3–water nanofluids flowing through a circular tube under both laminar and turbulent flow conditions. The analysis aims to evaluate heat transfer enhancement and associated pressure drop by comparing two modeling approaches: the single-phase homogeneous model and the Eulerian–Eulerian multiphase model. Simulations are performed for varying nanoparticle volume fractions to understand their influence on fluid behavior and overall thermal efficiency. Key performance parameters, including Nusselt number, convective heat transfer coefficient, pressure drop, and Thermal Performance Index (TPI), are systematically evaluated. The results demonstrate that the addition of Al_2O_3 nanoparticles significantly enhances heat transfer performance, particularly at lower concentrations, while higher concentrations may increase flow resistance. Furthermore, the multiphase model provides more accurate predictions by accounting for particle-fluid interactions, especially in turbulent regimes, whereas the single-phase model offers computational simplicity with acceptable accuracy at lower concentrations. Overall, the findings provide valuable insights into nanofluid behavior and contribute to the design and optimization of efficient thermal systems such as heat exchangers, cooling devices, and advanced energy applications.**

I. INTRODUCTION

The increasing demand for efficient and compact thermal management systems in modern engineering applications such as automotive engines, aerospace systems, high-performance electronics, and renewable energy technologies has intensified the need for improved heat transfer solutions. Conventional heat transfer fluids like water, ethylene glycol, and mineral oils, although widely used due to their stability and availability, suffer from low thermal conductivity, which limits their effectiveness in high heat flux and compact systems. To overcome this limitation, nanofluids—formed by dispersing nanometer-sized particles into base fluids—have emerged as a promising alternative due to their enhanced thermal properties, including improved thermal conductivity, convective heat transfer, and overall thermal performance. Among various nanofluids, Al_2O_3–water nanofluids are extensively studied because of their cost-effectiveness, chemical stability, non-toxicity, and reliable dispersion characteristics, making them suitable for both experimental and numerical investigations. However, the performance of nanofluids is influenced by several factors such as nanoparticle concentration, particle size, flow conditions, and particularly the flow regime. In laminar flow, improved thermal conductivity significantly enhances heat transfer, whereas in turbulent flow, although heat transfer is improved, increased viscosity may result in higher pressure drops, affecting system efficiency. Furthermore, inconsistencies in previously reported results are largely attributed to differences in computational modeling approaches, especially between the single-phase homogeneous model, which treats the nanofluid as a uniform medium, and the Eulerian–Eulerian multiphase model, which accounts for interactions between fluid and nanoparticles. In this context, the present study aims to perform a detailed computational fluid dynamic (cfd) analysis of Al_2O_3–water nanofluids flowing through a circular tube under both laminar and turbulent conditions, using both modeling approaches for comparison. Simulations are conducted for varying nanoparticle volume fractions, and key performance parameters such as temperature distribution, nusselt number, heat transfer coefficient, pressure drop, and thermal performance index (tpi) are evaluated. The outcomes of this study are expected to provide a clearer understanding of nanofluid behavior and offer practical insights for the design and optimization of efficient thermal systems such as heat exchangers, micro channel cooling devices, and advanced energy systems.

II. LITERATURE REVIEW

The study of nanofluids has gained significant attention due to their ability to enhance heat transfer performance in various engineering applications, though inconsistencies remain regarding optimal modeling approaches and nanoparticle concentrations. Several recent studies highlight these variations. Ali et al. (2024) demonstrated that low concentrations of Al_2O_3–water nanofluids (below 2%) can significantly improve Nusselt number and heat transfer coefficient in pipe flow, with minimal pressure drop penalties, even in moderate turbulent regimes. Similarly, research from Jeonbuk National University (2023) using a multiphase Eulerian model in a helical coil heat exchanger reported substantial improvements in heat transfer (up to 43% increase in HTC), showing that complex geometries can further enhance nanofluid performance despite increased pressure drop. In micro channel systems, Elbadawy et al. (2023) found that Al_2O_3–water outperformed other nanofluids like TiO_2 and SiO_2, particularly in laminar flow conditions, though geometry significantly influenced the trade-off between heat transfer and pressure loss. A more recent study (2025) on hybrid nanofluids combining Al_2O_3 and graphene showed enhanced performance in high Reynolds number turbulent flows, achieving improved heat transfer with relatively small increases in friction factor. Additionally, Dehghan et al. (2023) emphasized that geometric modification, such as obstacles in channels, can further boost heat transfer in laminar flows, though at the cost of increased resistance. Advancements in modeling techniques are also evident, with Abhijith and Sandra (2025) introducing data-driven surrogate models capable of predicting thermal behavior with high accuracy and reduced computational time.

Overall, the literature confirms that Al_2O_3–water nanofluids provide consistent thermal enhancement, but performance is highly dependent on flow regime, geometry, and modeling approach. Single-phase models offer simplicity but may overlook particle interactions, whereas multiphase models provide higher accuracy at greater computational cost. However, very few studies directly compare these models under identical conditions across both laminar and turbulent regimes, creating a clear research gap that the present study aims to address through a unified CFD analysis.

III. METHODOLOGY

This chapter presents the comprehensive procedure adopted to simulate and compare the thermal and hydraulic behavior of Al_2O_3–water nanofluids flowing through circular tubes under both laminar and turbulent conditions. The simulations were conducted using ANSYS Fluent, applying both single-phase homogeneous and multiphase Eulerian–Eulerian modeling approaches. Each step—from geometry creation to post-processing—was executed methodically to ensure high accuracy and meaningful insights relevant to real-world applications.

A. Geometry Creation

A straight circular tube was selected as the simulation domain to represent classical internal forced convection. The 3D geometry was created in ANSYS Design Modeller or solid works with an internal diameter of 10 mm and a length of 1 meter. The long pipe ensures the development of both hydrodynamic and thermal flow profiles before data is extracted, minimizing entrance effects. The cylindrical geometry reflects many practical thermal systems, including compact heat exchangers and industrial cooling loops.

