Influence of TiO_2 Nanofluid Concentration on Friction Factor and Reynolds Number in Laminar–Turbulent Flow through 4 mm and 6 mm Acrylic Pipes

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Abstract: This study examines the hydraulic and thermal performance of TiO_2–water nanofluids in small-diameter acrylic pipes, focusing on the influence of nanoparticle concentration and pipe geometry. Experiments were conducted using internal diameters of 4 mm and 6 mm, with TiO_2 volume concentrations of 0.3% and 0.5%. Nanofluids were prepared via a two-step method combining magnetic stirring and ultrasonic sonication to ensure uniform dispersion. Flow parameters, including Reynolds number, friction factor, and Nusselt number, were determined from measured pressure drop and flow rate data. Results show that increasing TiO_2 concentration elevates friction factor, with the effect more pronounced in smaller pipes due to intensified wall shear and higher surface-area-to-volume ratios. The 0.3% nanofluid consistently achieved higher Reynolds numbers and competitive heat transfer performance, while 0.5% concentration often reduced Nusselt number at equivalent flow conditions, likely due to viscosity-induced flow resistance and particle agglomeration. Deviations from classical laminar and turbulent correlations were observed, particularly in the transitional regime, indicating altered boundary layer behaviour. These findings highlight the need for optimised nanoparticle loading and diameter selection to balance heat transfer enhancement against hydraulic penalties in compact thermal management systems.

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Introduction

In recent years, there has been a growing emphasis on improving the efficiency of thermal and fluid systems, especially in response to the urgent need to reduce energy consumption and support sustainable industrial operations. According to the International Energy Agency, industrial and transportation sectors collectively account for over 30% of the world's total energy usage, underscoring the role of heat transfer systems in broader energy-saving efforts (World Energy Outlook 2023 – Analysis, 2023). This context has driven researchers and engineers to reevaluate existing thermal infrastructures and seek innovative means of optimization.

One such innovation that has steadily garnered attention is the application of nanotechnology to conventional heat transfer media. The idea of dispersing nanoparticles into base fluids creating what are known as nanofluids presents a compelling solution. Among the wide range of nanoparticle options, titanium dioxide (TiO_2) stands out due to its favorable thermal conductivity, chemical stability, and cost-efficiency (Duangthongsuk & Wongwises, 2010). Studies have shown that TiO_2–water nanofluids demonstrate notable improvements in thermal transfer capabilities without compromising system compatibility or environmental considerations (Madhu et al., 2023; Suthahar et al., 2023).

However, there is a trade-off that accompanies these thermal advantages. Increasing nanoparticle concentration generally results in higher viscosity, which in turn escalates pressure drop within the system. This dynamic presents a design dilemma: although higher concentrations of TiO_2 nanofluids can significantly elevate the Nusselt number and overall thermal efficiency, the concurrent increase in hydraulic resistance may offset these benefits. For instance, Madhu et al. (2023) and Suthahar et al. (2023) observed a 77% improvement in heat transfer performance in small-diameter helical pipes when increasing TiO_2 concentration from 0.1% to 0.5%, but this came at the cost of pronounced pressure escalation (Madhu et al., 2023; Suthahar et al., 2023). A similar trend was observed in automotive cooling systems by Elibol et al. (2023), who noted a modest 2.7% rise in pressure despite a substantial gain in heat transfer performance (Elibol et al., 2023).

From a theoretical standpoint, pressure loss and flow resistance in pipe systems are often described using models such as the Darcy–Weisbach and Hagen–Poiseuille equations. These models rely on flow parameters including Reynolds number and friction factor to predict behavior in laminar and turbulent regimes. While they provide foundational insight, their applicability to nanofluids is limited due to the complex interactions introduced by suspended nanoparticles. Factors such as altered viscosity, changes in density, and micro-scale turbulence require experimental validation to supplement or revise existing theoretical models (Zong & Yue, 2022).

Deviations in thermophysical behavior become increasingly critical when observed in micro-scale fluidic systems. Within domains such as electronic cooling or microreactor design, even slight variations in channel diameter or nanoparticle loading can significantly impact heat transfer and flow stability. A recent investigation by Heris et al. (2025) reported that incorporating a minimal TiO_2 nanoparticle concentration (0.01% by volume) into a water-based coolant yielded a notable 21–27% increase in the Nusselt number within mini-channel exchangers. However, this thermal performance gain was accompanied by a rise in pressure loss, particularly within the transitional flow regime. The study illustrates that microchannel applications are highly sensitive to subtle changes in fluid formulation and geometry, often leading to disproportionate shifts in thermal–hydraulic behavior (Heris et al., 2025)

Owing to its chemical stability, affordability, and minimal ecological impact, titanium dioxide (TiO_2) continues to be a material of growing interest in nanofluid-based thermal management. Recent advancements have seen its integration across various thermal platforms such as HVAC systems, solar thermal absorbers, microelectronic cooling circuits, and automotive engine loops (Vithanage et al., 2025). The consistent thermal enhancement observed, particularly at low particle concentrations, reinforces the need for expanded research into its use in conditions where heat transfer improvements can be achieved without inducing excessive hydraulic penalties.

