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Research Article

Experimental Investigation of Hybrid Al_2O_3 -CuO/Water Nanofluids in Counter Flow Double-pipe Heat Exchangers: Enhanced Heat Transfer Performance for HVAC Applications

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The research topic aims to address the urgent need for enhanced energy efficiency in HVAC systems by developing and optimizing efficient heat transfer fluids. Despite the significant attention given to single-component nanofluids, there is a lack of systematic study on the performance of Al_2O_3 -CuO hybrid nanofluids in a double-pipe heat exchanger for HVAC system applications. A comprehensive experimental investigation was done on the various hybrid nanofluid concentrations (0.05%, 0.1%, 0.15%) under different Al_2O_3 :CuO ratios (70:30, 60:40, 50:50) at Reynolds numbers 3,000-12,000. Results show that the 60: 40 Al_2O_3 :CuO hybrid nanofluid of 0.1% concentration exhibits a 42.3% enhancement in Nusselt number, a 38.7% increase in heat transfer coefficient, and a 28.4% improvement in thermal effectiveness over that of pure water, with tolerable friction penalties (15-22%). The obtained performance shows a remarkable increase when compared with other published works. The current correlation has a 42.3% higher increase than 13.8% reported by Suresh et al. for Al_2O_3 -Cu and 31% with Madhesh et al. for Cu-TiO₂ hybrid nanofluids. The hybrid shows a 35.5% improvement over the single Al_2O_3 nanofluids and a 13.5% improvement over CuO. A significant increase of 18- 25% is shown in this work as compared to single nanoparticles by using a hybrid system. It can be concluded that in the current research work, the experimental correlations were developed and validated, which could be used to implement the hybrid nanofluids in advanced energy-efficient HVAC systems. Finally, the study has developed and validated experimental correlations that enable the implementation of hybrid nanofluids in advanced HVAC systems to achieve higher energy efficiency.

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1. Introduction

The global increase in energy demands for heating, ventilation, and air conditioning (HVAC) systems has driven significant research interest in advanced heat transfer technologies. Heat exchangers are the key components in HVAC systems, and the thermal performance of heat exchangers determines the entire system's

performance as well as energy consumption [1], [2]. Traditional heat transfer fluids, including water, ethylene glycol, and various oils, exhibit relatively low thermal conductivity, limiting their heat transfer potential [3], [4], [5], [6]. The discovery of nanofluids, colloidal suspensions of nanoparticles in base fluids, has transformed heat transfer enhancement strategies, leading to a revolution in the approach to heat transfer

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enhancement. A lot of research has been carried out on the topic since the pioneering study by Eastman et al. [7], which established superior thermophysical properties of nanofluids relative to conventional heat transfer fluids. Nevertheless, the majority of research has been done on single-component nanofluids, and there remains a lot to be desired in terms of enhancing them with a hybrid formulation [8], [9], [10], [11], [12]. The hybrid nanofluids are a superior category of heat transfer fluids with two or more types of nanoparticles suspended in a base fluid. By doing so, they can be used to achieve synergistic effects, taking into account the special properties of various nanoparticles to achieve high thermal performance. Al_2O_3 nanoparticles are known for their excellent thermal conductivity and stability, making them a popular choice for heat transfer applications. On the other hand, CuO nanoparticles provide enhanced convective heat transfer characteristics due to their unique surface properties [13], [14], [15], [16]. HVAC systems are based on the use of double-pipe heat exchangers, especially when temperature regulation is necessary and the size is limited. The simplicity of their construction, the maintenance that can be done easily, and the performance in counter-flow configurations are the reasons why they are useful in the research of nanofluid performance [17], [18], [19], [20], [21]. Although they are commonly utilized, very little has been done in examining the usage of hybrid nanofluids in the double pipe heat exchanger in HVAC applications. Findings from recent research in the field of hybrid nanofluids portended encouraging outcomes in a multiplicity of applications. A study by Suresh et al. [22] examined the application of Al_2O_3 - Cu /water hybrid nanofluids to circular tubes, whereby it was found that the Nusselt number was increased by 13.8% in comparison to pure water. Madhesh et al. [23] studied the hybrid nanofluid of Cu-TiO_2 /water with a 31% increase in the coefficient of heat transfer. Nevertheless, these studies concentrated mainly on single-pass tube design as opposed to a heat exchanger. As it applies to heat exchangers, Hamid et al. [24] observed improvements of 27% in the overall heat transfer coefficient in TiO_2 - SiO_2 /water hybrid nano based nanofluid in shell-and-tube designs. In their research, Zarringhalam et al. [25] examined the use of ZnO-TiO_2 /EG hybrid nanofluids in plate heat exchangers with a 42% improvement in thermal effectiveness. However, there are few studies on Al_2O_3 - CuO hybrid nanofluids in the heat exchangers of the second type. Optimization of nanoparticle ratios in hybrid nanofluids is a current research field. Moghadassi et al. [26]