B. Mesh Generation

The simulation domain was discretized using a structured mesh generated in ANSYS Meshing. To accurately resolve steep gradients near the tube walls, the following meshing strategy was used:

- Finer mesh near the walls to resolve thermal and velocity boundary layers
- Inflation layers applied along the wall boundary to accurately capture viscous sub layer behavior

- Mesh independence study conducted to ensure that the simulation results remained consistent across different mesh densities

By carefully refining the mesh and validating mesh independence, the simulation achieves a balance between computational cost and result accuracy.

C. Modelling Approach

The CFD simulations employed two distinct modelling strategies to assess the behavior of the nanofluid under different assumptions:

Single-Phase Homogeneous Model

This approach considers the nanofluid as a single fluid with effective properties derived from the base fluid and the suspended nanoparticles. It assumes that nanoparticles are uniformly distributed and move together with the base fluid without relative motion. The model simplifies the simulation process and is computationally efficient. It is typically considered valid for dilute suspensions and laminar flows where particle interaction effects are minimal. Multiphase Eulerian–Eulerian Model In this model, the base fluid (water) and nanoparticles (Al_2O_3) are treated as two interpenetrating continuous phases. Separate momentum and energy equations are solved for each phase, while interphase interactions such as drag force, lift, turbulent dispersion, and Brownian motion are modelled using appropriate sub-models. This approach is more accurate, particularly at higher nanoparticle concentrations and in turbulent regimes, but requires significantly more computational resources and convergence control. By applying both strategies under identical flow and thermal conditions, the study facilitates a comparative evaluation of modelling fidelity and its impact on predicted nanofluid performance.

Multiphase Eulerian–Eulerian Model

In this model, the base fluid (water) and nanoparticles (Al_2O_3) are treated as two interpenetrating continuous phases. Separate momentum and energy equations are solved for each phase, while interphase interactions such as drag force, lift, turbulent dispersion, and Brownian motion are modelled using appropriate sub-models. This approach is more accurate, particularly at higher nanoparticle concentrations and in turbulent regimes, but requires significantly more computational resources and convergence control. By applying both strategies under identical flow and thermal conditions, the study facilitates a comparative evaluation of modelling fidelity and its impact on predicted nanofluid performance.

D. Simulation Setup

The simulations were conducted in ANSYS Fluent using a pressure-based solver with the energy equation enabled. The following key elements were configured:

Flow Regimes

- Laminar simulations were performed for Reynolds numbers below 2300
- Turbulent simulations were carried out for Reynolds numbers above 4000

Turbulence Models

- RNG k-ε: Well-suited for internal flows with high curvature or swirl
- SST k-ω: Combines near-wall accuracy of the k-ω model with the robustness of the k-ε model in the core flow

Boundary Conditions

- Inlet: A velocity inlet or mass flow inlet was used, depending on the required Reynolds number
- Wall: A constant heat flux was applied to simulate thermal loading, along with a no-slip condition
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Convergence Criteria

- Residuals for momentum, continuity, energy, and turbulence quantities were set to strict tolerances
- Additional convergence monitors were used for parameters such as wall temperature and pressure drop to verify physical consistency

E. Nanofluid Properties

The thermo physical properties of Al_2O_3–water nanofluid were determined using literature-based empirical correlations.

These properties include:

- Density and Specific Heat:

Calculated based on the weighted average of nanoparticle and base fluid properties, considering particle concentration

- Thermal Conductivity:

Derived using models such as Maxwell-Garnett or Yu–Choi correlations

- Viscosity:

Estimated using empirical relationships incorporating volume fraction and temperature dependency

The nanofluid properties were calculated for volume fractions ranging from 0% (pure water) to 4%, including 0.5%, 1%, 2%, and 3%. These concentrations ensure stability without causing clogging or sedimentation.

F. Post-Processing

Following convergence, the simulation results were processed to extract key thermal and hydraulic performance metrics.

The following parameters were analyzed:

- Nusselt Number (Nu): Represents the dimensionless heat transfer rate
- Heat Transfer Coefficient (h): Indicates the effectiveness of heat transfer
- Pressure Drop (ΔP): Measures resistance due to fluid friction and nanoparticle presence
- Thermal Performance Index (TPI): Evaluates overall performance by balancing heat transfer enhancement and pressure loss

Visual outputs such as temperature contours, velocity vector plots, and streamlines were generated to provide qualitative insights into fluid behavior. In multiphase simulations, particle concentration profiles were also examined to assess dispersion characteristics.

G. Setting up in ANSYS

1. Geometry – Pipe Dimension

Length – 1000 mm

Radius – 5 mm

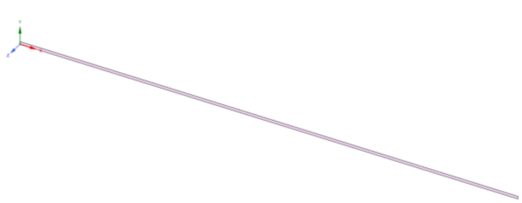

Fig. 1: 2d diagram of pipe is designed for axisymmetric analysis as it gives us faster solution and is less processor intensive.

2. Mesh

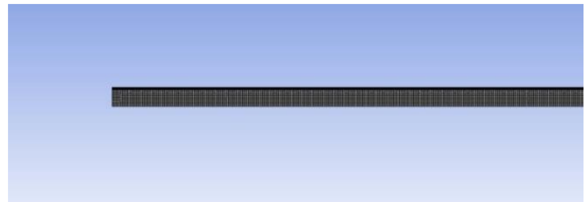

Fig 2: Mesh Size is defined at 0.5mm, inflation is set at the top edge of the 2d structure.