Nanofluids are widely characterized as suspensions of ultrafine particles typically within the 1–100 nm range dispersed in a conventional base fluid. Their thermal transport properties deviate significantly from those of single-phase fluids, primarily due to nanoparticle-induced enhancements in thermal conductivity. Classical models such as Maxwell's equation and the Hamilton–Crosser correlation remain foundational, identifying particle shape and volume fraction as dominant factors in conductivity augmentation. More recent studies, including khan et al. (2025) and Djentoe et al. (2025), have expanded this understanding by demonstrating that boundary layer thickness, particle–wall interactions, and micro-convection effects substantially alter both flow and temperature fields, especially in systems where surface-to-volume ratios are high(Djentoe et al., 2025; Khan et al., 2025).

High nanoparticle concentrations can reduce nanofluid efficiency. Sundaram (2025) found that exceeding 0.5 vol% TiO_2 significantly increases viscosity, raising pumping power demands and limiting flow performance, highlighting the need for precise concentration control in thermal system applications (Sundaram, 2025). For this reason, current explorations often focus on lower concentrations—specifically 0.3% and 0.5%—to strike a balance between heat transfer gains and manageable pressure drops (Bose et al., 2023).

This focus has become increasingly significant in micro-scale thermal management, particularly in biomedical devices, miniaturized electronics, and university laboratory systems. Studies such as Abuwatfa et al. (2025) emphasize that even small adjustments in channel diameter (e.g., 4–6 mm) can substantially influence pressure gradients and pumping effort due to the sensitivity of microfluidic systems. In educational setups, the use of transparent acrylic pipes offers a practical benefit: enabling both low-cost implementation and direct flow visualization, which enhances student engagement and experimental accuracy (Abuwatfa et al., 2025).

Moreover, recent investigations show that nanofluids used in laminar and transitional flow regimes tend to experience a progressive pressure loss with increasing nanoparticle concentration. This trend was reaffirmed by Zhang et al. (2025) in TiO_2–water systems across a range of Reynolds numbers, where even mild loading induced noticeable pressure variation. While CFD techniques offer predictive support, empirical validation remains indispensable—particularly for narrow-diameter acrylic channels where minor design changes lead to large hydraulic shifts. Studies by Singh & Verma (2024) and Memon et al. (2024) have recommended integrating computational models with hands-on prototyping to better capture real-world behavior (Memon et al., 2024; Singh & Verma, 2024; Zhang et al., 2025).

Although nanofluids have shown considerable promise in enhancing thermal systems, a critical research gap remains regarding their behavior in low-cost, small-diameter acrylic piping, especially at low TiO_2 concentrations. The majority of existing studies focus on metal-based or industrial-scale systems, overlooking academic-scale infrastructures that prioritize affordability, transparency, and accessibility. This omission is particularly relevant in developing countries such as Indonesia, where water continues to be the default base fluid and acrylic microchannels are widely used in university laboratories for visualization and cost-efficiency (Abuwatfa et al., 2025; Memon et al., 2024). Despite their prevalence, these systems are rarely included in flow modeling validations, resulting in limited applicability of conventional empirical correlations under such conditions.

Thus, this study seeks to investigate how TiO_2 nanofluid concentrations of 0.3% and 0.5% influence flow behavior in acrylic pipes with internal diameters of 4 mm and 6 mm. The research examines actual versus theoretical friction factor values, calculates Reynolds numbers across varying flow rates, and measures pressure drop through controlled experimentation. By comparing empirical data with classical models like Darcy–Weisbach and Colebrook–White, the study aims to generate insights that are both practically useful for small-scale thermal systems and theoretically meaningful for the continued refinement of flow modeling in nanofluid applications.

