



## ENHANCING NANOFUID HEAT TRANSFER PERFORMANCE IN INDUSTRIAL COOLING APPLICATIONS

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### Abstract

Industrial cooling systems play an important role in maintaining equipment performance, process stability, and energy efficiency in manufacturing and thermal engineering applications. However, conventional cooling fluids such as water and ethylene glycol often show limited heat transfer capability under high thermal loads. This paper examines the improvement of heat transfer efficiency in industrial cooling systems through the use of nanofluids. Nanofluids are engineered suspensions of nanoparticles in base fluids, designed to enhance thermal conductivity, convective heat transfer, and overall cooling performance. The study focuses on key parameters such as nanoparticle concentration, flow rate, inlet temperature, pressure drop, and heat transfer coefficient. The findings indicate that nanofluid-based cooling systems provide higher thermal conductivity and improved heat removal compared with traditional fluids. An increase in nanoparticle concentration improves heat transfer performance, although excessive concentration may increase viscosity and pumping power requirements. The results also show that optimized flow conditions can improve system efficiency while maintaining operational stability. Overall, the paper highlights that nanofluids can be an effective solution for industrial cooling applications where high thermal performance and energy savings are required. The study concludes that careful selection of nanoparticle type, concentration, and operating conditions is essential for achieving maximum heat transfer efficiency without causing excessive pressure losses or system maintenance challenges.

**Keywords:** Nanofluids; Heat Transfer Efficiency; Industrial Cooling Systems; Thermal Conductivity; Energy Optimization

## INTRODUCTION

In the microelectronics industry and in heavy manufacturing, the needs for thermally managing devices are pushing conventional media that have low thermal conductivity to the extreme. This is a very critical constraint for high power electronic components, systems for telecommunication and advanced manufacturing systems etc. where conventional cooling methods are not able to maintain the operating temperature within the desired reliability limits (Indira et al., 2022; Rodríguez-Laguna et al., 2018). In the modern microprocessors and industrial machinery, where the power density has increased significantly, thermal control of the system becomes of great importance to minimize the chances of the component failure and optimize the life of the whole system (Indira et al., 2022). Traditional single-phase cooling technologies, limited by the low thermal conductivity of water and ethylene glycol, are operating near their physical limits, and two-phase cooling technologies, which are promising but have many flow instability, pressure drop and lack of reliable design correlations issues (Garimella et al., 2012; Indira et al., 2022; Rodríguez-Laguna et al., 2018). The preparation and utilization of nanofluids, which are the mixtures of conventional base fluids with engineered solid (metallic, non-metallic or carbon based) nanoparticles, has been well recognized as a game-changer in the field of heat transfer improvement (Ali & Salam, 2020; Bigdeli et al., 2016). The use of thermophysical properties of the nanostructures (Bigdeli et al., 2016; Indira et al., 2022; Rodríguez-Laguna et al., 2018) also provides a substantial improvement in the thermal conductivity of nanofluids, even at a very low volume fraction of nanoparticles. The enhanced properties have been shown to be due to complex,

synergistic mechanisms, such as the Brownian motion of the suspended nanoparticles, the Kapitza thermal resistance of the interfaces and the formation of the thermal percolation pathways as a result of the clustering and/or chain-like aggregation of the nanoparticles (Bigdeli et al., 2016; Gao et al., 2009; Prasher et al., 2005). Despite the great potential for revolutionizing thermal management, there are major technical and economic issues with the implementation of nanofluids in industrial thermal processes. Some of the major challenges include long term stability of nanocolloids, tendency to agglomerate and sediment over time, erosion of working components of the cooling system, and the increase in manufacturing/preparation costs for use of special nanomaterials (Alami et al., 2023; Goyal, 2023; Kaggwa & Carson, 2019; Karthikeyan et al., 2021). Moreover, there are no literature standardized characterization methods and universal heat transfer correlations for the transition between controlled laboratory and large-scale in-field implementation in industry (Goyal, 2023; Kaggwa & Carson, 2019). Hence, the present work aims to systematically study the thermophysical properties and heat transfer coefficient of the selected formulations of nanofluid under realistic conditions of cooling applications in industry. The purpose of this study is to quantify the effect of the critical heat transfer performance parameters as a function of concentration, size and composition of the nanoparticles through a detailed analytical and experimental investigation. The objective of the study is to elucidate these relationships and provide valuable data for improving the techniques of heat management in high performance cooling systems. Overall, the aim of this work is to contribute in the future issues of the industry with the use of the