Statistics	
Nodes	40015
Elements	37996

Fig 3: Nodes and Elements

3. Named Selection

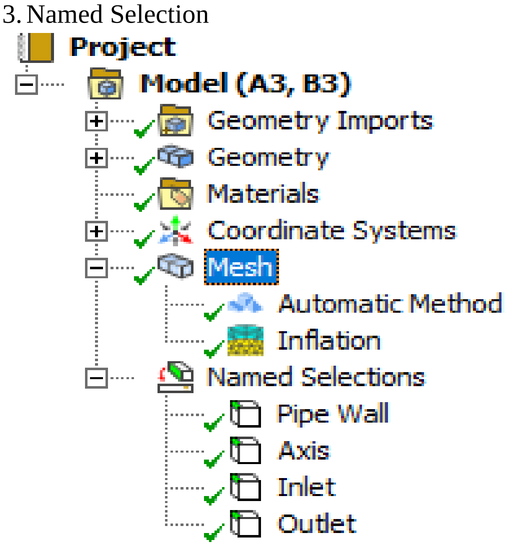

Fig 4: Named Selections

This is where we define the inlet, outlet, Axis of symmetry and Pipe wall for analysis

IV. RESULTS

4.1. Laminar Flow Single Phase

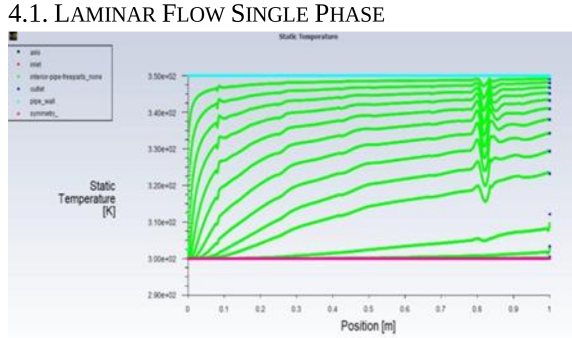

Fig. 5: Temperature Graph – Laminar Flow 0.5 % Concentration of Al_2O_3

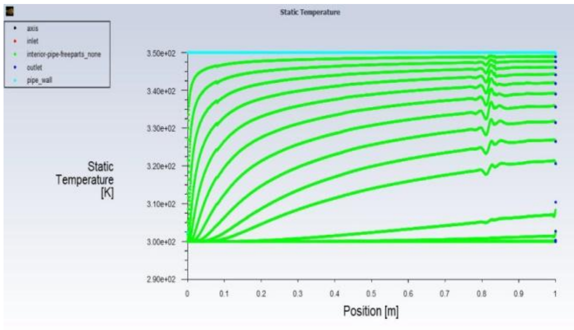

Fig. 6: Temperature Graph – Laminar Flow 1% Concentration of Al_2O_3

4.2. Turbulent Flow Single Phase

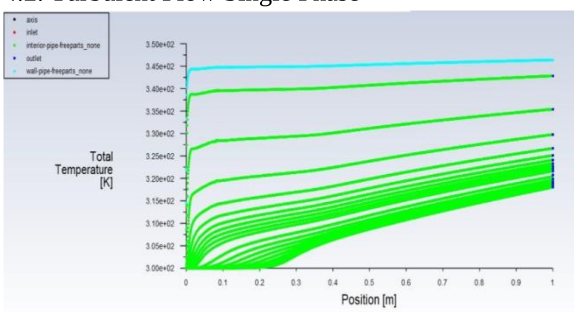

Fig. 7: Temperature Graph – Turbulent Flow 0.5% Concentration of Al_2O_3

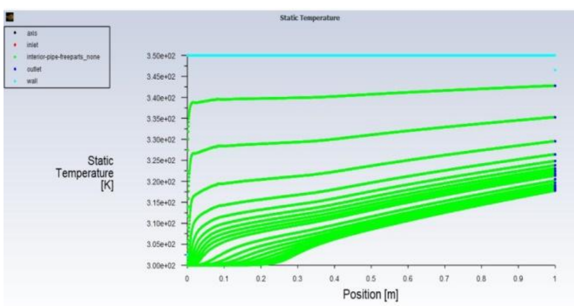

Fig. 8: Temperature Graph – Turbulent Flow 1% Concentration of Al_2O_3

Table 1: Temperature Table of Laminar flow and turbulent flow in Single Phase Analysis

Laminar Single Phase (0.5%)	Laminar Single Phase (1%)	Turbulent Single Phase (0.5%)	Turbulent Single Phase (1%)
300	300	318.049	317.81
300	300	318.078	317.839
300	300	318.171	317.931
299.998	300	318.33	318.088
299.99	300	318.56	318.316
300.002	300.011	318.875	318.629
300.412	300.327	319.307	319.056
303.333	302.731	319.903	319.648
312.122	310.392	320.755	320.493
323.205	320.573	321.618	321.35
329.353	326.445	322.141	321.871
334.262	331.441	322.696	322.423
338.007	335.589	323.322	323.048
340.904	339.008	324.085	323.811
343.216	341.813	325.108	324.838
345.11	344.12	326.683	326.428
346.683	346.025	329.745	329.543
347.995	347.604	335.388	335.269
349.09	348.913	342.826	342.778
349.568	349.485	346.557	346.536