Table 1 Physical Properties of Water (Basic Fluid) and TiO_2 Nanoparticles

Physical Property	Water (H_2O)	TiO_2 Nanoparticles	Reference Source
Density (ρ)	997 kg/m³	~3900–4250 kg/m³	(Djentoe et al., 2025)
Specific Heat Capacity (cp)	4182 J/kg·K	686 J/kg·K	(Murshed et al., 2005)
Thermal Conductivity (k)	0.606 W/m·K	~8.4–11.8 W/m·K	(Heris et al., 2025)
Dynamic Viscosity (μ)	0.89×10^{-3} Pa·s		(Vithanage et al., 2025)

Research Method

This study investigates the effect of TiO_2 nanofluid concentration variations (0.3% and 0.5% by volume) on pressure drop characteristics in a closed-loop pipe system with small internal diameters. The working fluid consists of a water-based nanofluid prepared via the two-step method. TiO_2 nanoparticles with a size distribution of 20–50 nm were dispersed into deionized water using a combination of magnetic stirring and ultrasonic sonication for 60 minutes to ensure uniform suspension and long-term stability. This preparation method has been validated in previous studies for its effectiveness in producing homogeneous nanofluid solutions (Memon et al., 2024; Sundaram, 2025).

All experiments were conducted at ambient temperature (27 ± 2 °C) and repeated for each test condition to improve data reliability. The experimental setup was constructed in a closed-loop configuration, driven by a centrifugal pump (Lakoni 8P130A) with a maximum flow capacity of 35 L/min, rated power of 125 W, operating speed of 2850 rpm, a maximum head of 25 m, and a suction lift of 9 m. The fluid was circulated from a reservoir tank through a 1-inch PVC conduit pipe (680 mm length, 625 mm height) and directed into two parallel test sections with different diameters: 4 mm and 6 mm, each 200 cm in length. Flow rate adjustments were made using a ball valve with opening angles ranging from 10° to 90°.