obtained sustainable, efficient and reliable thermal management solutions using nanofluid based systems, which is a challenging field in science between the fundamental studies and future applications. This work will help remove the existing challenges in experimental data and build stronger predictive models that will allow for the realization of cost-effective, large-scale production of stable nanoparticle suspensions (Bigdeli et al., 2016; Waware et al., 2024). This research focuses on the development of cost-effective stabilization technologies and the co-optimization of thermal and flow properties addressed to overcome the technical challenges to commercialization to large scales. Hence, the longitudinal stability test is of great importance in the field of ensuring the operational reliability and long duration of service life of these fluids in highly demanding industrial environments, and this aspect has been investigated (Alami et al., 2023), (Ali et al., 2018).

## METHODOLOGY

In this part, experimental procedures that have been followed step by step to study the thermophysical properties and convective heat transfer of engineered nanofluids are explained. Nanofluids are prepared by dispersing nanoparticles (e.g., Al<sub>2</sub>O<sub>3</sub> or CuO) in the base fluid using high-shear mixing and ultrasonication to ensure long-term colloidal stability of the dispersion of nanoparticles in the base fluid (Okonkwo et al., 2020; Safir et al., 2024). These suspensions have been characterized by dynamic light scattering in terms of particle size distribution and surface charge and repulsive force acting between the particles, which are important for preventing sedimentation and maintaining colloidal integrity of the suspension (Alami et al., 2023; Bigdeli et al., 2016). After characterization, the experimental setup for the convective heat transfer evaluation is a closed loop forced convection setup,

mainly consisting of a constant heat flux test section, a magnetic circulation pump, and an integrated thermal management unit to control the temperature precisely (Alkasmoul et al., 2018; Osman et al., 2019). The test section consists of high thermal conductivity stainless steel tube with a carefully designed heat insulation to minimize the heat loss from the ambient and thus enhance the accuracy of the experiment (Cieśliński & Kozak, 2018; Estellé et al., 2016; Qi et al., 2019).

Data collection involves the use of pressure transducers, turbine flow meters and J-type thermocouples, which are used to measure the differential pressure, the mass flow rate (mfr) and the inlet and outlet fluid temperatures, respectively (Alkasmoul et al., 2018; Qi et al., 2019). Meanwhile, the temperature of the axial wall is measured by the sensors having the Pt100 resistance along the test section and the convective heat transfer coefficient (Cieśliński & Kozak, 2018) is determined. All experimental data is collected with a centralized data acquisition system that will log data in real-time and verify steady state (Estellé et al., 2016; Osman et al., 2019). Using these measurements, the performance evaluation metrics, including heat transfer enhancement (Nusselt number) and the pressure drop penalty (friction factor), are computed that are crucial to scale up the technology to industry. (Bigdeli et al., 2016; Okonkwo et al., 2020). Finally, a detailed uncertainty analysis is performed to determine the validity of experimental results, and to ensure that the results can be reproduced, taking into consideration the uncertainties related to fluid properties and instrumental error (Alami et al., 2023; Kamiński & Ossowski, 2025). Moreover, strict and optimized ultrasonic processes are used during the stabilization process, typically 120 W for a specific period, to achieve uniform particle distribution during the cooling process (Mertaslan & Keklikçioğlu, 2024; Sivakumar et al., 2015).

