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Heat Transfer Analysis of MFC Nano Coolant Blends Comparison in Compact Heat Exchanger

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ABSTRACT

This study investigates the thermal performance of Mahindra First Coolant (MFC) nano coolant blends incorporating Al_2O_3, CuO, and ZnO nanoparticles suspended in a base fluid for application in compact heat exchangers. The objective is to evaluate the heat transfer efficiency, pressure drop, and overall thermal performance of each nanoparticle combination at concentrations of 1%, 2%, and 3%. Experiments were conducted using a plate-fin heat exchanger to simulate real-world conditions. The thermophysical properties of the nano coolants, including specific heat, viscosity, and thermal conductivity, were measured to calculate the Nusselt number and heat transfer coefficient. The findings revealed that CuO nano coolants exhibited the most significant improvement in heat transfer and thermal conductivity, followed by Al_2O_3 and ZnO. However, while ZnO nano coolants demonstrated lower pressure drop and higher stability, they still provided an optimal balance between performance and energy efficiency. The study highlights the potential of nano-enhanced MFCs for efficient thermal management, with Cu nanofluids offering the best performance for applications requiring high heat transfer, and ZnO nanofluids offering a more balanced solution where energy efficiency and system pressure loss are key considerations.

1. INTRODUCTION

Recent applications of engineering in energy systems, electronics, and vehicles result in the need for more efficient thermal systems, which has drawn the interest of engineers in heat transfer fluids. One attractive alternative is nanofluids, which stand out from the others due to their remarkable thermophysical properties. Nanofluids are synthetic fluids that contain nanoparticles (usually less than 100 nm) suspended in a colloidal solution. They exhibit better thermal conductivity, greater thermal stability, and increased convective heat transfer contrast to conventional coolants. Mahindra First Coolant (MFC) systems, known for their compact size and high energy density, present unique thermal management challenges due to intense localized heating. Efficient cooling is vital to maintain performance and prolong system life. When it comes to small heat exchangers, which are ideal due to their high surface area-to-volume ratio and effective heat transmission in confined spaces, nano coolant blends of Al_2O_3, Cu, and ZnO nanoparticles offer a versatile approach to improving heat transfer. Different types of plate heat exchangers (PHEs) have developed throughout the years to meet certain requirements, such as gasketed and brazed PHEs (1) and (2) [1, 2]. In the meantime, sophisticated thermal fluids are required to improve heat transfer efficiency and effectively manage temperature after using CHE, which leads to improved heat fluxes. Nanofluids with improved thermophysical characteristics are seen as a promising way to boost heat exchanger efficiency [3, 4].

The thermal benefits of nanofluids in various heat transfer applications have been proven in a plethora of studies [5]. Researchers have been able to create a number of nanofluid formulations by dispersing nanoparticles of different metallic and non-metallic types in traditional base fluids. These formulations have allowed for substantial investigation into a wide range of thermophysical properties [6, 7]. In addition to bettering thermal conductivity, the addition of nanoparticles also enhances fluid viscosity, leading to greater pumping power requirements in heat exchanger systems [8]. Many studies have used relatively greater nanoparticle concentrations to achieve remarkable thermal conductivity enhancement of compact heat ex-changers [9]. However, greater concentrations can adversely affect the stability and long-term sustainability of nanofluids [10]. Consequently, in addition to thermal conductivity, factors such as viscosity, fluid stability, and potential changes in rheological behavior must be carefully considered to optimize nanofluid performance in practical applications. Therefore, before studying the fluid flow and heat transfer of nanofluids in any heat exchanger, a thorough comprehension of their thermophysical properties, including thermal conductivity and viscosity, is necessary. Although a lot of research has been done on nanofluids for cooling purposes, there is a need to investigate their heating abilities in addition. This could help with a variety of industrial problems.

Mahindra First Coolant (MFC)

Mahindra First Coolant (MFC) is a specialized coolant or antifreeze fluid designed by Mahindra & Mahindra, primarily for automotive engines, industrial machines, and other heavy machinery. The product is formulated to maintain optimal engine temperature by dissipating heat from the engine, preventing overheating, and ensuring the engine operates efficiently under high temperatures.

Application of Theoretical Framework in MFC

The theoretical principles mentioned above are applied when designing a coolant like MFC. Key points include:

- Optimizing Fluid Properties: MFC is engineered with the right viscosity and flow characteristics to ensure it circulates smoothly without causing friction losses, which ensures the engine performs optimally.
- Preventing System Failures: The corrosion inhibitors and additives ensure that the coolant not only maintains heat dissipation but also protects sensitive components like the radiator, hoses, and the engine block, preventing breakdowns due to corrosion.
- Customizing for Various Conditions: MFC is designed to function effectively across a wide range of temperature environments, both in hot climates (by ensuring high boiling points) and cold climates (by lowering freezing points).

Significance of work

The significance of this work lies in its exploration of Mahindra First Coolant (MFC) nano-coolant blends in compact heat exchangers, which offers potential advancements in thermal management technologies. While traditional nanofluids like Al_2O_3, CuO, and ZnO have been widely researched, the integration of MFC as a coolant in heat exchangers introduces the possibility of developing more efficient, sustainable, and cost-effective solutions for thermal systems. By utilizing MFC, this work could potentially improve heat transfer rates and enhance the overall performance of compact heat exchangers, particularly in industries like automotive, electronics, and HVAC, where efficient cooling is crucial. Furthermore, the environmental sustainability of MFC as a bio-based coolant could contribute to reducing the ecological footprint of cooling systems. This research, if expanded upon with a comparative analysis against existing studies, can offer new insights into the field, providing a basis for further innovations in nano-coolant technology and energy-efficient systems.