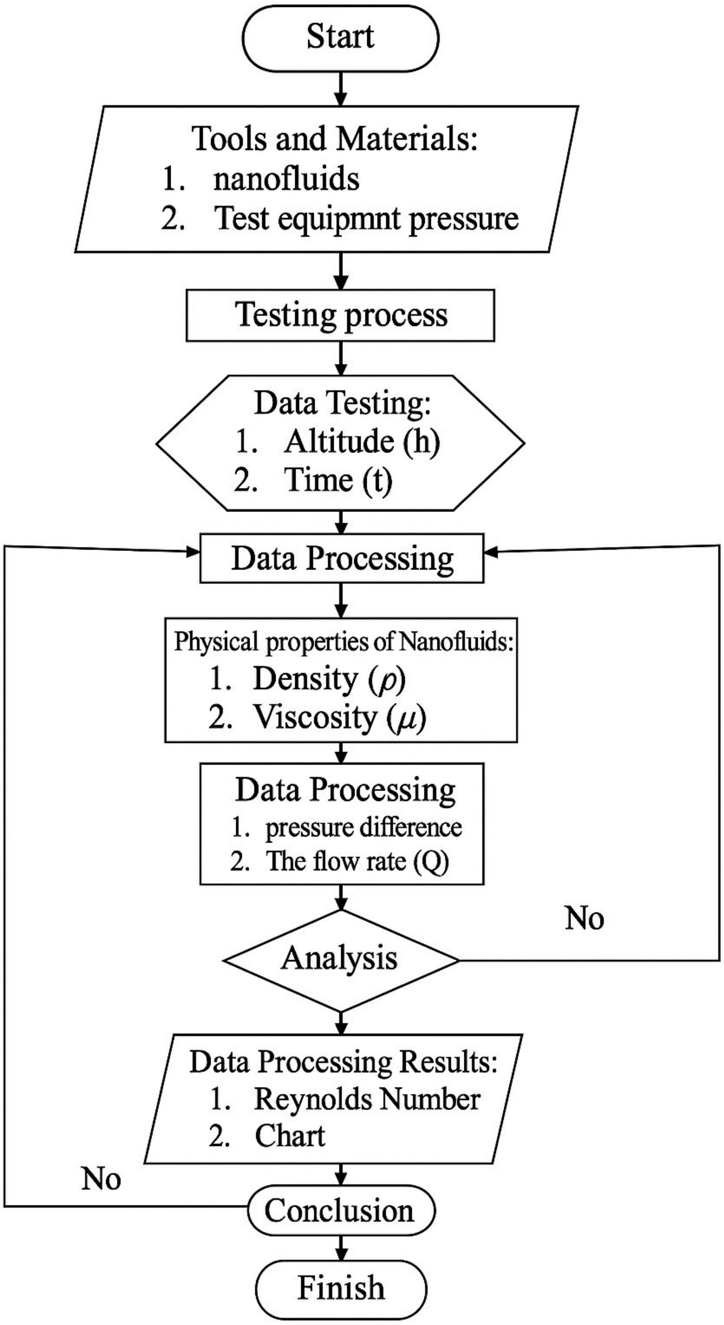

Figure 1 Flowchart

The experimental procedure followed in this study is summarised in the flowchart presented in Figure 1. The process begins with the preparation of tools and materials, including TiO_2–water nanofluids at predetermined concentrations and the pressure test equipment. The testing process involves circulating the nanofluid through the experimental setup under controlled conditions. During data testing, three primary variables are measured: altitude (h), representing the vertical height or head difference; time (t) required for a fixed volume to pass; and the actual volume (v) of fluid collected. The recorded data are processed to determine the physical properties of the nanofluid, namely density (ρ) and viscosity (μ). Subsequently, the pressure difference (ΔP) and volumetric flow rate (Q) are computed from the measured parameters. The data are then subjected to an initial analysis to verify completeness and consistency; if anomalies are found, the process returns to the data processing stage for recalculation. Validated results include the calculation of the Reynolds number and the generation of performance charts for further interpretation. The procedure concludes with the synthesis of results into a comprehensive conclusion, marking the completion of the experimental cycle.

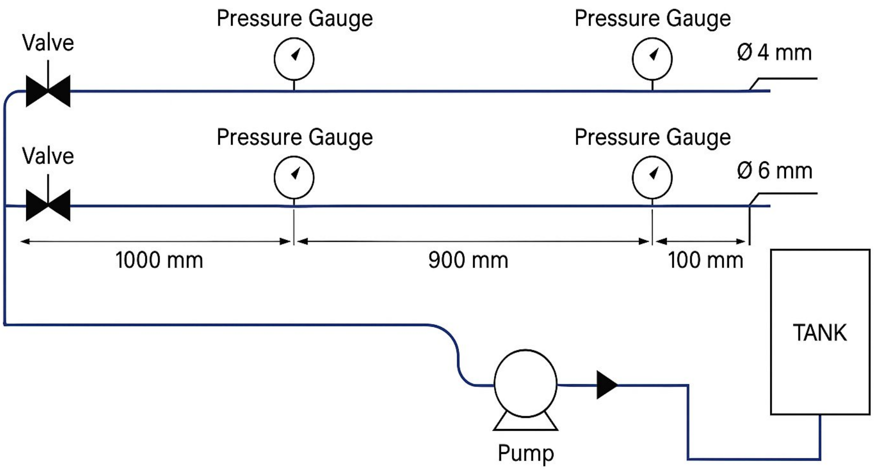

Figure 2 Experimental Set Up

Each test pipe was equipped with two pressure taps (2 mm diameter, 20 mm length), positioned 1000 mm downstream from the inlet. The spacing between the taps was precisely 900 mm. These taps were connected to digital pressure gauges (range: 0–10 bar, accuracy ±0.25%) to measure pressure differences directly. A stopwatch was used in parallel to measure the time interval for fluid passage, allowing for accurate calculation of actual flow rate (Q) based on time and volume.