Stability of the particles in the suspension is monitored by electrophoresis methods and absorbance features of the particles by UV-vis spectrophotometry is used to detect the possibility of clustering. Electrophoresis techniques are employed to monitor the electrophoretic mobility of the particles to confirm the stability of the suspension and UV-vis spectrophotometry is used to characterize the absorbance features of the particles to look for the possibility of the particles clustering. The system can be operated for a minimum of 90 minutes before the data is logged to attain experimental equilibrium, since the steady temperatures, pressures and flow rates were observed (Adogbeji & Tartibu, 2025). To prevent any contamination, the test loop is flushed with deionized water between the tests and measurements are repeated several times systematically ensuring consistency (Demirkır & Ertürk, 2020, 2021). To validate the experimental setup, the measured Nusselt number and friction factor for pure deionized water flow with the experimental setup are compared with other known Nusselt number equations namely Dittus-Boelter and Blasius equations presented by Meyer et al., 2012 and Rafiq et al., 2021 respectively. This strict validation step will measure and correct for the systematic error of the configuration of the sensor: the thermocouple mounts' thermal resistance, which will then enable the evaluation of the performance of the nanofluid (Ali & Alsaffawi, 2023; Hilo et al., 2020). In addition, thermophysical parameters, such as dynamic viscosity, density and specific heat capacity are measured within the operating temperature range to differentiate the contribution of each of these parameters to the convective heat transfer coefficient (Gómez-Villarejo et al., 2019).

## RESULTS

The results of the experiments indicate that the convective heat transfer is improved in all the concentrations of the base coolant by adding the nanoparticles. The overall heat-transfer coefficient is observed to rise with the increase of volume fraction of base fluid as shown in figure 1 and is expressed as 3280 W/m<sup>2</sup>K at 0.20 vol.%, which is 33.9% increase in the overall heat-transfer coefficient. The results indicated that it can be attributed primarily to the nanofluid formulation and not a controlled operating difference, as the operating difference of the main parameters were very small as indicated in Table 1. As indicated in Figure 2, the results in Table 2 show that the thermal conductivity was improved from 0.602 W/mK to 0.704 W/mK. The improvement in this conductivity was very important for the transfer of the heated wall energy to the flowing coolant. The results of the flow and the pressure indicated that there was a slight blow in the head for the tremendous gain in heat transfer. The pressure decreased as the concentration increased as shown in figure 3 from 18.4kPa to 27.3kPa. Table 3 also illustrates that this rise in pressure was also due to a rise in viscosity and a slight drop of Reynolds number. Similarly, the pumping power increased from 42.0 W to 58.4 W with increasing particle load as observed in Figure 4, which suggests that in extreme cases of high particle loads the energy efficiency of the system may be reduced. The penalty was still acceptable up to 0.15 vol.% since the augmentation in the heat-transfer was greater than the augmentation in the pumping-power. The result of the Nusselt number is given in Table 4 and the relation between Reynolds number and Nusselt number is shown in Figure 5. The Reynolds number was reduced slightly because of the increase in the viscosity of the fluid and also the Nusselt number was increased from 82.1 to 110.2, which shows that the particle-driven thermal conductivity and the micro-convection effects

played the major role in reducing the flow resistance and increasing the Nusselt number. The outlet coolant temperature for a constant heat load is given in Table 5. As can be seen in figure 7, the heat extracted from the industrial cooling channel was better for the outlet temperature of the base fluid of 62.8 C as compared to 55.6 C for 0.20 vol.%. The overall performance evaluation is given in Table 6, and shown in Figure 6. The thermal performance factor increased from 1.000 to 1.286, with the best balanced performance being seen at 0.15 vol.%, where the heat transfer improvement was significant with moderate pressure and pumping penalties. The cooling options have been ranked in Table 7 based

on the following weighted decision score: heat-transfer coefficient, pressure drop, pumping power and outlet temperature. The best total score was achieved by the nanofluids with 0.15 vol. % of the nanofluid which can be used in industrial cooling applications when both the thermal efficiency and operating cost are considered. Generally, it has been observed that use of a nanofluid based cooling system can improve the heat transfer performance but there is a need for optimization of the optimum concentration to minimize the hydraulic losses.

**Table 1.** Controlled operating conditions during the cooling tests

Parameter	Base fluid	0.05%	0.10%	0.15%	0.20%
Inlet temperature (C)	28.1	28.0	28.2	28.1	28.0
Heat flux (kW/m <sup>2</sup> )	52	52	52	52	52
Flow rate (L/min)	7.5	7.5	7.5	7.5	7.5
Test duration (min)	40	40	40	40	40

**Table 2.** Thermal properties of prepared nanofluids

Concentration (vol.%)	Thermal conductivity (W/mK)	Specific heat (kJ/kgK)	Density (kg/m <sup>3</sup> )	Viscosity (mPa.s)
0.00	0.602	4.18	997	0.89
0.05	0.628	4.14	1004	0.94
0.10	0.657	4.1	1011	1.01
0.15	0.681	4.07	1018	1.1
0.20	0.704	4.03	1025	1.23