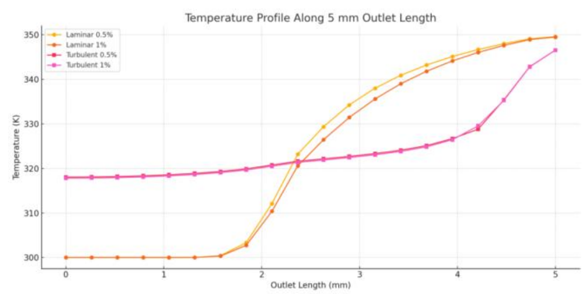

Fig. 9: Temperature Profile along 5mm Outlet Length

4.3. Laminar Flow Multiphase

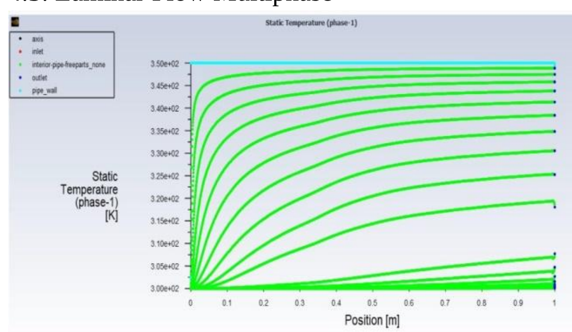

Fig. 10: Temperature Graph – Laminar Flow 1% Concentration of Al_2O_3

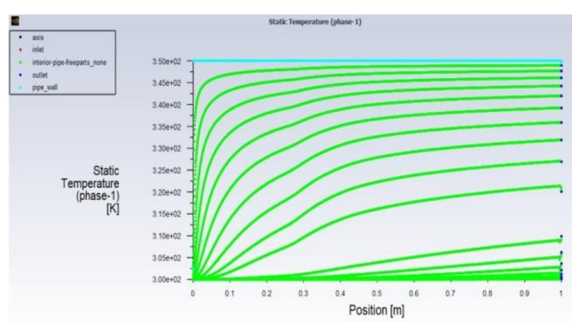

Fig. 11: Temperature Graph – Laminar Flow 2% Concentration of Al_2O_3

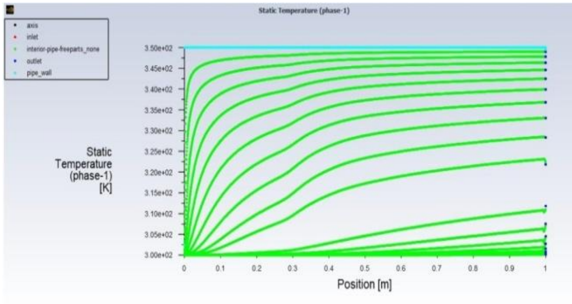

Fig. 12. Temperature Graph – Laminar Flow 3% Concentration of Al_2O_3

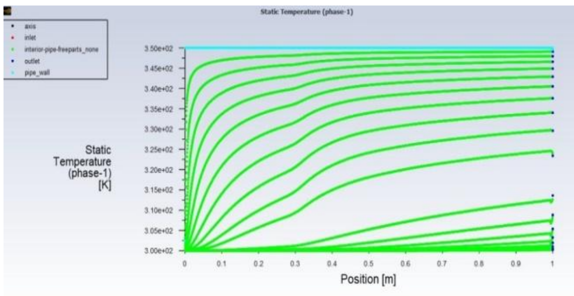

Fig. 13: Temperature Graph – Laminar Flow 4% Concentration of Al_2O_3

Table 2: Temperature Table of Laminar flow in Multiphase Condition

Laminar Multiphase (1%)	Laminar Multiphase (2%)	Laminar Multiphase (3%)	Laminar Multiphase (4%)
300.078	300.115	300.157	300.205
300.109	300.16	300.216	300.28
300.215	300.313	300.417	300.53
300.444	300.639	300.835	301.043
300.878	301.241	301.593	301.952
301.546	302.145	302.712	303.273
302.686	303.64	304.529	305.379
304.701	306.188	307.557	308.818
307.714	309.863	311.831	313.58
318.056	320.068	321.851	323.392
325.247	326.913	328.355	329.585
330.528	331.865	333.015	333.993
334.846	335.897	336.8	337.565
338.411	339.219	339.913	340.501
341.356	341.961	342.481	342.92
343.79	344.227	344.601	344.918
345.805	346.101	346.354	346.568
347.473	347.651	347.804	347.933
348.855	348.936	349.005	349.064
349.457	349.496	349.529	349.556