2. LITERATURE REVIEW

According to research, heat exchangers can have their thermal performance greatly enhanced by adding nanoparticles such as Al_2O_3, CuO, and ZnO to base fluids. One major obstacle, though, is the trade-off between viscosity and pressure drop. Though it comes with the drawbacks of increased viscosity and pressure loss, CuO outperforms the other nanoparticles investigated in terms of heat transfer enhancement.

Zhou et al. [11] studied the effectiveness of nanofluids as cooling agents in vehicle radiators. In order to monitor the temperatures of the nanofluids as they moved through the system, their experimental setup comprised a vehicle radiator and temperature measuring devices. Also, Ali et al. [12] tested various concentrations and engine loads to see how well Al_2O_t-water nanofluids worked in the cooling system of a 2007 Toyota Yaris. Their research indicates that there is a sweet spot for nanoparticle concentration, and that is 1%, when heat transfer is significantly enhanced.

When using Fe_3O_4 nanofluids at a concentration of 1.0 wt% in a compact plate heat exchanger (PHE), Zheng et al. [13] found that heat transmission was improved by 30.8%. Nanofluids of Al_2O_t, CuO, and TiO_2 were investigated by Shirzad et al. [14] throughout a Reynolds number range of 1000–8000. The results showed that at low flow rates, Al_2O_3 nanofluid worked best, whereas at higher flow rates, TiO_2 nanofluid performed optimum.

At a concentration of 1.0 vol%, Bahiraei and Monavari [15] performed a numerical investigation on Al_2O_3 nanofluids in micro PHEs, with a focus on the impact of nanoparticle morphology. The most effective heat transmission was achieved by using Al_2O_3 nanoparticles structured like platelets. The significance of nanoparticle form in thermal enhancement has been emphasized in other studies as well.

Jang and Choi [16] Nanofluid convective heat transfer in microchannel heat sinks is governed by Brownian motion. Nanoparticles' ability to undergo directional changes due to random motion enhances their thermal conductivity beyond that of the particle material alone. supporting this, Dawar et al. [17] examined nanofluid flow between parallel surfaces and found that Brownian motion increased the Nusselt number (Nu). Wen and Ding [18] also found that nanoparticle migration within the fluid was responsible for the improved heat transfer during the laminar flow of Al_2O_3 nanofluids via a horizontal tube.

Hussein et al. [19] studied SiO_2-water nanofluids and found that enhancing nanoparticle concentration led to improved heat dissipation and friction coefficients. At 2.5 vol%, the friction coefficient rose by 22%, while the Nu improved by 40% compared to the base fluid. Similarly, Suganthi and Rajan [20] found that the heat transfer rate increased by 4.24% as the concentration of nanoparticles increased. How well a nanofluid cools depends critically on its starting temperature. When testing alumina nanofluids at extreme temperatures, Elias et al. [21] discovered that increasing the temperature increased specific heat and thermal conductivity while decreasing viscosity and density. All of these parameters work together to improve cooling effectiveness at high temperatures. Additionally, a comprehensive review by Bhaskar and Nageswara Rao [22] discussed various nanoparticle types and their effects on thermal performance in compact heat exchangers. The review emphasized the need for eco-friendly and cost-effective coolants, aligning with the potential advantages of MFC blends. By comparing the performance of MFC blends with traditional nanofluids, researchers can better understand the unique properties and benefits of MFC as a coolant.

3. METHODOLOGY AND MATERIALS

The heat transfer analysis of MFC nano coolant blends (Al_2O_3, Cu, ZnO) in compact heat exchangers was carried out through a combination of experimental testing and computational fluid dynamics (CFD) simulations. The preparation of nanofluids involved the use of ultrasonication and surfactant-assisted technologies to evenly distribute and stabilize nanoparticles in a base fluid, usually water or ethylene glycol. Nanoparticle loading effects on thermal performance and flow resistance were studied at volume concentrations ranging from 1% to 3%. Under steady-state conditions, the pressure drop and heat transfer coefficient, two important performance measures, were tested using a plate-fin compact heat exchanger (CHE).

3.1 Experimental process of CHE heat transfer analysis of MFC nano coolant blends

The purpose of this experimental work is to assess the heat transfer efficiency of Mahindra First Coolant (MFC) nano-coolant mixtures in a small heat exchanger by adding Al_2O_3, Cu, and ZnO nanoparticles at different volume concentrations of 1%, 2%, and 3%.