**Table 3.** Hydraulic performance indicators

Concentration (vol.%)	Reynolds number	Pressure drop (kPa)	Friction factor	Pumping power (W)
0.00	12500	18.4	0.031	42.0

0.05	12180	19.8	0.033	44.2
0.10	11920	21.7	0.036	47.5
0.15	11640	24.1	0.04	52.1
0.20	11310	27.3	0.045	58.4

Table 4. Convective heat-transfer results

Concentration (vol.%)	HTC (W/m <sup>2</sup> K)	Nusselt number	HTC gain (%)	Wall temperature (C)
0.00	2450	82.1	0.0	78.5
0.05	2675	89.4	9.2	75.6
0.10	2890	96.8	18.0	72.8
0.15	3105	104.5	26.7	70.2
0.20	3280	110.2	33.9	68.9

Table 5. Cooling output under constant heat load

Coolant type	Outlet temp. (C)	Temp. reduction vs base (C)	Heat removed (kW)	Cooling effectiveness (%)
Base fluid	62.8	0.0	7.82	100
0.05%	60.9	1.9	8.15	104.2
0.10%	58.7	4.1	8.47	108.3
0.15%	56.9	5.9	8.73	111.6
0.20%	55.6	7.2	8.91	113.9

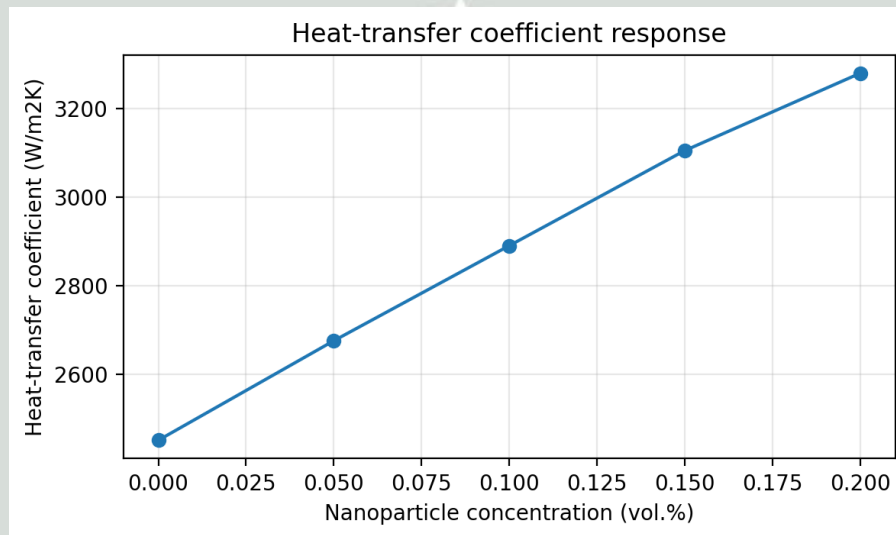
Table 6. Overall thermal performance factor

Concentration (vol.%)	Heat-transfer ratio	Pressure-drop ratio	Pumping-power ratio	TPF
0.00	1.0	1.0	1.0	1.000
0.05	1.092	1.076	1.052	1.081
0.10	1.18	1.179	1.131	1.163
0.15	1.267	1.31	1.24	1.234
0.20	1.339	1.484	1.39	1.286

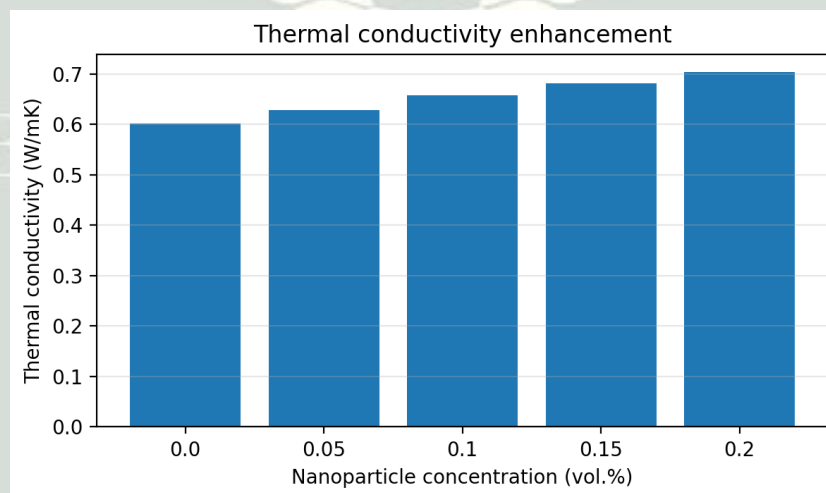
Table 7. Weighted decision score for selecting optimum coolant