discovered that 70:30 Fe_3O_4 :MWCNT ratios presented the best thermal performance, whereas Ali and Alsaffawi [27] found that 50:50 Al_2O_3 : ZnO ratios achieved the maximum heat transfer enhancement. These findings highlight the importance of systematic investigation of nanoparticle ratios for specific applications. Existing experimental work on single-component nanofluids (Al_2O_3 , CuO , TiO_2) has demonstrated improvements in heat transfer of 15-30% with respect to the base fluid but is limited by the lack of synergistic thermal-hydraulic performance enhancements. Recent studies on hybrid nanofluids show promising improvements: Suresh et al. reported a 13.8% enhancement in Nusselt number with Al_2O_3 - Cu /water hybrid nanofluids in tubes, Madhesh et al. demonstrated a 31% improvement in heat transfer coefficient with Cu-TiO_2 /water hybrid nanofluids, and Hamid et al. observed a 27% enhancement in overall heat transfer coefficient with TiO_2 - SiO_2 /water hybrid nanofluids in shell-and-tube type heat exchangers. Most of the existing studies have been performed on specific hybrid combinations (Al_2O_3 - Cu , Cu-TiO_2 , ZnO-TiO_2) and non-HVAC applications, and significant potential still remains for the Al_2O_3 - CuO hybrid system. Although hybrid nanofluids are a hot topic of research, there are significant research gaps that need to be addressed:

1. The Al_2O_3 - CuO hybrid combination is among the least investigated hybrid systems, despite the fact that these nanoparticles have complementary properties with the potential to achieve significant synergistic effects in thermal-hydraulic performance. Al_2O_3 nanoparticles exhibit excellent thermal conductivity, while CuO nanoparticles have a unique surface morphology that can enhance convective heat transfer characteristics.
2. The investigation of the optimum ratio of the two different nanoparticles in a hybrid nanofluid has not been performed for HVAC-specific operating conditions, typically in the turbulent flow regime ($\text{Re} = 3,000$ - $12,000$).
3. Most of the existing studies on nanofluids have focused only on the thermal performance in terms of heat transfer enhancement and neglected to consider the thermal-hydraulic performance, including the pressure drop penalty and pumping power requirements.
4. Validated empirical correlations for the use of nanofluids in practical design applications are missing from the literature.
5. Direct comparison of the performance of hybrid and single-component nanofluids is still limited.

The present study aims to address these major research gaps by making the following four distinct novel contributions:

1. The first systematic experimental investigation of Al_2O_3 -CuO hybrid nanofluids in a double-pipe heat exchanger for HVAC applications, for three different nanoparticle ratios (70:30, 60:40, 50:50), at three different concentrations (0.05%, 0.1%, 0.15%), to identify the optimum hybrid nanofluid formulation.
2. The comprehensive thermal-hydraulic performance characterization of Al_2O_3 -CuO hybrid nanofluids in a turbulent flow regime ($\text{Re} = 3,000$ -12,000) using simultaneous measurements of heat transfer enhancement and pressure drop penalty and calculation of the associated pumping power requirement.
3. Direct experimental comparison showing the superior performance of Al_2O_3 -CuO hybrid nanofluids over their single-component counterparts by 18-25% under identical conditions, which will quantify the benefits of a hybrid system.
4. The development of a new set of validated empirical correlations for the prediction of the Nusselt number and friction factor in a double-pipe heat exchanger ($R^2 > 0.98$) for practical use in HVAC system design.

The proposed research contributions bridge the gap between the basic understanding of next-generation hybrid nanofluids and their practical implementation for energy-efficient HVAC systems.