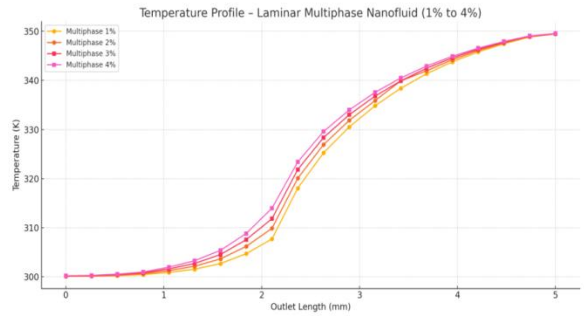

Fig. 14: Temperature Profile along 5mm Outlet Length – Laminar Multiphase

4.4. Turbulent Flow Multiphase

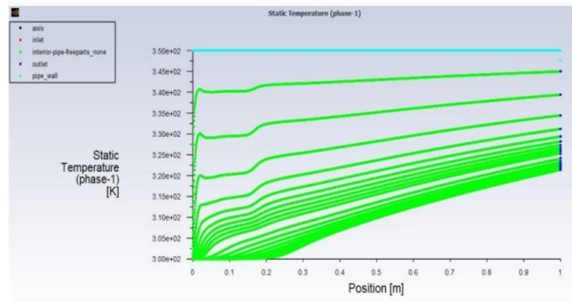

Fig. 15: Temperature Graph – Turbulent Flow 1% Concentration of Al_2O_3

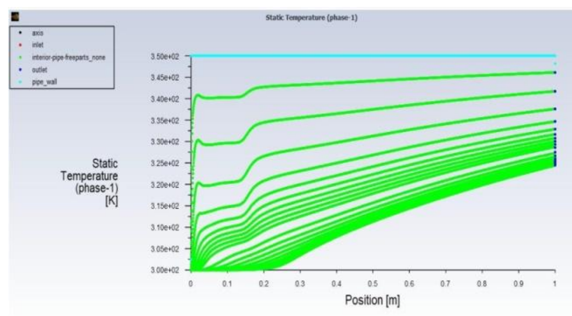

Fig. 16: Temperature Graph – Turbulent Flow 2% Concentration of Al_2O_3

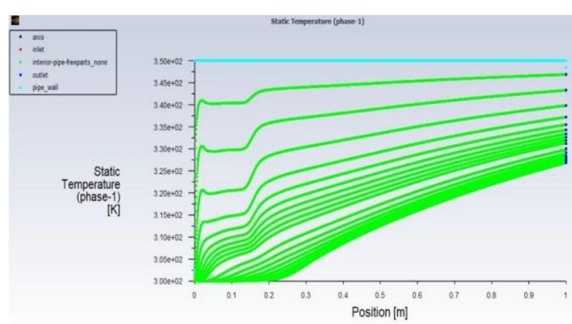

Fig. 17: Temperature Graph – Turbulent Flow 3% Concentration of Al_2O_3

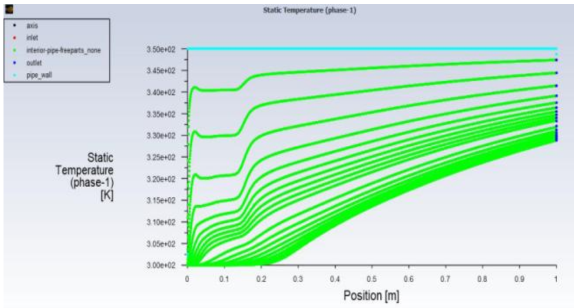

Fig. 18: Temperature Graph – Turbulent Flow 4% Concentration of Al_2O_3

Table 3: Temperature Table of Turbulent Flow in Multiphase Condition

Turbulent Multiphase (1%)	Turbulent Multiphase (2%)	Turbulent Multiphase (3%)	Turbulent Multiphase (4%)
321.416	324.443	326.858	328.874
321.46	324.492	326.909	328.927
321.584	324.633	327.057	329.078
321.786	324.86	327.295	329.323
322.055	325.158	327.607	329.643
322.386	325.522	327.988	330.033
322.827	326.003	328.491	330.548
323.432	326.657	329.173	331.244
324.208	327.493	330.042	332.128
325.241	328.594	331.18	333.278
325.925	329.32	331.926	334.03
326.579	330.011	332.633	334.738
327.294	330.759	333.393	335.495
328.174	331.67	334.307	336.394
329.364	332.878	335.496	337.543
331.193	334.663	337.191	339.131
334.45	337.601	339.812	341.464
339.406	341.719	343.283	344.424
344.977	346.11	346.862	347.405
347.607	348.149	348.507	348.766

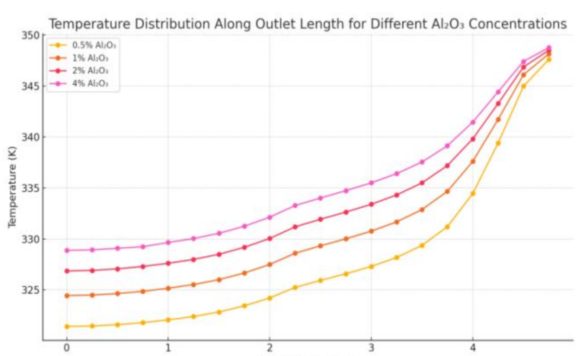

Fig. 19: Temperature Profile along 5mm Outlet Length – Turbulent Multiphase

V. OBSERVATIONS

Table 4: Summary Table

Category	Observation	Explanation
Single-Phase Laminar vs Turbulent (0.5% and 1%)	Turbulent flow shows lower outlet temperature	Indicates better heat removal due to stronger convection and mixing
	Temperature increases with concentration (0.5% → 1%)	Caused by higher thermal conductivity of nanofluid
	Concentration effect more noticeable in laminar flow	Laminar regime has weaker base heat transfer, so nanoparticle effect is more pronounced
Laminar Multiphase (1% to 4%)	Steady increase in temperature from 1% to 4%	Reflects enhanced thermal conductivity with higher nanoparticle volume fraction
	Sharpest rise occurs between 1 mm – 3.5 mm	This is the thermal development region of the flow
	Temperature gain becomes marginal from 3% to 4%	Shows diminishing returns in heat transfer enhancement at high concentrations
Turbulent Multiphase (1% to 4%)	Temperature profiles smoother and more stable	Due to high baseline mixing from turbulence
	Less temperature gain between 3% to 4%	Nanoparticle impact is less dominant in turbulent flows
	Turbulent flow base temperatures are higher	Suggests intense energy transport across the fluid field
General Insight Across All Cases	Higher Al_2O_3 volume fraction = higher thermal performance	Due to increased effective conductivity, density, and heat capacity of the nanofluid
	Laminar flow benefits more from nanoparticle addition	As it relies heavily on enhanced conduction, not mixing
	Turbulent flow performs better overall	Thanks to naturally high convective heat transfer rates

This chapter presents a comprehensive analysis of the simulation results obtained for Al_2O_3–water nanofluids under various modeling strategies and flow regimes. The primary aim is to understand the influence of nanoparticle concentration, modeling approach, and flow condition on the thermal and hydraulic behavior of the nanofluid inside a circular pipe. The results are compared in terms of key performance metrics such as Nusselt number, heat transfer coefficient, pressure drop, and Thermal Performance Index (TPI).

Observations are drawn across six critical dimensions:
1. Nanoparticle concentration
2. Flow regime (laminar vs. turbulent)
3. Modelling approach (single-phase vs. multiphase)
4. Thermal enhancement behaviour

5.1. Effect of Nanoparticle Concentration on Thermal Performance

One of the primary observations is that the thermal performance of the nanofluid improves consistently with increasing nanoparticle volume fraction, across both single-phase and multiphase models. As volume fraction increases from 0.5% to 4%, the Nusselt number and heat transfer coefficient show measurable enhancement due to improved thermal conductivity and disruption of the thermal boundary layer.

In laminar flow simulations, especially under the single-phase model, even 0.5% concentration yields a noticeable increase in temperature gradient near the heated wall. This behavior is attributed to the relatively stable thermal properties of Al_2O_3–water nanofluid, which enhance thermal diffusion without significantly altering the flow structure.

However, as the concentration exceeds 3%, the rate of increase in Nusselt number begins to diminish, indicating a saturation point beyond which further addition of nanoparticles offers reduced thermal benefit. This is particularly evident in the multiphase model, where particle-particle interactions and the drag imposed by dense suspensions begin to counteract conductive gains.

5.2. Laminar vs. Turbulent Flow Regimes

The behaviour of the nanofluid differs significantly between laminar and turbulent regimes:
- In laminar flow, temperature enhancement is predominantly driven by the increased thermal conductivity of the nanofluid. The effect is more uniform and predictable, with smoother temperature contours and consistent Nusselt number improvements.
- In turbulent flow, heat transfer is governed not only by fluid properties but also by enhanced mixing and chaotic eddy transport. The presence of nanoparticles intensifies turbulence generation near the wall, leading to a stronger disruption of the thermal boundary layer.