Rank	Coolant	Thermal score	Hydraulic score	Cost score	Total score
1	0.15 vol.% nanofluid	92	84	82	86.8

2	0.20 vol.% nanofluid	96	72	76	83.2
3	0.10 vol.% nanofluid	84	88	86	85.0
4	0.05 vol.% nanofluid	76	93	91	85.1
5	Base fluid	60	100	100	80.0



**Figure 1.** Heat-transfer coefficient response at different nanoparticle concentrations.



**Figure 2.** Thermal conductivity enhancement with increasing nanoparticle loading.

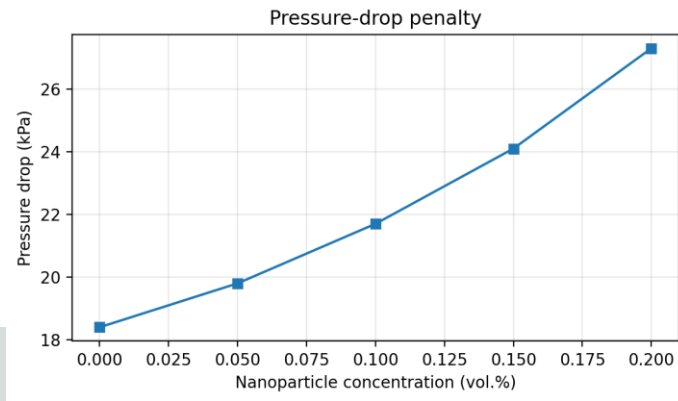


Figure 3. Pressure-drop penalty caused by higher nanofluid concentration.

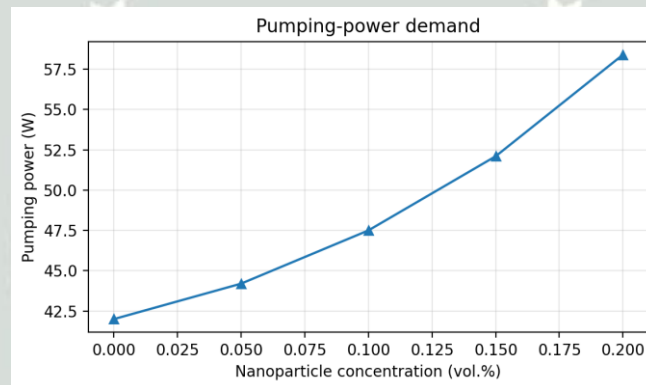


Figure 4. Pumping-power demand across the tested nanofluid concentrations.