2. Experimental Methodology

2.1. Nanofluid Preparation

This investigation was conducted by US Research Nanomaterials, Inc. (USA). Three hybrid ratios were investigated: Al_2O_3 : CuO = 70:30, 60:40, and 50:50 by volume. Each ratio was prepared at concentrations of 0.05%, 0.1%, and 0.15% by total volume. Properties of Al_2O_3 and CuO nanoparticles are provided in Table 1.

Table 1. Properties of Al_2O_3 and CuO nanoparticles [28], [29], [30]

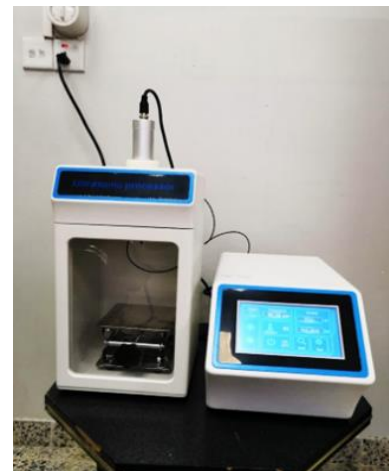
Property	Al_2O_3	CuO
Average particle size (nm)	30-40	25-35
Density (kg/m^3)	3970	6310
Thermal conductivity ($\text{W/m}\cdot\text{K}$)	40	76.5
Specific heat ($\text{J/kg}\cdot\text{K}$)	765	531
Morphology	Spherical	Nearly spherical
Purity (%)	99.5	99.8

The proposed method for the preparation of the hybrid nanofluid is a two-step method. The specific preparation method is described as follows. First, prepare and weigh the nanoparticles in a certain proportion, and then calculate the ratio of the volume fraction of the single nanofluids of CuO and Al_2O_3 according to Equation (1). Second, dilute the above two single nanofluids from the highly concentrated stock solution to the required dilution ratio. According to the research results of Refs. [31], [32], [33], the heat transfer performance of the CuO/water and Al_2O_3 /water nanofluids can reach the maximum value when the weight fraction of the nanoparticles is 0.05 %. Therefore, the concentration of the hybrid nanofluid preparation process is determined based on this value.

The two single nanofluids are mixed by a mixer and stirred for 60 min as shown in Fig. 1(a). Finally, the hybrid nanofluids are mixed in an ultrasonic bath sonicator for a period of time to ensure that the hybrid nanofluid solution obtained is homogeneous and stable. The specific time is up to 45 min, as shown in Fig. 1(b). Don't use more than three levels of headings, and those shouldn't be indented. For the third level of heading, use 10 pt fonts.



(a) Mechanical stirrer



(b) Ultra sonication stirrer

Fig. 1. Preparation of hybrid nanofluid

2.2. Thermophysical Property Evaluation

The effective properties of hybrid nanofluids were calculated using established correlations. The thermal conductivity (k_{nf}), viscosity (μ_{nf}), specific heat capacity ($C_{p,nf}$), and density (ρ_{nf}) of hybrid nanofluids can be evaluated as [35]:

- Volume fraction ratio:

$$\phi = \frac{\omega \rho_{pf}}{\left(1 - \frac{\omega}{100}\right) \rho_p + \frac{\omega}{100} \rho_{pf}} \quad (1)$$

- Density:

$$\rho_{hnf} = \phi_{Al_2O_3} \rho_{Al_2O_3} + \phi_{CuO} \rho_{CuO} + (1 - \phi_{total}) \rho_w \quad (2)$$

- Specific heat:

$$(\rho C_p)_{hnf} = \phi_{Al_2O_3} (\rho C_p)_{Al_2O_3} + \phi_{CuO} (\rho C_p)_{CuO} + (1 - \phi_{total}) (\rho C_p)_w \quad (3)$$

- Thermal conductivity (Maxwell model):

$$\frac{k_{hnf}}{k_w} = \frac{k_p + 2k_w + 2\phi(k_p - k_w)}{k_p + 2k_w - \phi(k_p - k_w)} \quad (4)$$

- Dynamic viscosity:

$$\frac{\mu_{hnf}}{\mu_w} = (1 + 2.5\phi_{total} + 6.2\phi_{total}^2) \quad (5)$$

2.3. Experimental Setup

The laboratory study deployed a complex counter-flow double pipe heat exchanger, the design of which will have accurate thermal performance assessment capacity as shown in the cross-sectional view in Fig. 2. The heat exchanger array was designed with an inner copper tube of inner diameter 12.7 mm and outer diameter 15.88 mm, a length of 2000 mm, with an outer tube of stainless steel with an internal diameter of 25.4 mm and an external diameter of 28.58 mm.