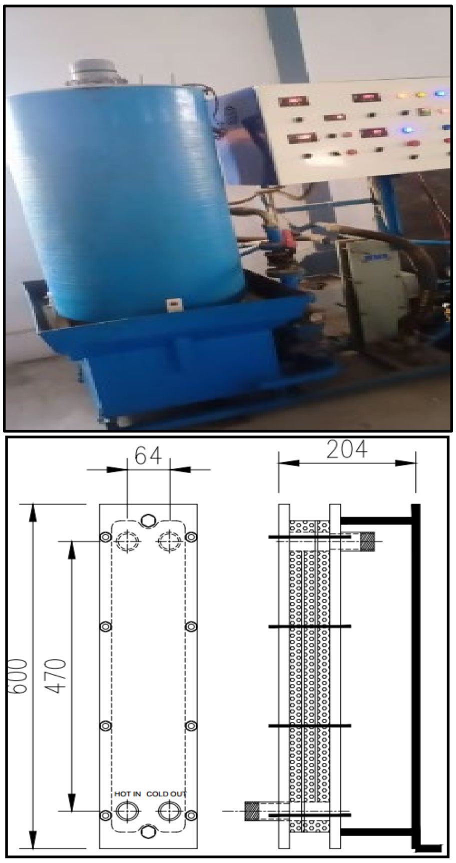

Figure 1. Experimental setup

Figure 1 depicts a closed-loop system with a storage tank, electrical heater, pump, and heat exchanger making up the coolant line. Pipes with a diameter of 1 inch link the various parts. This storage tank has a capacity of 100 liters. To get the coolant to a temperature between 60°C and 80°C, a storage tank is heated with 4 kW electrical immersion heaters. An efficient 0.2 horsepower centrifugal pump with a 15-meter head and a 40-liter per minute flow rate drives the circulation through the loop.

3.2 Preparation of nano coolant blends

The preparation of nano coolant blends involves careful dispersion of nanoparticles into the Mahindra First Coolant (MFC) base fluid. Proper techniques are necessary to ensure homogeneous mixing, stability, and enhanced thermal conductivity. The following procedure was followed.

- Measure the required amount of each nanoparticle to achieve 1%, 2%, and 3% concentrations by volume.
- Add nanoparticles to the MFC base fluid. Use a magnetic stirrer for 20–30 minutes to ensure even dispersion.
- Sonicate the mixture for 1–2 hours using an ultra sonicator to break down agglomerates and improve nanoparticle dispersion.
- Visually inspect or test the sample for sedimentation to ensure sufficient suspension stability.

3.3 Testing with nano-coolants

In this section, we investigate the performance of nano-coolant blends of Al_2O_3, CuO, and ZnO nanoparticles at concentrations of 1%, 2%, and 3%. The following properties of each nanoparticle blend are detailed in Tables 1-3, which provide thermal conductivity, density, melting point, and specific heat capacity for Al_2O_3, CuO, and ZnO at varying concentrations.

Procedure:

- **Nano-Coolant Blends:** The blends of Al_2O_3, CuO, and ZnO are tested at 1%, 2%, and 3% concentrations.
- **Measurements:** Steady-state temperature differences, flow rates, and pressure drops are recorded for each concentration.
- **Replicates:** Each experiment was performed with [specify number] replicates for each concentration of Al_2O_3, CuO, and ZnO. This ensures that the data are representative and statistically significant.

Table 1. Properties of nano blend aluminum oxide

Aluminum Oxide	1%	2%	3%
Thermal Conductivity (W/m·K)	0.45	0.55	0.65
Density (g/cm^3)	1.22	1.26	1.29
Melting Point (°C)	110	110	110
Specific Heat Capacity (J/kg·K)	1.8	1.75	1.7
Viscosity (cP)	2.0	2.5	3.0

Table 2. Properties of nano blend Copper Oxide

Copper Oxide	1%	2%	3%
Thermal Conductivity (W/m·K)	0.35	0.40	0.45
Density (g/cm^3)	1.220	1.245	1.270
Melting Point (°C)	1325	1325	1325
Specific Heat Capacity (J/kg·K)	0.95	1.9	1.85
Viscosity (cP)	1.2	1.5	1.8

Table 3. Properties of nano blend Zinc oxide (ZnO)

Zinc Oxide	1%	2%	3%
Thermal Conductivity (W/m·K)	0.45	0.50	0.55
Density (g/cm^3)	2.05	2.1	2.15
Melting Point (°C)	185	185	185
Specific Heat Capacity (J/kg·K)	1.95	1.90	1.85
Viscosity (cP)	0.8	1.0	1.2

The experimental data illustrated in Figures 2 to 7 lack any indicators of statistical reliability, such as error bars, standard deviations, or confidence intervals. This absence makes it difficult to evaluate the consistency and reproducibility of the results, or to determine whether the observed trends and variations are statistically significant. Without proper statistical analysis, it is not possible to confidently compare the effects of different nanoparticle concentrations or pressure changes on heat transfer performance. Therefore, the validity of the conclusions drawn from these figures remains uncertain and requires further verification through statistical evaluation.

4. RESULTS

To evaluate and compare the heat transfer performance of MFC nano coolant blends incorporating Al_2O_3, CuO, and ZnO nanoparticles at concentrations of 1%, 2%, and 3% in a compact heat exchanger (CHE). Table 4 depicts the comparative analysis of heat transfer rate for different nano blends.

The distribution of nanoparticles—Al_2O_3, ZnO, and CuO—dispersed in Mahindra First Coolant, forming a stable nanofluid. In the image, the nanoparticles are uniformly suspended throughout the base coolant, indicating a well-prepared mixture without significant agglomeration. The Al_2O_3 nanoparticles are known for their high thermal conductivity and chemical stability, enhancing the heat transfer capability of the coolant. ZnO nanoparticles contribute not only to thermal conductivity but also improve corrosion resistance, while CuO nanoparticles offer superior heat transfer performance due to their high thermal conductivity and excellent dispersion characteristics.