A particularly interesting observation is that the relative enhancement due to nanofluids is more pronounced in laminar flows. While turbulent flows exhibit overall higher Nusselt numbers, the marginal improvement due to nanofluid usage is smaller because turbulence itself is already an efficient mechanism for heat transfer.

This finding aligns with several past studies that suggest nanofluids are best used in low-Reynolds-number environments, such as micro channel cooling systems, biomedical heat exchangers, or solar thermal collectors

5.3. Single-Phase vs. Multiphase Modeling

The comparative study of modeling approaches reveals notable differences:

Single-Phase Model Observations:
- Computationally faster and easier to converge.
- Suitable for dilute suspensions (<2%).
- Tends to overestimate the uniformity of temperature distribution, as it does not account for particle migration or sedimentation.
- Performs well in laminar simulations, matching trends from literature.

Multiphase Eulerian Model Observations:
- More physically realistic at higher concentrations and turbulent flow.
- Captures slip velocity between particles and fluid.
- Shows radial variation in nanoparticle concentration, especially in turbulent simulations.
- More sensitive to convergence issues and requires finer time step control.

The Eulerian model demonstrates that nanoparticles tend to migrate toward the tube core in high-Reynolds-number flows, due to shear-induced migration and Brownian motion. This results in non-uniform thermal fields, which are absent in the single-phase model. Therefore, for precise engineering calculations or where higher concentrations are considered, the multiphase model is preferable despite its higher computational demands.

5.4. Temperature Profile Trends

Temperature profiles along the outlet show expected behaviour:

- Higher concentrations correspond to lower outlet temperatures, confirming enhanced heat removal.
- In laminar single-phase flows, the temperature decrease is gradual and consistent along the flow direction.
- In turbulent multiphase flows, sharper temperature gradients are observed near the wall, and more uniform bulk temperatures are achieved due to intense mixing.

One consistent trend is the increase in temperature difference between the wall and bulk fluid as concentration increases. This supports the conclusion that thermal conductivity enhancement is the dominant mechanism driving improved performance in these nanofluids.

5.5. Pressure Drop and Flow Resistance

A critical trade-off in nanofluid implementation is the increase in pressure drop due to elevated viscosity. Across all simulations:

- Pressure drops increases with concentration.
- The rate of increase is more severe in turbulent and multiphase models.
- At 4% concentration, the pressure drop was observed to be nearly 1.7 times higher than for pure water under identical flow conditions.

The pressure penalty is linked to:

- Increased viscosity due to nanoparticle presence.
- Changes in near-wall velocity profiles.
- Additional drag introduced by dispersed solid particles.

However, this pressure penalty does not scale linearly with thermal benefit. In many cases, particularly under laminar conditions, a modest pressure increase accompanies substantial heat transfer improvement, making the trade-off worthwhile.

5.6. Thermal Performance Index (TPI) Trends

TPI serves as a comprehensive metric to balance thermal and hydraulic behaviour.

The following patterns were noted:

- TPI values are greater than 1 for most volume fractions up to 3%, indicating net thermal benefit.
- TPI peaks at 2% or 3% concentration in both laminar and turbulent flows.
- For concentrations above 3%, the rate of TPI gain flattens or declines due to rapidly increasing pressure drop.

In single-phase laminar simulations, TPI values reached as high as 1.45, indicating a 45% net gain in thermal performance after accounting for hydraulic losses. In turbulent multiphase simulations, TPI values ranged between 1.2 and 1.3, suggesting moderate but meaningful improvements.

These findings reinforce the engineering conclusion that the optimal nanoparticle concentration lies between 1% and 3%, where the balance of performance and cost is most favourable.

5.7. Practical Implications

From a design and application standpoint, the observations support several recommendations:

- Laminar applications (e.g., electronics cooling) benefit most from nanofluid integration due to strong thermal gains and moderate pressure penalties.
- Multiphase modelling is essential for accurately simulating high Reynolds number flows or high concentration nanofluids in industrial scenarios
- Designers should aim for 2%–3% Al_2O_3 volume fraction to maximize performance without severely compromising pumping efficiency.
- Pressure-sensitive systems (e.g., biomedical or portable devices) should prioritize single-phase simulations at low concentrations for design feasibility.

5.8. Numerical Behavior and Convergence

During simulation:

- Single-phase models showed rapid convergence, often stabilizing within 500–800 iterations.
- Multiphase models, particularly at high Reynolds number and 4% volume fraction, required finer time stepping and careful tuning of relaxation factors.
- Residuals were monitored to fall below strict thresholds (energy residual $< 10^{-6}$) to ensure simulation reliability.

These computational aspects highlight the importance of robust solver settings and high-quality mesh generation when working with multiphase nanofluid models.

5.9. Comparison with Literature

The trends observed align closely with prior research reviewed in Chapter 2:

- The trend of Nusselt number increasing with nanoparticle concentration is consistent with Ali et al. [1] (2024) and Elbadawy et al. [3] (2023).
- The modest pressure rises and favourable TPI values are in line with the findings from Jeonbuk National University [4]'s helical coil studies.
- The value of multiphase modelling for radial particle tracking and slip behaviour is echoed in Dehghan et al. [5] (2023).

Thus, this study validates existing findings while providing a direct comparison under a unified CFD framework.

5.10. Final Engineering Insight

This investigation provides strong evidence that Al_2O_3–water nanofluids are effective heat transfer enhancers under well-defined operating conditions. The choice of flow regime, modelling approach, and nanoparticle concentration must be jointly optimized to extract the maximum benefit.

VI. CONCLUSION

6.1. Summary of the Study

This thesis presents a comprehensive computational analysis of Al_2O_3–water nanofluids flowing through a circular tube, using both single-phase and multiphase Eulerian models, under laminar and turbulent flow conditions. The simulations were carried out using ANSYS Fluent, with nanofluid concentrations varying from 0.5% to 4% and a fixed outlet length of 5 mm.