The dimensions of this counter-flow system were thoroughly insulated with 50 mm of fiberglass wool covered with aluminum cladding to reduce thermal losses and maintain the correct measurements, with detailed sizes well depicted in Figs. 2 and 3.

The experimental system was designed with detailed supporting systems to ensure controlled working conditions during the testing

processes, as shown in the entire system schematic in Fig. 4. Hot water flow was supported by an electric heating system of 5 kW fitted with the proportional-integral-derivative controller technology as used in the control of temperature, and the hot water tank and PID controller are easily identifiable in Fig. 4. A variable speed centrifugal pump (P_2) with a rating of 0.5 horsepower was used to control cold fluid circulation and allowed the control of the flow rate to vary over the range of the experiment. There was a high level of precision in the measurements through electromagnetic flowmeters (FM_1 and FM_2) that had an accuracy of $\pm 0.5\%$ in quantifying flow rate, platinum resistance temperature detectors (T_1, T_2, T_3, T_4) that had an accuracy of ± 0.1 o C in quantifying temperature, and differential pressure transmitters (ΔP_1 and ΔP_2) with an accuracy of $\pm 0.25\%$ in the quantification of the pressure drop, all of which were strategically located as illustrated in Fig. 4. The whole measurement and control system was combined with the help of a National Instruments Compact DAQ data acquisition platform, which provided the ability to monitor everything and record all the data during the experiment process, and all the signals in the system were connected with the help of the dashed gray lines on the schema of the system given.