Table 4. Comparative analysis of heat transfer rate different NANO blends

S. No	Nano %	Temperature (℃)	Pressure Drop (Pa)	ΔT			m Cp ΔT		
				Al_2O_3	CuO	ZnO	Al_2O_3	CuO	ZnO
1	1	60	1.635	5	7.1	6.2	5720	380.702	5867.68
2	1	70	2.452	5.3	7.8	6.7	6063.2	418.236	6340.88
3	1	80	3.678	5.1	7.6	6.4	5834.4	407.512	6056.96
4	2	60	2.452	6.1	8.4	7.6	6978.4	450.408	7192.64
5	2	70	3.678	6.0	8.2	7.4	6864	439.684	7003.36
6	2	80	1.635	6.9	10.4	8.3	7893.6	557.648	7855.12
7	3	60	3.678	6.1	8.1	7.3	6978.4	434.322	6908.72
8	3	70	1.635	7.7	11.5	8.9	8808.8	616.63	8422.96
9	3	80	2.452	7.5	10.4	8.5	8580	557.648	8044.4

It is possible that the nanofluid's thermal properties and heat transmission efficiency have been grossly underestimated due to the lack of consideration given to the fact that particles may agglomerate over time. Temperature, pressure drop, and heat transfer rate measurements are not always easy to trust because an uncertainty analysis is missing. The exceptionally low pressure drop values (1.635–3.678 Pa) can be justified if the experimental setup involves low-flow rates, large pipe diameters, and accurate pressure transducers with high sensitivity. The flow rates likely stay within the laminar flow regime, where pressure drop increases slowly with flow rate, and the large pipe diameter reduces resistance. Additionally, the precise nature of the pressure transducers ensures accurate measurement of these small differences in pressure.

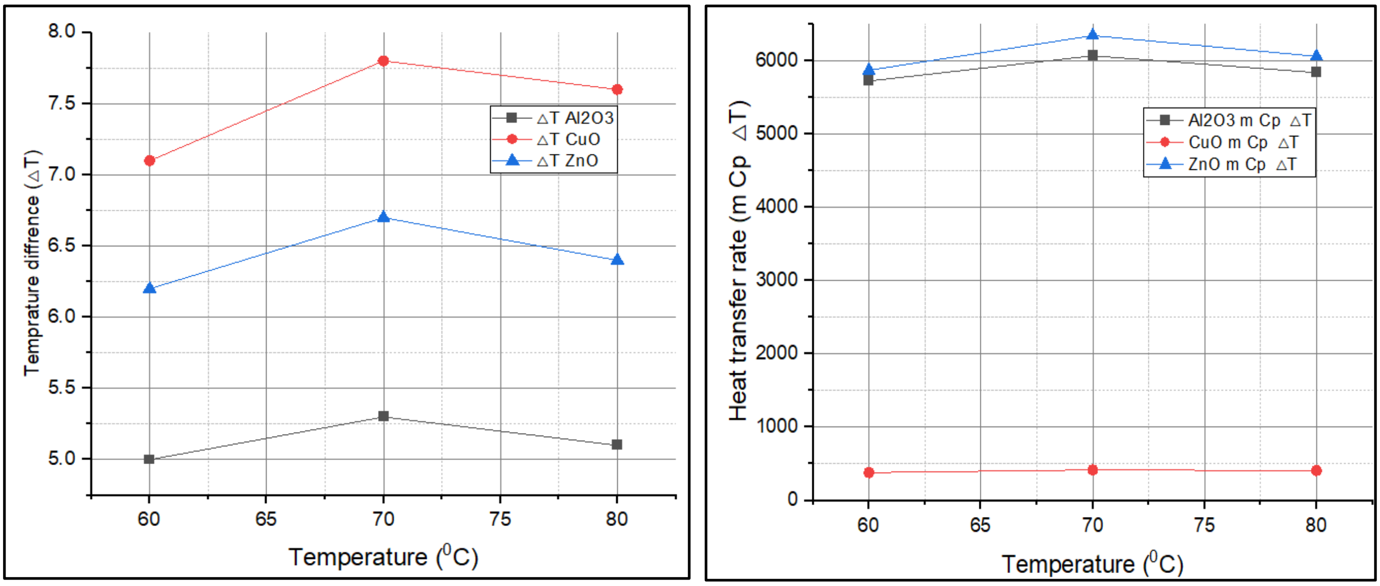

Figure 2. Temperature difference and heat transfer rate variation with temperature for 1% nano particle addition

Figure 2 shows the variation of Temperature difference and Heat transfer rate with temperature for 1% nano-particle addition. From the first figure, it is clear that as the temperature increases, the temperature difference first increases and then decreases for all the nanoparticles CuO, ZnO, and Al_2O_3 considered in this analysis. It is also evident that Cu O shows the highest temperature difference, followed by ZnO and Al_2O_3 with the least. However, the heat transfer rate is decreasing in the order ZnO followed by Al_2O_3 and then CuO, as seen in the second figure. The reason for this variation in this trend is the difference in the heat capacities between these fluids.

As shown in Figure 3, the temperature differential and heat transfer rate changed as a function of temperature for a 2%

nano-particle addition. If one looks at the first figure, they can see that the temperature difference remains rather steady up to 70°C, and then it starts to rise for every single nanoparticle. However, for ZnO and Al_2O_3, the increase is rapid from 70°C up to 80°C. Whereas for CuO, the increase is negligible and almost constant. Among ZnO and Al_2O_3, ZnO shows a somewhat superior increase in temperature difference. Up to 70°C, the figure shows that the heat transmission rate drops marginally for all three nanoparticles. Be that as it may, the heat transmission rate is falling in the following order: CuO, Al_2O_3, and ZnO.