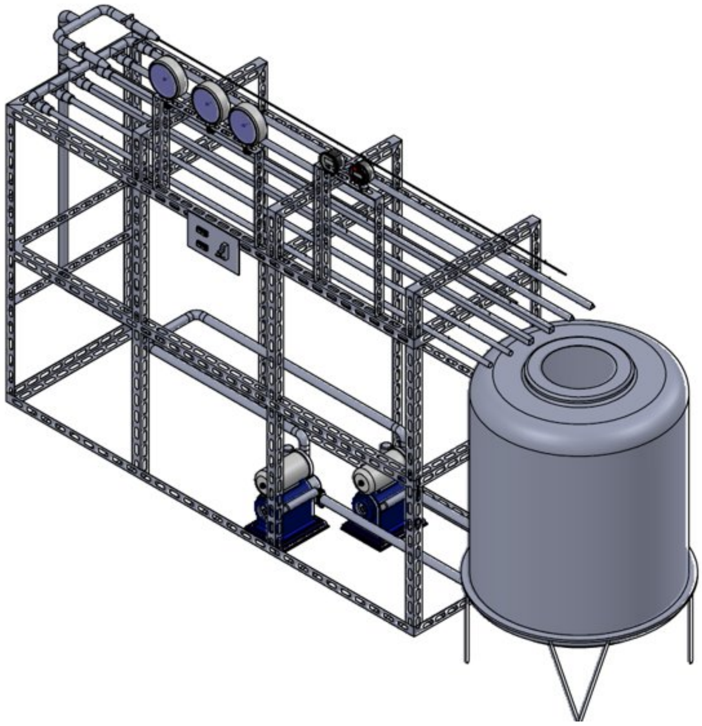

Figure 3 Scheme Test Equipment

Flow parameters, including Reynolds number, friction factor, and Nusselt number, were calculated using the Darcy–Weisbach and Colebrook–White equations. The pressure drop (ΔP) across the test section was derived from pressure gauge readings. Experimental results were validated by comparison with empirical correlations and prior literature (Memon et al., 2024; Subramanian et al., 2020; Sundaram, 2025).

All instruments were calibrated prior to use to ensure measurement accuracy. The testing procedure began with filling the reservoir tank with the designated nanofluid concentration. Upon system activation, pressure readings were taken from both taps while recording the flow time. These data points were then used to compute pressure loss, flow rate, Reynolds number, and friction factor. Each condition defined by a specific combination of TiO_2 concentration and pipe diameter was tested repeatedly to ensure consistency and reproducibility.

The overall system design and testing methodology were adapted from established experimental frameworks in nanofluid research and were intended to characterize laminar, transitional, and turbulent flow regimes in small-diameter circular pipes.

Result and Discussion

The experimental outcomes are synthesized in Figures 4–8, which present the effects of TiO_2 nanofluid concentration and pipe diameter on hydraulic and thermal behaviour. The discussion focuses on the underlying mechanisms driving the observed trends, their alignment with the study objectives, and their implications for microscale thermal–hydraulic applications.

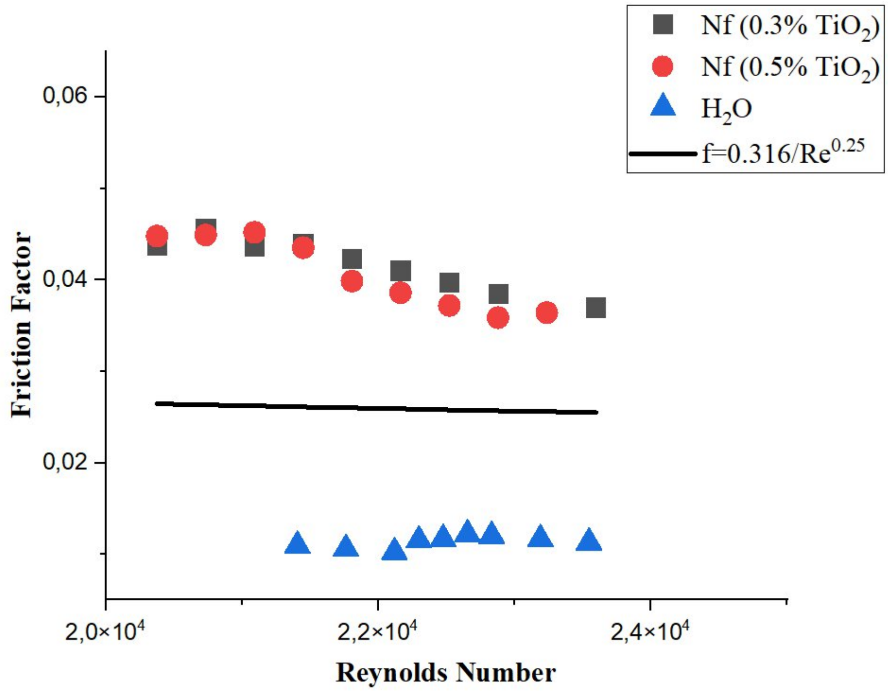

Figure 4 Graph of Actual Friction and Blasius Friction to Reynolds Number on 4 mm Pipe Diameter

Figure 4 shows that TiO_2–water nanofluids consistently yield higher friction factors than pure water across the investigated Reynolds number range. This increase is more pronounced at 0.5 vol% concentration due to elevated viscosity, which intensifies wall shear stresses. The decreasing trend in friction factor with increasing Reynolds number aligns with turbulent flow theory, where inertial forces progressively dominate over viscous resistance. However, measured values remain above the Blasius prediction, indicating additional energy losses from nanoparticle–wall interactions, micro-scale turbulence modulation, and possible particle clustering.

However, TiO_2 nanofluids consistently exhibit higher friction factors compared to the base fluid (water). This increase is primarily attributed to the higher viscosity induced by the nanoparticles, which generates greater internal shear forces. These findings are consistent with previous reports (Sundaram, 2025), which confirmed that nanoparticle addition at certain concentrations increases flow resistance despite enhancing heat transfer performance.