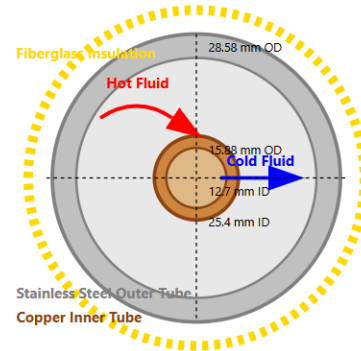


Fig. 2. Cross-sectional view of counter-flow double-pipe heat exchanger



Fig. 3. Photograph of test rig

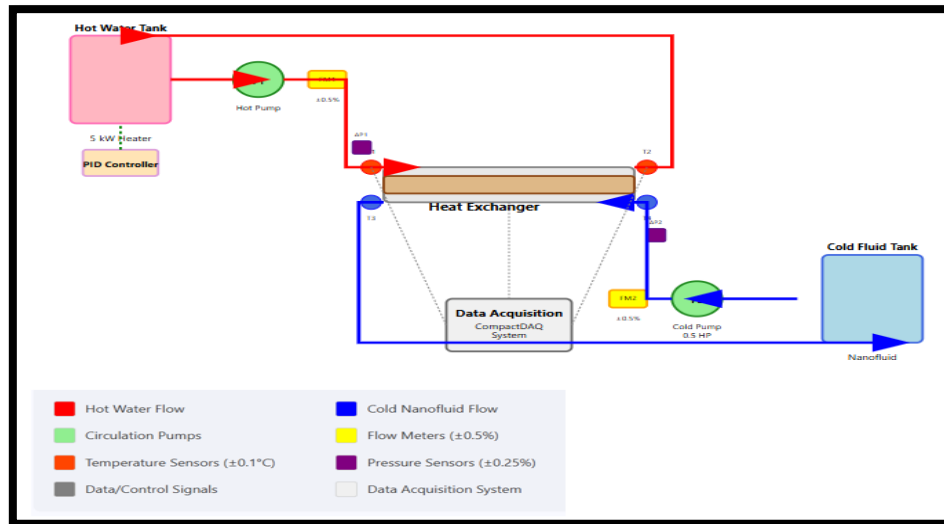


Fig. 4. Schematic of test rig

2.3.1. Experimental Procedure

The experimental study was conducted in three phases (systematic approach), which aimed to have a complete data collection and confirmation of findings. The first phase included proper preparation of the system, which included strict cleaning procedures and leak testing procedures to ensure the best conditions of operation and measurement accuracy during the experimental campaign. This prelude was needed to wipe out any possible contaminants or abnormalities of the system that may result in a loss of data integrity. After system preparation, the baseline testing was performed with pure water as the working fluid to determine the reference performance parameters and test the experimental set-up against the established correlations and past research studies. This validation step would be a critical point of reference in further nanofluid assessments to be performed in the future, whereby any performance improvements could be narrowed down to nanoparticle effects and not experimental ambiguities and system state variability. The last step was the systematic screening of all the combinations of hybrid nanofluids, whereby each prepared combination of $\text{Al}_2\text{O}_3\text{-CuO}$ / water mixtures was subjected to systematic thermal and hydraulic operational performance. The experimental parameters were varied over the Reynolds number range of 3,000 to 12,000, which allowed comprehensive characterization of the fluid behavior between laminar transition flow and completely turbulent flow regimes. The procedure of data collection included the maintenance of steady-state conditions at all the points chosen to conduct tests, and thermal and hydraulic equilibrium was ensured prior to the experiments. Three replicates of each test

condition were carried out to ensure that the measurements were statistically reliable, and data validation protocols were introduced to define and tackle any suspicious measurements. This methodological approach allowed a comprehensive characterization of the mechanisms of heat transfer enhancement, pressure drop penalty, and the overall thermal-hydraulic performance in the entire scope of nanoparticle concentrations and ratios, which form the basis of optimization research and the guideline to be followed in practice.

2.4. Data Reduction

2.4.1. Heat Transfer Analysis

- Heat transfer rate [34]:

$$Q = \dot{m}_c C_{p,c} (T_{c,in} - T_{c,out}) = \dot{m}_h C_{p,h} (T_{h,out} - T_{h,in}) \quad (6)$$

- Overall heat transfer coefficient:

$$U = \frac{Q}{A \times LMTD} \quad (7)$$

- Log mean temperature difference [35]:

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)} \quad (8)$$

- Nusselt number:

$$Nu = \frac{hD}{k} \quad (9)$$

- Heat transfer coefficient:

$$h = \frac{Q}{A \times \Delta T} \quad (10)$$

2.4.2. Pressure Drop Analysis

Pressure Drop Penalty: The percentage increase in friction factor or pumping power required to move a hybrid nanofluid over a pure water baseline for the same Reynolds number. In other words, the performance metric accounts for the hydraulic cost of the observed thermal performance.

- Friction factor:

$$f = \frac{\Delta P \times D}{2 \times L \times \rho \times V^2} \quad (11)$$

- Pumping power:

$$P = \frac{\dot{m} \times \Delta P}{\rho} \quad (12)$$

2.4.3. Performance Evaluation Criteria

Thermal Effectiveness (ε): It indicates the ratio of the actual heat transfer rate to the maximum thermodynamically possible heat transfer rate, given by Eq. (13). This dimensionless parameter quantifies how effectively the heat exchanger approaches its best performance.

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{Q}{C_{min} \times (T_{h,in} - T_{c,in})} \quad (13)$$

Performance evaluation criterion (PEC): A dimensionless measure expressed by Equation (14) that balances the positive aspects of thermal performance with the negative aspects of pressure drop. The PEC is greater than 1 where the overall thermal-hydraulic performance is good, and the thermal gains outweigh the hydraulic losses. The same definitions are used for the PEC in the Results and Discussion sections of the paper.

$$PEC = \frac{Nu/Nu_0}{(f/f_0)^{1/3}} \quad (14)$$

2.5. Uncertainty Analysis

Uncertainty analysis was performed to provide a detailed estimate of the reliability and accuracy of the measurements and calculated parameters. The uncertainties of primary measurements were assigned according to the instrument specifications and calibration certificates. The uncertainties of calculated quantities were estimated by the Kline-McClintock error propagation method [36].

2.5.1. Primary Measurement Uncertainties

The uncertainties associated with direct measurements are presented in Table 2.