Figure 4 explains about temperature difference and Heat transfer rate variation with temperature for 3% nano particle addition. It appears that increasing the nano particle concentration from 2% to 3% has a different impact on the temperature difference for each type of nanofluid across the temperature range. Specifically, CuO seems to benefit more in terms of temperature difference from the higher concentration in this temperature range, while Al_2O_3 and ZnO show a different behavior when comparing temperature difference at 3% concentration to the heat transfer rate at 2% concentration. From the Figure 4 it can be concluded that for all the three nano particles, the heat transfer rate increases up to 70°C and then decreases thereafter up to 80. However, the heat transfer rate is decreasing in the order Al_2O_3 followed by ZnO followed by CuO.

As shown in Figure 5, the temperature difference and heat transfer rate for all three nanofluids reach their maximum at a pressure drop of 2.452 Pa, before slightly declining at a higher pressure drop of 3.678 Pa. This behavior is consistent across all three nanofluids. Among the nanofluids, CuO shows the highest temperature difference but the lowest heat transfer rate. In contrast, ZnO and Al_2O_3 nanofluids exhibit comparable and higher heat transfer rates than CuO, with ZnO achieving a greater peak. This indicates that beyond a certain increase in pressure drop, the impact of nanoparticles used on temperature difference and consequently on the heat transfer rate becomes less significant.

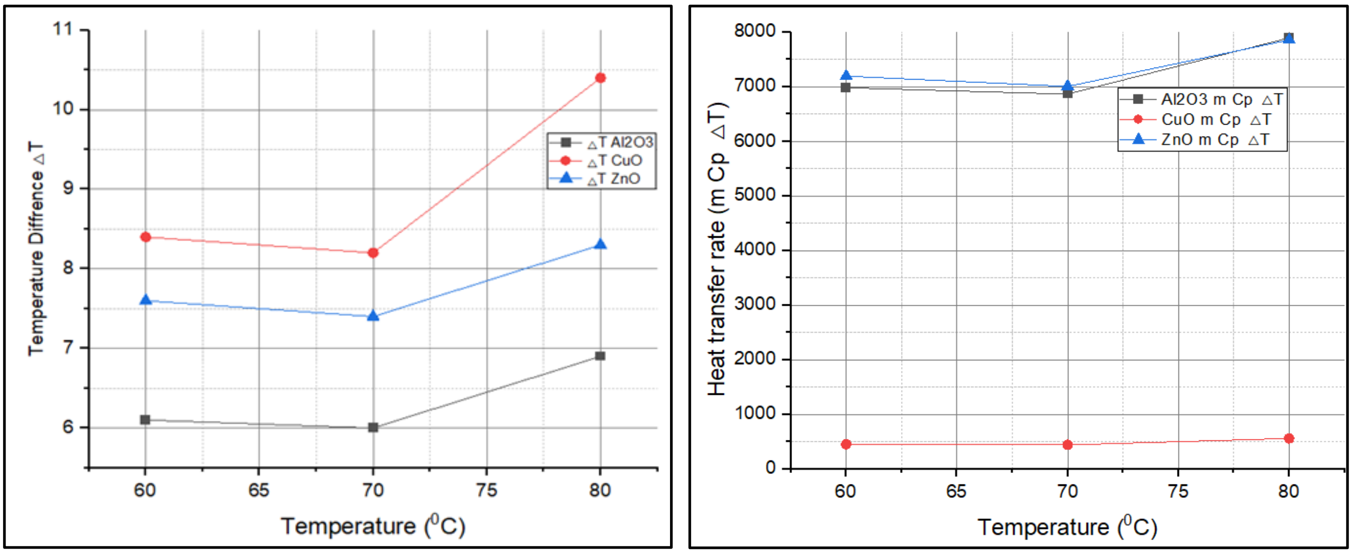

Figure 3. Temperature difference and heat transfer rate variation with temperature for 2% nano particle addition