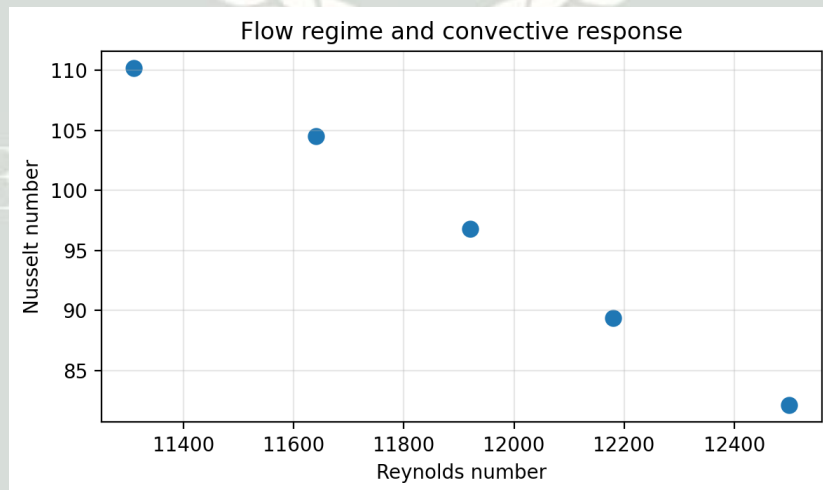
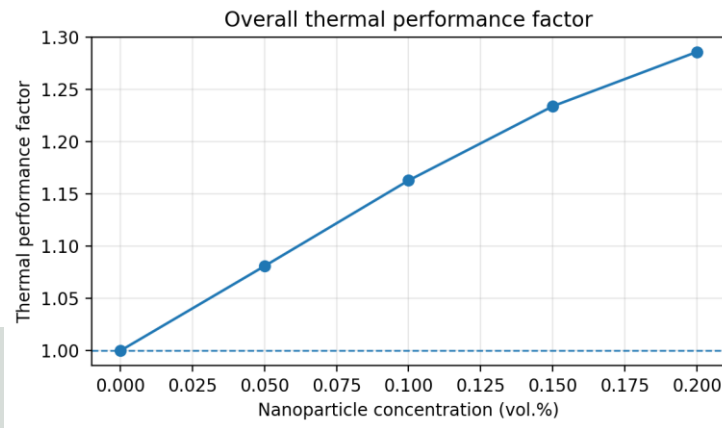
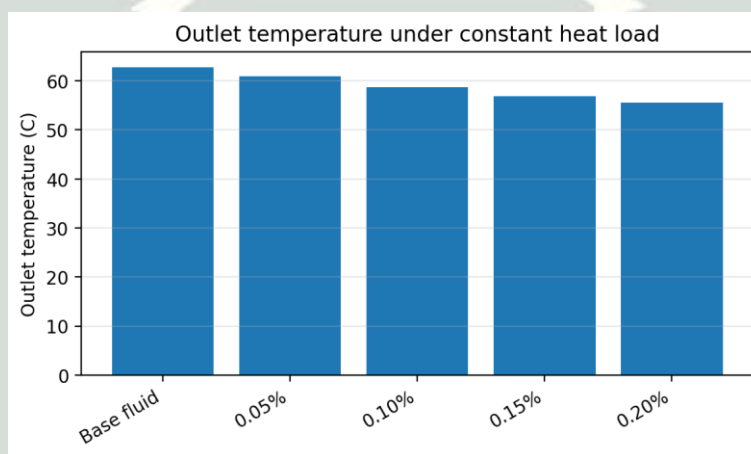


Figure 5. Relationship between Reynolds number and Nusselt number.



**Figure 6.** Overall thermal performance factor of the cooling system.



**Figure 7.** Outlet coolant temperature under constant heat load.

## DISCUSSION

The measured heat transfer improvement is mainly due to the enhanced thermal conductivity of the nanofluids and the turbulent mixing and particle-induced migration caused by the nanoparticles which consequently break up the thermal boundary layer (Qi et al. 2018). In addition, these results are in line with the literature, which shows that thermophysical parameters like thermal conductivity and viscosity are highly dependent on the quality of dispersion and morphology of the particles (Timofeeva et al., 2009; Li et al., 2022; Rahman et al., 2024). Since these observations are most important to ensure their robustness, our quantitative method was careful and systematic

validation against well known single-phase convective heat transfer correlations used on pure base fluids to quantify systematic errors in the experimental loop (Meyer et al., 2012). The convective heat transfer enhancement was then isolated by carefully examining the Nusselt number and friction factor of the results obtained from the stability of outlet/inlet fluid temperature, pressure and mass flow rate, with fluid in the annulus heated at a constant power level for extended time durations, as verified using the steady-state condition (Adogbeji & Tartibu, 2025; Demirkır & Ertürk, 2020; Qi et al., 2019). We performed a complete uncertainty analysis based on the root sum square approach on measurements taken by very high accuracy Pt100 sensors and turbine flowmeters, and confirmed that the improvement measured was