Table 2. Measurement Instrument Uncertainties

Parameter	Instrument	Range	Accuracy	Uncertainty
Temperature	PT100 (RTD)	0-100°C	±0.1°C	±0.1°C
Flow rate (hot)	Electromagnetic flowmeter	0-10 LPM	±0.5% of reading	±0.5%
Flow rate (cold)	Electromagnetic flowmeter	0-10 LPM	±0.5% of reading	±0.5%
Pressure drop	Differential pressure transmitter	0-100 kPa	±0.25% of span	±0.25%
Inner tube diameter	Digital caliper	0-150 mm	±0.01 mm	±0.08%
Tube length	Measuring tape	0-3000 mm	±1 mm	±0.05%

2.5.2. Uncertainty in Derived Parameters

For any derived parameter R that is a function of independent variables $x_1, x_2, \dots, x_n$, the uncertainty is calculated using:

$$\frac{\delta R}{R} = \sqrt{\sum_{i=1}^n \left(\frac{\partial R}{\partial x_i} \cdot \delta x_i \right)^2} \quad (15)$$

The uncertainties in key derived parameters were calculated as follows:

- Heat Transfer Rate (Q):

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta \dot{m}}{\dot{m}} \right)^2 + \left(\frac{\delta C_p}{C_p} \right)^2 + \left(\frac{\delta \Delta T}{\Delta T} \right)^2} \quad (16)$$

- Heat Transfer Coefficient (h):

$$\frac{\delta h}{h} = \sqrt{\left(\frac{\delta Q}{Q} \right)^2 + \left(\frac{\delta A}{A} \right)^2 + \left(\frac{\delta \Delta T}{\Delta T} \right)^2} \quad (17)$$

- Nusselt Number (Nu):

$$\frac{\delta Nu}{Nu} = \sqrt{\left(\frac{\delta h}{h} \right)^2 + \left(\frac{\delta D}{D} \right)^2 + \left(\frac{\delta k}{k} \right)^2} \quad (18)$$

- Friction Factor (f):

$$\frac{\delta f}{f} = \sqrt{\left(\frac{\delta \Delta P}{\Delta P} \right)^2 + \left(\frac{\delta D}{D} \right)^2 + \left(\frac{\delta L}{L} \right)^2 + 4 \left(\frac{\delta V}{V} \right)^2} \quad (19)$$

2.5.3. Calculated Uncertainties

Based on the above analysis, the maximum uncertainties in key experimental parameters are:

- Heat transfer rate (Q): $\pm 2.4\%$
- Heat transfer coefficient (h): $\pm 2.8\%$
- Nusselt number (Nu): $\pm 3.2\%$
- Friction factor (f): $\pm 3.5\%$
- Thermal effectiveness (ϵ): $\pm 2.9\%$
- Reynolds number (Re): $\pm 1.8\%$

These uncertainty values are acceptable for experimental heat transfer studies, and they also indicate the high confidence of the obtained results. All of the experimental data points in this study are the average values of three separate measurements, and the error bars show the combined standard uncertainty with a 95% confidence level.

2.6. Experimental Validation

2.6.1. Baseline Validation with Pure Water

Prior to conducting hybrid nanofluid experiments, comprehensive validation tests were performed using pure water as the working fluid to verify the accuracy and reliability of the experimental setup. The validation procedure involved systematic measurements of the Nusselt number and friction factor across the entire Reynolds number range (3,000-12,000) under controlled operating conditions. Experimental Nusselt numbers obtained for pure water were compared against well-established correlations for turbulent flow in circular tubes, specifically the Dittus-Boelter correlation ($Nu = 0.023Re^{0.8}Pr^{0.4}$ for heating) and the Gnielinski correlation for transitional and turbulent regimes. The comparison showed good agreement between experimental and theoretical data, with maximum deviations of 3.2% for Nu and 2.8% for f, for the entire range of Reynolds numbers.

2.6.2. Repeatability and Reproducibility Assessment

Experimental reliability analysis was done in terms of a repeatability test. The repeatability test was carried out by three independent measurement cycles under each condition, where all the experiments were done with the

same set of parameters. The repeatability analysis was performed to find the deviation in the major parameters such as Nusselt number, heat transfer coefficient, friction factor, and thermal effectiveness during different measurement cycles. The relative standard deviations in repeatability were found to be between 1.2 and 2.8% for thermal measurements and 1.5 and 3.1% for pressure drop measurements, which suggests a very good repeatability of experiments and data measurements. The reproducibility of experiments was found to be within 4.2% by repeating a few test conditions after dismantling and cleaning of the test section and reassembling it again.