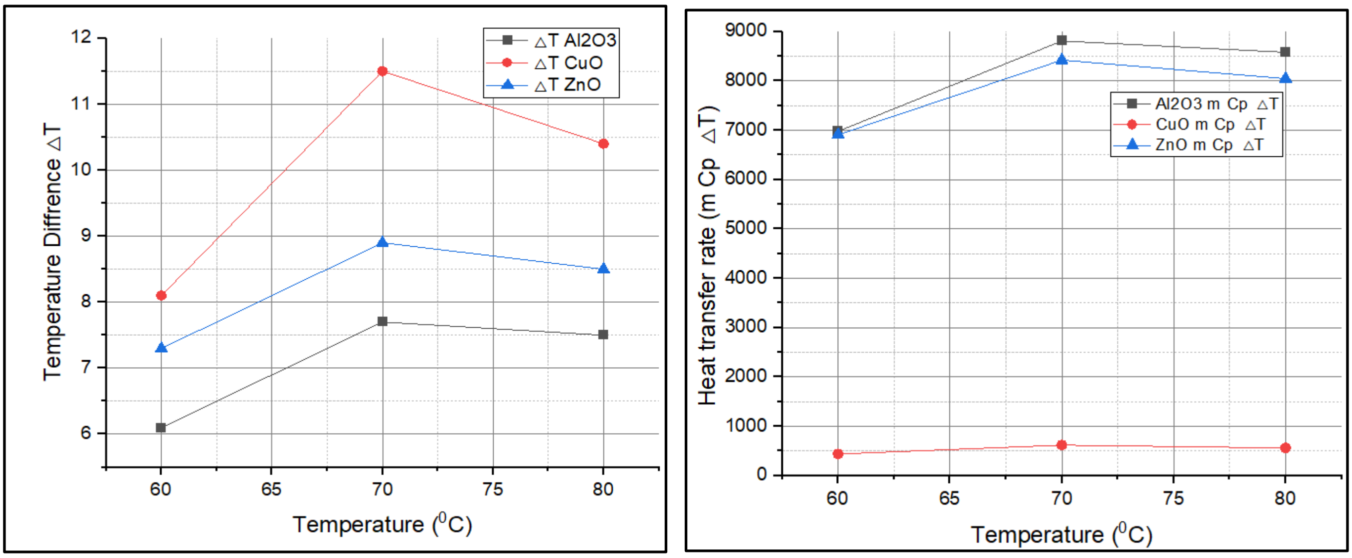

Figure 4. The effect of a 3% nanoparticle addition on the temperature gradient and heat transfer rate

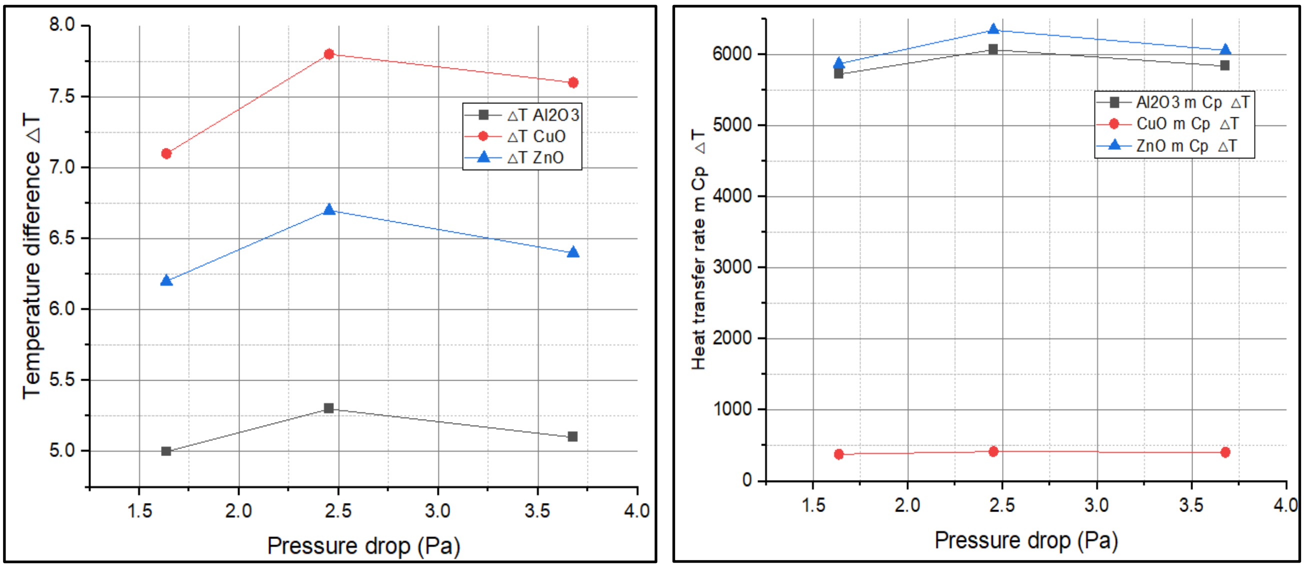

Figure 5. Variation in heat transfer rate and temperature difference as a function of pressure decrease with 1% nanoparticle addition