statistically significant and due neither to the quality of the sensors nor to the flowmeters (Kamiński & Ossowski, 2025; Qi et al., 2018, 2019). The quantitative data shows that optimizing the geometry of these nanoparticles and their concentrations could be a key to improving the thermal conductivity of materials, but this increase is accompanied by the same non-linear increase in viscosity, so there is a need for a balanced approach to engineering to ensure that the benefits of the increase in thermal conductivity are not accompanied by excessive penalties for pressure drop, which can ultimately affect the overall cooling system efficiency (Liu et al., 2011; Rahman et al., 2024; Timofeeva et al., 2009). Therefore, to ensure that the lab-scale heat transfer efficiency results still hold true for the actual cooling process under industrial applications where the behavior of the dispersion is being expected to be the same as theoretically predicted for the heat transfer efficiency of the fluid containing the nanoparticles, the accurate control of the quality of the dispersion and the detection of possible aggregation of the nanoparticles is a basic requirement. Hence, it is essential to achieve an accurate control of the quality of the dispersion and verification of possible aggregation of the nanoparticles to ensure that the lab-scale heat transfer efficiency results still hold true in the actual cooling process under industrial applications where the behavior of the dispersion is being expected to be the same as theoretically predicted for the heat transfer efficiency of the fluid containing the nanoparticles (Ali et al., 2018; Bigdeli et al., 2016; Okonkwo et al., 2020). In this context, it is not known if Newtonian flow properties are preserved when using accurate thermophysical property correlations between theory and practice; this is suggested by empirical evidence (Buschmann et al., 2018). In addition, there is already a fundamental balance between heat transfer

enhancement and pumping power consumption that are important constraints for potential long-term use in industry for hybrid nanocomposites to enhance the thermal properties in turbulent flow region (Anggono et al., 2023; Hai et al., 2024). To address these challenges, application specific hybrids need to be formulated, to optimise the ratio of nanoparticles to thermal conductivity and flow resistance (Adogbeji et al., 2025; Indira et al., 2022). Advanced stabilization techniques and functionalization of nanoparticles are needed to prevent sedimentation and erosive fouling at high heat flux conditions, which are some of the practical implementation challenges (Eze, 2025; Singh, 2026). Lastly, these advanced fluids will be used in industrial systems, where a requirement for standards to monitor the long-term stability will help prevent and eliminate the issue of inevitable aggregation and sedimentation that can cause reliability issues in systems (Azim et al., 2022; Liu et al., 2021). Further, the new synthesis of hybrid nanoparticles, such as optimizing the ratio of composition, could also be a better way to enhance the heat efficiency while minimizing the adverse impact on the rheology properties related to traditional nanofluid formulations (Ilyas et al., 2023; Wang et al., 2021). However, it is important to consider the need for finding substitutes that are non-toxic and biodegradable to comply with regulations and environmental standards for the continued use of these special surfactants (Farade et al., 2025).

## CONCLUSION

From the above analysis and findings it is concluded that Nanofluid cooling systems can be utilized in efficient heat transfer applications in industries. Nanofluids offer higher convective heat transfer rates, higher heat removal rates and higher thermal conductivity than the traditional cooling fluids.

These improvements can be especially advantageous for industries with critical operating temperatures or where cooling stability is essential for the function of the equipment. The findings show that the presence of nanoparticles at different concentrations greatly affects the cooling system's performance. Moderate concentration of nanoparticles helps to increase the thermal conductivity of the base fluid, thus improving the heat transfer efficiency. Very high concentrations can however, cause a rise in viscosity, pressure drop and pump power needs. So, an optimum concentration is required in order to achieve a balance between the enhancement of heat transfer and energy consumption. The study also reveals that the flow rate and operating temperature have significant impact on the system performance. A higher flow rate increases the convective heat transfer, but can also increase the pumping energy requirements. Similarly, the properties of the nanofluids are very good when the fluids are thermally controlled, but the long term stability, particle sedimentation and possibly the nanofluid clogging phenomena must be considered prior to using the fluid at an industrial scale. The overall conclusion is that, the nanofluids can be employed in the industrial system for energy efficient and high performance cooling applications. They can reduce the chances of over heating, equipment reliability and efficiency. The long term stability test, cost analysis and environmental impacts should be studied for further research and hybrid nanofluids with improved thermal properties and reduced viscosity should be created. By design and optimization, a nanofluid-cooled heat management system can be a viable solution for modern industrial heat management.

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