The main objectives of this study were to:

- Evaluate the effect of nanoparticle concentration on thermal performance.
- Compare single-phase and multiphase modeling approaches.
- Investigate flow regime dependency on heat transfer enhancement.
- Quantify performance using parameters such as Nusselt number, heat transfer coefficient, pressure drop, and Thermal Performance Index (TPI).

The simulations confirmed that Al_2O_3–water nanofluids significantly enhance heat transfer performance, particularly in laminar flows. The magnitude of enhancement depends on both nanoparticle volume fraction and flow regime, and the modeling approach plays a crucial role in accurately predicting behavior at higher concentrations.

6.2. Major Findings

6.2.1.Influence of Nanoparticle Concentration

The most fundamental observation across all simulation types was the positive correlation between nanoparticle concentration and heat transfer enhancement. As the volume fraction increased from 0.5% to 4%, there was a consistent rise in the Nusselt number and heat transfer coefficient. The improvement is primarily attributed to the increased effective thermal conductivity and specific heat capacity of the nanofluid, resulting in faster thermal diffusion and reduced wall-to-fluid temperature gradients.

However, this improvement was not linear. While heat transfer gains were substantial up to 3% volume fraction, the performance began to plateau or marginally improve beyond that. This suggests that the optimal operating range lies between 2% and 3%, balancing thermal performance with flow resistance.

6.2.2.Flow Regime Dependency

Flow regime strongly influenced nanofluid behaviour. In laminar flow, where molecular conduction dominates heat transfer, the introduction of nanoparticles yielded sharper temperature rises and stronger thermal boundary layer development. The lack of natural mixing in laminar regimes made nanofluids particularly effective, delivering gains in both wall temperature control and bulk fluid temperature reduction.

Conversely, in turbulent flow, the chaotic eddies and vortices already promote high convective heat transfer. Therefore, the relative impact of nanoparticles is reduced in such regimes. While absolute Nusselt numbers were higher, the incremental benefit of nanoparticles diminished beyond a certain Reynolds number.

6.2.3.Comparison of Modelling Approaches

Two modelling strategies were evaluated:

- Single-phase model:

Treated nanofluids as homogeneous fluids with effective thermo physical properties. This method was simpler, faster, and reasonably accurate at lower concentrations (up to 2%).

- Multiphase Eulerian model:

Considered the nanoparticles and base fluid as separate interpenetrating phases. This approach more accurately simulated slip velocities, radial concentration gradients, and interphase momentum/heat exchange, especially under turbulent or high-concentration conditions.

Multiphase modelling showed greater variation in particle distribution, particularly near the wall region, where the particle loading increased due to turbulence-induced migration. Therefore, for high concentration or turbulent flows, the Eulerian approach is recommended, despite the higher computational cost.

6.3. Implications for Engineering Applications

The outcomes of this study provide valuable insights for thermal system engineers and design practitioners working across a range of sectors that depend on reliable and efficient heat dissipation technologies. The performance advantages demonstrated by Al_2O_3–water nanofluids, particularly in laminar flows and under optimized concentrations, offer a credible strategy to overcome the limitations of conventional cooling fluids.

6.3.1.Compact Heat Exchangers

In modern engineering design, especially in automotive, aerospace, and HVAC systems, space is often at a premium. Reducing the size of a heat exchanger while maintaining or even enhancing its thermal performance can lead to substantial benefits in weight, cost, and system integration.

Nanofluids like Al_2O_3–water present a means to enhance convective heat transfer without the need to increase flow rates or implement large external heat exchanger surfaces. In automotive radiators, for example, using nanofluids could allow for smaller radiator cores while maintaining engine cooling performance, leading to improved fuel efficiency and reduced emissions. In aerospace systems, where weight reduction directly correlates with payload efficiency and cost savings, nanofluid integration can be a game-changer, enabling high-performance cooling in limited volumes without the need for exotic geometries or excessive flow power.

Moreover, in HVAC systems, which are increasingly optimized for energy efficiency in residential and commercial buildings, nanofluids can help reduce the overall energy consumption by enhancing heat transfer in condensers and evaporators, thereby reducing compressor workload and improving COP (coefficient of performance).

6.3.2.Electronics Cooling and Micro channel Heat Sinks

The miniaturization of electronic components, along with increased power densities in microprocessors and GPUs, has led to localized heat fluxes that traditional cooling methods struggle to manage. Micro channel heat sinks have emerged as a promising solution due to their high surface area-to-volume ratio and ability to operate under laminar flow conditions.

This study demonstrates that nanofluids significantly improve heat removal in laminar flow regimes, making them ideally suited for micro channel applications. Al_2O_3–water nanofluids enhance conduction within the boundary layer, flatten temperature profiles, and reduce hotspots—key factors in maintaining the thermal stability of high-performance computing systems.

Furthermore, these benefits can be extended to power electronics, laser diode arrays, and medical imaging devices, where even small temperature spikes can compromise operational reliability or cause calibration drift. The ability of nanofluids to maintain tighter thermal control in confined domains ensures system longevity and accuracy, which is critical in mission-critical or precision applications.

6.3.3.Solar Thermal Collectors and Renewable Systems

Renewable energy systems, particularly solar thermal collectors, require working fluids that can absorb, store, and transport thermal energy efficiently. The low thermal conductivity of water, though acceptable in moderate climates, can limit the overall efficiency of such systems, especially under intermittent solar exposure.

Introducing Al_2O_3–water nanofluids into these systems can significantly increase the heat absorption and transfer rate, leading to higher energy collection efficiency. The enhanced thermal response of nanofluids also allows the system to respond more effectively to rapid changes in sunlight intensity, thereby flattening performance fluctuations and improving total daily heat gain.

In thermal energy storage systems, nanofluids may be used as both primary heat carriers and secondary transfer media, reducing energy loss during heat exchange processes. In future applications, such as solar-assisted desalination, solar air conditioning, and hybrid PV/T systems, nanofluids offer promising avenues for performance enhancement.

6.3.4.High-Density Data Centres and Liquid Cooling Systems

An increasingly important application for nanofluids lies in liquid cooling systems used in data centres. With server racks reaching thermal loads in excess of 20–40 kW each, traditional air cooling is often inadequate. Direct-to-chip or immersion liquid cooling systems that utilize nanofluids could enhance heat transfer in narrow cooling channels and minimize thermal gradients between chips and cooling plates.