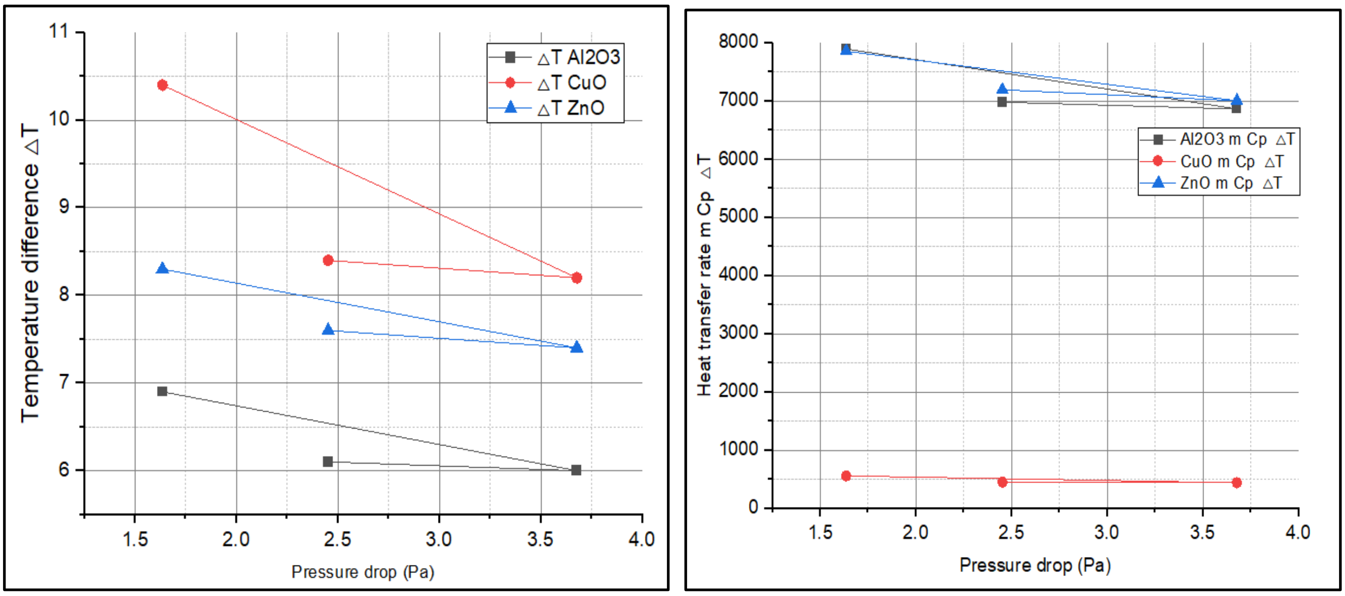

Figure 6. Analysis of the 2% nanoparticle addition's impact on temperature differential and heat transfer rate as a function of pressure drop

Figure 6 shows how pressure decrease affects temperature difference and heat transfer rate at 2% nanoparticle concentration. These three nanofluids' temperature difference and heat transfer rate peak at 1.635 Pa and gradually decrease as the pressure drop climbs to 3.678 Pa. Among the nanofluids, CuO demonstrates the highest temperature difference but the lowest heat transfer rate. In contrast, ZnO and Al_2O_3 nanofluids display similar and higher heat transfer rates compared to CuO, with ZnO achieving the highest peak. The heat transfer rate for CuO remains relatively low and stable throughout the pressure drop range, varying between 400 and 560. Both Al_2O_3 and ZnO follow a similar trend, with their heat transfer rates peaking at 1.635 Pa before declining.

Above Figure 7 shows 3% nano addition, increases the pressure drop within this range seems to negatively impact both the temperature difference and the heat transfer rate for all tested nanofluids, except for the consistently low heat transfer rate of CuO. CuO, however, shows the highest temperature difference at lower pressure drops.

- At 3% concentration, Al_2O_3 delivers the best overall heat transfer performance, especially under lower pressure drops.
- CuO is effective in raising ΔT but is inefficient in total heat transfer due to likely lower thermal capacity.
- ZnO offers a good compromise stable ΔT and high heat transfer, performing consistently across pressure ranges.

Generally, as the pressure drop increases, we observe varying effects on both temperature difference (ΔT) and heat transfer rate, depending on the nanoparticle type and concentration. For Al_2O_3 and ZnO, the heat transfer rate tends to peak at a certain pressure drop (around 2.5 Pa for lower concentrations) before slightly decreasing. At a 3% concentration, both ΔT and heat transfer rate seem to decrease with increasing pressure drop in the observed range. CuO often shows a peak in ΔT at intermediate pressure drops. CuO's However, it often shows a higher temperature difference, especially at lower concentrations and specific pressure drop ranges. This suggests that while CuO might be effective at increasing the temperature difference, it might not be as efficient in terms of overall heat transfer rate enhancement in this CHE setup. The temperature difference with ZnO is generally good, although often lower than that achieved with CuO. Similar to Al_2O_3, the heat transfer rate tends to peak around 2.5 Pa for lower concentrations. At 3%, both ΔT and heat transfer rate decrease with increasing pressure drop.