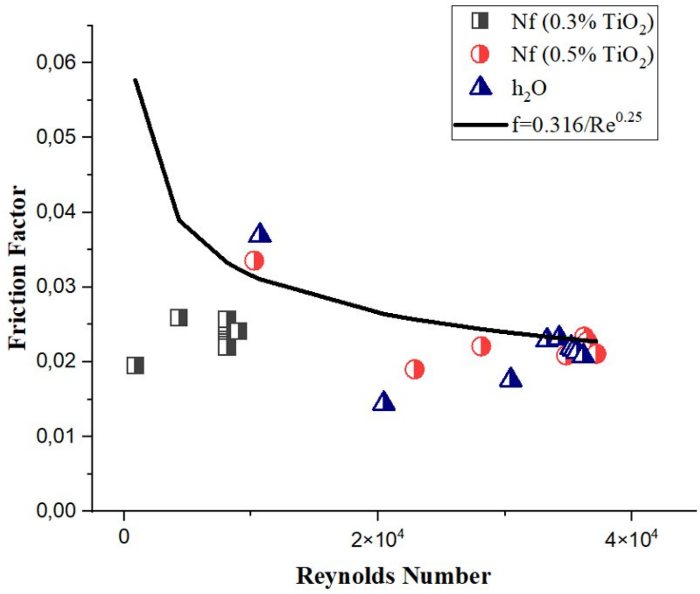

Figure 5 Graph of Actual Friction and Blasius Friction to Reynolds Number on 6 mm Pipe Diameter

As shown in Figure 5, 6 mm pipes exhibit similar qualitative behaviour, with friction factors for nanofluids exceeding the Blasius curve—especially at low to mid Reynolds numbers. The wider channel reduces the wall-effect amplification seen in the 4 mm case, but higher particle loading still increases viscous drag. The data confirm that while diameter moderates hydraulic penalties, concentration remains the primary factor controlling viscous resistance.

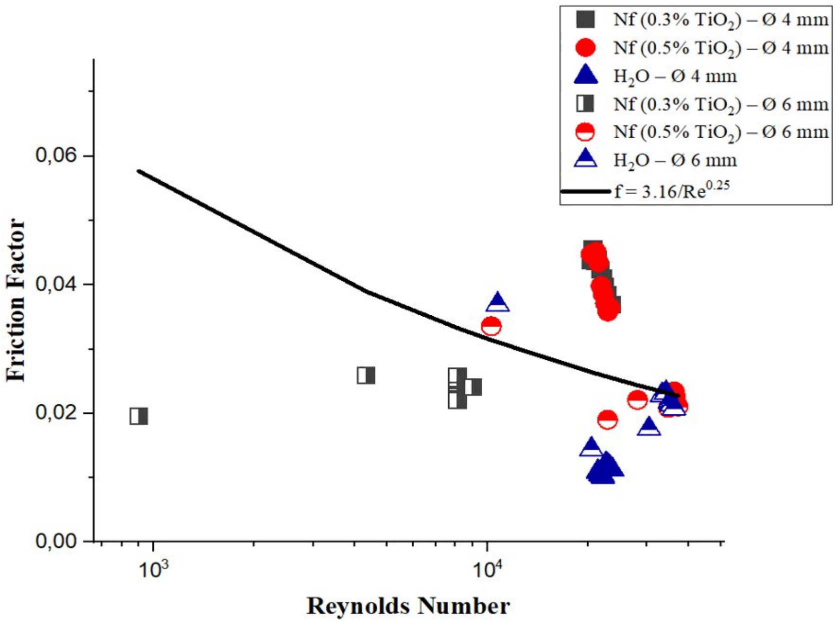

Figure 6 Comparison of Actual Friction Factor Based on Reynolds Number for 0.3% and 0.5% TiO_2 Nanofluids and Water in 4 mm and 6 mm Pipes

Figure 6 directly compares friction factors between 4 mm and 6 mm pipes. Smaller diameters intensify wall effects and surface-area-to-volume ratio, amplifying viscous losses in nanoparticle-laden flows. The 0.5 vol% TiO_2 nanofluid consistently produces higher friction factors than 0.3 vol% at equivalent Reynolds numbers, reaffirming the hypothesis that viscosity increase from particle loading outweighs the benefits of enhanced thermal conductivity in narrow channels.