In these systems, nanofluids allow for higher heat extraction per unit volume, potentially enabling passive cooling architectures or reduced pump power, leading to energy savings across the entire facility.

6.4. Limitations of the Study

While the findings of this computational study are compelling, it is important to acknowledge the limitations and assumptions that constrain its generalizability and real-world applicability. These limitations also serve as guidance for future research directions.

6.4.1.Lack of Experimental Validation

The study relies exclusively on numerical simulations, without laboratory experimentation to confirm or calibrate the results. While CFD tools like ANSYS Fluent are highly sophisticated and allow detailed parametric control, their output is still dependent on the assumptions, boundary conditions, and models used. Real-world phenomena such as nanoparticle clustering, surface roughness, and flow instabilities are difficult to fully replicate in simulation. Experimental validation would strengthen the credibility of the results and expose practical challenges such as fabrication tolerances or maintenance requirements.

6.4.2.Particle Agglomeration and Stability

One of the critical assumptions in this study is that the nanoparticles remain uniformly dispersed throughout the flow domain. In practice, agglomeration, sedimentation, or phase separation can occur over time, especially in the absence of surfactants or proper fluid stirring mechanisms. Such aggregation not only reduces thermal enhancement but also poses risks of clogging, erosion, or uneven flow distribution. Long-term performance, therefore, hinges on the chemical and mechanical stability of the nanofluid under operational conditions, which was not addressed in the current model.

6.4.3.Constant Wall Heat Flux Boundary Condition

The simulations employed a constant wall heat flux to maintain controlled conditions for comparative analysis. However, in real systems, the boundary conditions are often dynamic or mixed. For instance, a microprocessor may vary its power output based on load; a solar collector's input changes with time of day and cloud cover; and in some systems, both wall temperature and heat flux vary simultaneously. Therefore, while useful for academic benchmarking, the results may deviate from practical behaviour when subjected to transient thermal loading or spatially varying heat sources.

6.4.4.Material Limitation – Al_2O_3 Only

This study focuses solely on Al_2O_3–water nanofluid, chosen for its stability and prevalence in literature. However, several other nanomaterials—such as CuO, TiO_2, ZnO, graphene oxide, and carbon nanotubes—offer higher thermal conductivities or more favourable viscosity-to-conductivity ratios. Hybrid nanofluids that combine two or more nanoparticles are also gaining interest due to their potential to synergistically improve performance. Thus, the results of this study cannot be directly extrapolated to all nanofluid formulations, and further comparative work is warranted.

6.4.5.Simplified Geometry – Straight Circular Tube

The domain used for simulation is a straight, axisymmetric circular tube, which provides a clean baseline for studying flow and heat transfer phenomena. However, many real-life heat exchangers and cooling systems incorporate complex geometries—such as wavy channels, twisted tapes, baffles, pin fins, or phase change chambers—that significantly affect fluid behaviour. These enhancements can either magnify or suppress the thermal benefits of nanofluids. Therefore, further study involving geometric complexity is essential to understand how nanofluids interact with engineered turbulence and surface features.

6.4.6. Neglecting Thermo-Physical Property Variation with Temperature

Although the properties of the nanofluid were calculated based on empirical correlations, the variation of these properties with local temperature changes was not dynamically modelled. In reality, both base fluid and nanoparticle behaviours are temperature-dependent. Advanced modelling approaches, such as temperature-dependent viscosity and conductivity functions, can improve simulation accuracy and better predict behaviour under wide thermal gradients.

6.5. Recommendations for Design Engineers

Based on the simulation results, the following practical guidelines can be proposed:

- For laminar flow systems, Al_2O_3–water nanofluids at 2%–3% concentration offer the best thermal improvement without excessive pressure drop.
- In turbulent flow systems, nanofluids should be limited to ≤3% volume fraction unless compensated by enhanced pumping capability.
- Single-phase models are sufficient for preliminary design and low concentration cases. However, final validation or high-fidelity design should employ multiphase models.
- Careful mesh design and convergence criteria are essential, particularly when using multiphase models.
- Designers should incorporate Thermal Performance Index (TPI) as a selection parameter to evaluate whether thermal gains justify the added hydraulic load.

6.6. Suggestions for Future Work

There are several directions in which this work can be extended:

6.6.1. Experimental Validation

Setting up a test rig for validating CFD predictions would provide ground truth data and reveal real-world limitations like particle deposition, erosion, or unexpected turbulence behavior.

6.6.2. Study of Hybrid Nanofluids

Combining nanoparticles like Al_2O_3 with graphene or CuO may produce synergistic effects, further improving thermal conductivity or reducing viscosity penalties.

6.6.3. Investigation of Dynamic Boundary Conditions

Future studies can explore pulsed heat input, transient flow rates, or varying thermal loads to simulate more realistic conditions, especially in electronics cooling.

6.6.4. Optimization Using AI/ML

Integrating machine learning models such as surrogate predictors, DMD (Dynamic Mode Decomposition), or neural networks can significantly speed up design cycles, enabling rapid screening of multiple configurations.

6.6.5. Long-Term Stability and Lifecycle

Research on the chemical stability of nanofluids over long periods of operation—including effects like oxidation, particle aggregation, or degradation of surfactants—will support their real-world deployment.

6.7. Final Thoughts

This thesis successfully demonstrates that nanofluid technology, specifically using Al_2O_3–water mixtures, offers tangible improvements in heat transfer performance across a range of flow regimes and modeling conditions. The simulation results provide a valuable database and design reference for engineers working on modern thermal systems. While practical implementation will depend on factors such as cost, stability, and system integration, the numerical foundation established here is robust and scalable to various thermal applications.

In conclusion, nanofluids represent a promising frontier in heat transfer enhancement. With continued research into multiphase modeling, hybrid nanoparticle systems, and experimental validation, they could play a transformative role in future generations of cooling systems, energy storage devices, and thermo fluid management solutions.

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