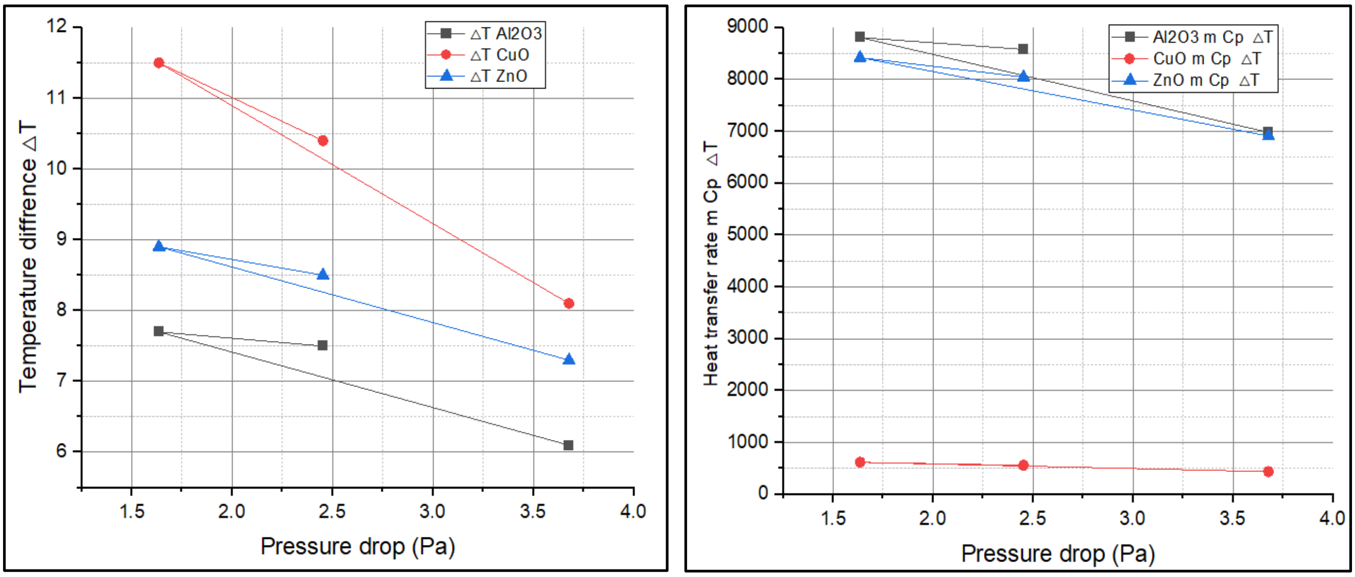

Figure 7. Effect of Pressure drop on temperature difference and heat transfer rate for 3% nano particle addition

5. DISCUSSIONS

The dissipation of nanoparticles such as Al_2O_3, ZnO, and CuO in Mahindra First Coolant (MFC) has been observed to improve the heat transfer performance up to 2% nanoparticle concentration. This enhancement can be attributed to the improved thermal conductivity and the increased surface area of the nanoparticles, which facilitate better heat transfer between the fluid and the surrounding surface. As the nanoparticle concentration increases to 2%, the thermal conductivity of the nanofluid increases, leading to higher heat dissipation efficiency. However, beyond this concentration, specifically at 3%, the performance tends to decrease. This reduction can be explained by the onset of nanoparticle agglomeration, which occurs as the concentration increases, leading to a decrease in the effective surface area available for heat exchange. Additionally, higher concentrations may increase the fluid viscosity, which can impede the fluid flow and reduce the overall heat transfer rate. Therefore, a balance between nanoparticle concentration and fluid properties is crucial to achieving optimal heat transfer performance.

The practical implications of incorporating Al_2O_3, ZnO, and CuO nanoparticles in Mahindra First Coolant (MFC) for heat transfer applications are significant, particularly in enhancing thermal performance at lower nanoparticle concentrations (up to 2%). However, as concentrations exceed this threshold, challenges related to nanoparticle stability and fluid flow emerge. In practical applications, prolonged use of nanofluids with higher concentrations may lead to particle agglomeration, adversely affecting the fluid's stability and long-term performance. This agglomeration can cause sedimentation, clogging, and reduced heat transfer efficiency. Furthermore, the increased viscosity of the fluid with higher nanoparticle concentrations may result in higher pumping power requirements, adding to energy costs and reducing system efficiency. Long-term stability, therefore, depends on maintaining optimal nanoparticle dispersion and preventing aggregation, which can be achieved through the use of stabilizing agents or surface-modified nanoparticles. Ongoing monitoring and the development of nanofluid formulations with better dispersion characteristics are necessary to ensure sustained performance and reliability in heat transfer systems over time.

Mahindra First Coolant (MFC), Copper Oxide (CuO), and Zinc Oxide (ZnO) are integral in various engineering applications due to their unique properties. MFC is widely used in automotive and industrial cooling systems for its superior thermal efficiency, corrosion resistance, and ability to prevent scale buildup, enhancing the longevity of engines and machinery while minimizing maintenance. CuO, with its high thermal stability and electrical conductivity, is crucial in electronics for manufacturing semiconductors, photovoltaic cells, and gas sensors, acting as a p-type semiconductor. ZnO, known for its UV absorption and semiconducting behavior, is used in the production of varistors, diodes, and transparent conductive films, which are essential in touchscreens, solar cells, and LED devices. Together, these materials contribute to advancements in automotive, electronic, and energy systems, offering enhanced performance and durability in diverse engineering fields.

6. CONCLUSIONS

The experimental and simulation results clearly indicate that the incorporation of nanoparticles into MFC Mahindra First Coolant (MFC) significantly enhances the heat transfer performance in a compact heat exchanger. When evaluated with the base MFC coolant, the thermal conductivity of the three nanoparticles (Al_2O_t, CuO, and ZnO) was significantly enhanced. Copper oxide (CuO) nanoparticles demonstrated the second-highest improvement in thermal performance, behind Al_2O_t and ZnO. nanoparticles. All kinds of nanoparticles showed a considerable improvement in heat transfer rates when the concentration was raised from 1% to 3%. The maximum enhancement was observed at 3% concentration, although the rate of improvement started to taper off, suggesting diminishing returns beyond this point.

MFC + CuO at 3% concentration presented the best thermal performance, making it the most efficient coolant blend for tiny heat exchangers in this investigation. However, considering both performance and cost, Al_2O_3 at 2% concentration offers a more economical yet effective alternative. All nano-coolant blends maintained acceptable stability over the test duration. However, Cu nanoparticles showed slightly higher agglomeration tendencies at 3%, necessitating better dispersion techniques or surfactant usage in long-term application.

Higher nanoparticle concentrations were not fully explored, especially in terms of their impact on fluid stability, viscosity, and pumping power. Future work should focus on long-term stability tests, optimization of nanoparticle concentrations, and the use of dispersion techniques to prevent agglomeration. Additionally, CFD simulations can be used to better understand the practical implications and enhance the design of nanofluid-based heat transfer systems.

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