Comparison between experimental friction factor values and the Blasius correlation for 4 mm (Figure 5) and 6 mm (Figure 6) pipes reveals that all experimental data points lie below the theoretical predictions. The deviation becomes more pronounced at higher TiO_2 concentrations (0.5%), indicating changes in flow behavior caused by nanoparticle effects, such as wall slip phenomena, non-uniform particle distribution, and potential micro-turbulence generation. This outcome highlights the limitations of classical correlations such as Darcy–Weisbach or Blasius when applied to nanofluids in microscale channels.

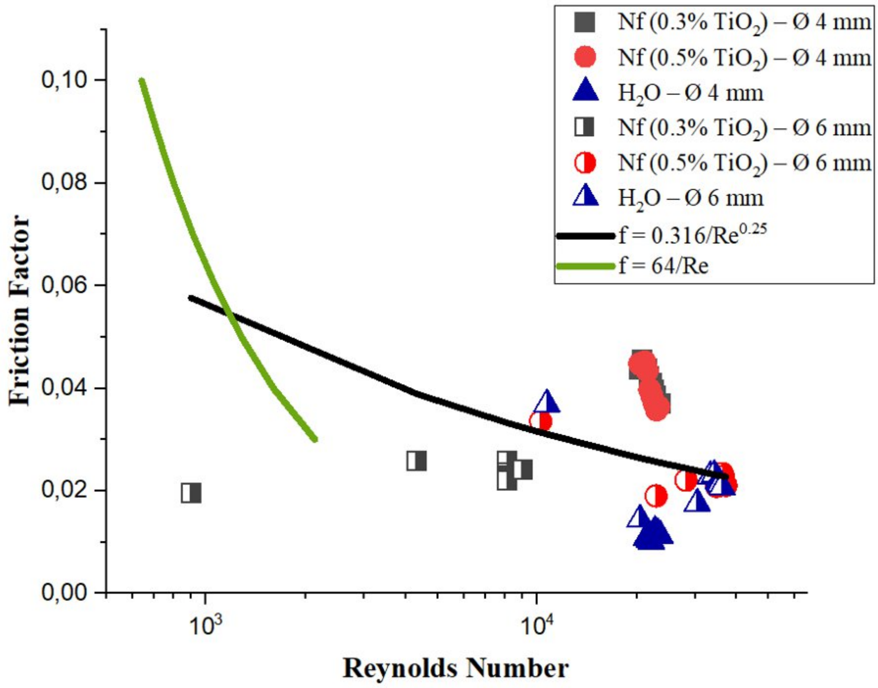

Figure 7 Comparison of Friction Factor vs Reynolds Number for 0.3% and 0.5% TiO_2 Nanofluids and Water in 4 mm and 6 mm Pipes with Laminar and Turbulent Flow Correlations

Figure 7 compares the friction factor of TiO_2–water nanofluids (0.3% and 0.5% vol.) and pure water in 4 mm and 6 mm pipes against both laminar (f = 64/Re) and turbulent (Blasius, f = 0.316/Re^0.25) correlations. The results show that most experimental points fall in the transitional-to-turbulent regime, lying closer to the turbulent prediction line. Nanofluids, particularly at 0.5% concentration, exhibit higher friction factors than pure water for similar Reynolds numbers, reflecting the combined influence of increased viscosity and particle-induced micro-scale turbulence. In contrast, pure water data tend to align more closely with the Blasius curve, indicating lower hydraulic resistance in the absence of nanoparticles.

In Figure 7, all nanofluid data—especially the 0.5% TiO_2 in the 4 mm pipe—show large deviations from the laminar (f = 64/Re) and turbulent (f = 3.16/Re^0.25) correlation curves. The most evident deviations occur in the transitional regime, indicating a shift in flow characteristics due to increased viscosity and particle–wall interactions. This observation aligns with Zhang et al. (2025), who reported that nanoparticle addition accelerates flow regime transition and increases hydraulic resistance in narrow channels (Zhang et al., 2025).