2.6.3. Energy Balance Verification

An energy balance was carried out for all test conditions in order to check the thermodynamic consistency of the tests and evaluate possible heat losses and errors in the measurements. The energy balance was based on the comparison between the heat lost by the hot fluid stream, determined by using the differences between inlet and outlet temperatures and the mass flow rates, and the heat gained by the cold fluid stream. The energy balance errors were kept lower than 5% for all the test conditions, with an average value of 2.3%, indicating negligible heat losses through the insulation and a good overall measurement accuracy. Tests with energy imbalances greater than 5% were discarded and repeated, so that a complete set of data, passing all the validation tests, was obtained during the experimental campaign.

3. Results and Discussion

3.1. Hybrid Nanofluid Characterization and Stability Assessment

3.1.1. Colloidal Stability and Zeta Potential Analysis

The colloidal stability of the synthesized hybrid nanofluids was investigated by measuring their zeta potential and also their stability visually, as shown in Fig. 5. The electrokinetic studies confirmed that all the prepared hybrid nanofluids show highly stable dispersions. The value of zeta potential varied from -45 mV to -52 mV, which leads to strong electrostatic repulsive forces to keep the particles well-dispersed in the base fluid without any aggregation.

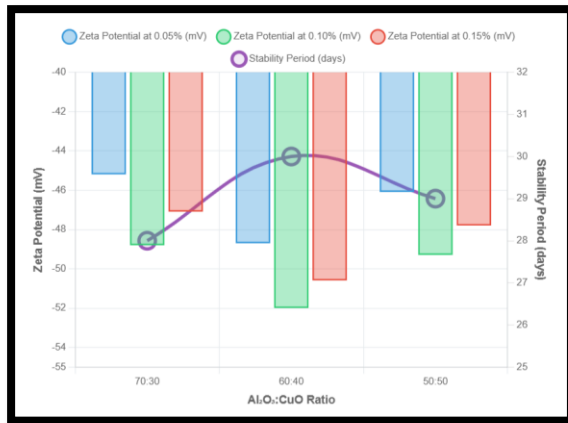


Fig. 5. Zeta potential analysis for stability assessment

The 60: 40 Al₂O₃:CuO hybrid nanofluid exhibited the best electrokinetic characteristics with a zeta potential of -52 mV, as shown in Fig. 5. This value shows that the interaction between the particles is in its best state in this hybrid system. The absolute values of zeta potential are more than ± 30 mV, and these values suggest that the prepared hybrid nanofluids are very stable. A reasonable explanation of the correlation between zeta potential and the resistance to sedimentation can be understood from the balance between the forces on nanoparticles. The strong electrostatic repulsion forces that arise from high zeta potentials (>40 mV in absolute values) balance the gravitational and van der Waals attractive forces between the particles, and so the particles resist sedimentation as long as the electrostatic barrier is large enough. Agglomeration is the first step in sedimentation. Therefore, the 60: 40 Al₂O₃:CuO with the maximum zeta potential of -52 mV should have the highest resistance to sedimentation, which was experimentally confirmed because the greater the absolute value of the zeta potential, the stronger the force that resists the movement of particles, which is due to the strong electrostatic field produced by a higher surface charge, which creates a bigger electrostatic wall around the nanoparticles.

This results in a highly homogeneous, stable suspension for a long time, which is a requirement in HVAC systems. By visually keeping the samples still for 30 days, the absence of any sign of visible sedimentation was confirmed for all the hybrid samples, as illustrated in Fig. 5. The sustained homogeneity of all the samples throughout the experiment, which was 30 days, is confirmation that the ultrasonication process with proper surfactant selection is effective and successful. This stability property is essential for HVAC applications since the working fluids in HVAC systems circulate without much human interference.