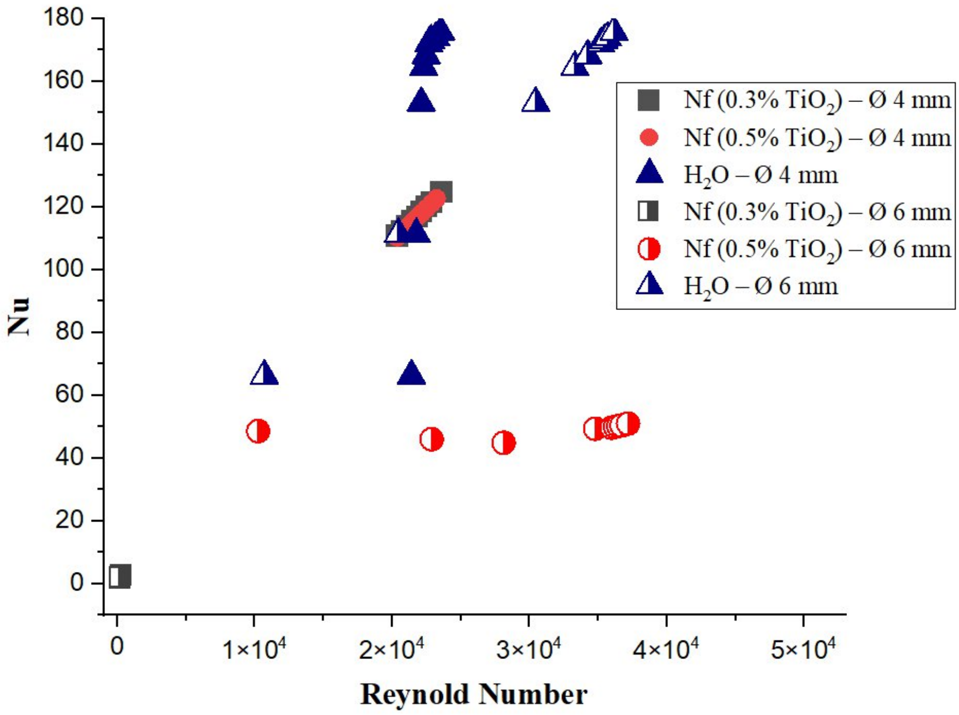

Figure 8 Variation of Nusselt Number with Reynolds Number for TiO_2–Water Nanofluids and Base Fluid

Figure 8 illustrates that the Nusselt number (Nu) increases with Reynolds number (Re) across all test conditions, confirming that higher flow velocities enhance convective heat transfer. For the 4 mm pipe, the base fluid (H_2O) exhibits the highest Nu values, followed by the 0.3% TiO_2 nanofluid, while the 0.5% concentration generally yields lower Nu at comparable Re. This behaviour suggests that although nanoparticle addition improves thermal conductivity, excessive concentration can increase viscosity and promote particle agglomeration, thereby reducing flow mixing and weakening heat transfer performance. In the 6 mm pipe, a similar trend is observed, with the gap between fluids becoming more pronounced at higher Re. These findings are consistent with recent studies by Madhu et al. (2023) and Suthahar et al. (2023), which highlighted that nanofluid thermal performance depends on balancing thermophysical property enhancement with hydraulic penalties (Madhu et al., 2023; Suthahar et al., 2023). Additionally, Modi et al. (2022) reported that significant Nu improvements occur at moderate nanoparticle concentrations, whereas excessive loading can diminish micro-turbulence near the wall. Therefore, optimising nanoparticle concentration and pipe diameter is critical to maximising thermal benefits while avoiding substantial increases in pumping power (Modi & Rathod, 2022).

Figure 8 demonstrates a consistent increase in the Nusselt number (*Nu*) for TiO_2 nanofluids compared to the base fluid in both 4 mm and 6 mm pipes. The enhancement becomes more pronounced at higher Reynolds numbers, with the 6 mm pipe showing a steeper rise in *Nu* due to stronger inertial forces that promote micro-mixing. This behavior supports the findings of Madhu et al. (2023) and Suthahar et al. (2023), who reported that nanofluid heat transfer enhancement is strongly Reynolds-dependent (Madhu et al., 2023; Suthahar et al., 2023).

Conclusions

This experimental study examined the hydraulic and thermal behaviour of TiO_2–water nanofluids at 0.3% and 0.5% volume concentrations in 4 mm and 6 mm diameter pipes, using pure water as the baseline. The results showed that higher nanoparticle concentrations consistently increased the friction factor, with greater deviations from the Blasius correlation at lower Reynolds numbers, and that smaller pipes produced higher friction factors than larger ones at the same Reynolds number due to stronger wall effects. Nusselt numbers increased with Reynolds number for all cases, but the 0.5% nanofluid often yielded lower values than the 0.3% nanofluid and pure water, suggesting that excessive particle loading can raise viscosity and promote agglomeration, limiting turbulence and heat transfer efficiency. These findings confirm that optimal performance is achieved at moderate nanoparticle concentrations, where thermal conductivity enhancement outweighs hydraulic penalties, underscoring the importance of balancing concentration, pipe diameter, and flow regime to maximise heat transfer gains while minimising pumping power requirements in practical applications.

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