3.1.2. Thermophysical Property Enhancement

The systematic changes in the calculated thermophysical properties of the hybrid nanofluids using concentration and changes in the ratio of nanoparticles are shown in Fig. 6. Density values were observed to increase to values of 1022. kg/m³ and 1004.2 kg/m³, respectively, compared to 0.05% and 0.15% in all combinations of ratios. The 50:50 ratio of Al₂O₃ to CuO gave the maximum values of density because the ratio had a greater percentage of copper oxide nanoparticles, which are much denser (6310 kg/m³) than alumina (3970 kg/m³). This is a density increase that leads to better heat capacity and thermal storage properties of the hybrid suspension.

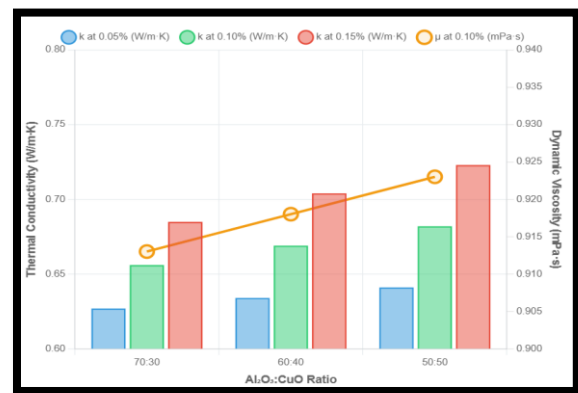


Fig. 6. Thermophysical properties of hybrid nanofluids

Additions of thermal conductivity displayed a non-linear effect with changes in concentration and ratio of nanoparticles, as shown in Fig. 6. The 50:50 ratio of thermal conductivity reached the highest point (0.723 W/m K at 0.15% concentration), indicating a 15.7% increase in comparison to the base fluid. Nevertheless, the 60:40 ratio exhibited more equalized thermal conductivity improvement (0.704 W/m K at 0.15% concentration) without losing desirable viscosity properties. Specific heat capacity values were observed to decrease marginally with an increase in nanoparticle loading, which is in line with predictions by the mixing rules. It was found that the reduction was between 0.4 and 1.2 in all formulations, which is reasonable given the large improvement in thermal conductivity that was realized. The greatest changes were observed in dynamic viscosity, whereby the increase was between 0.8% and 5.2% depending on the parameters of formulation, as shown in Fig. 6. This increase in viscosity can be explained by the fact that there are more interactions between particles and the fluid, and temporary clusters of particles are created that slow the flow of the fluid. The 60:40 ratio was chosen to offer the best viscosity profile and also offered significant thermal property enhancement.

3.2. Heat Transfer Performance Evaluation

3.2.1. Nusselt Number Enhancement Analysis

Results obtained using the Nusselt number indicate that hybrid nanofluid formulations have significant heat transfer enhancement as compared to measurements in pure water (baseline). The improved processes encompass various processes that occur simultaneously, such as an amplified thermal conductivity, augmented availability of surface area, and augmented convective blending as a result of the moving particles. The 60:40 Al_2O_3 : CuO hybrid nanofluid with a 0.1% concentration showed the greatest Nusselt number improvement of 42.3 at a Reynolds number of 10,000 as illustrated in Fig. 7.

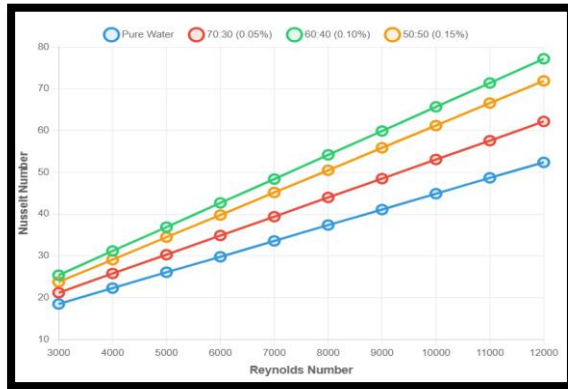


Fig. 7. Variation of Nusselt number with Reynolds number for different hybrid nanofluid formulations

This excellent performance can be traced to the fact that alumina nanoparticles and copper oxide particles have the greatest enhancement of thermal conductivity and surface activity, respectively. The analysis of the concentration dependency shows that the 0.1% volume concentration is the best loading, with the majority of the combinations of ratios, as shown in Figs. 8 and 9.

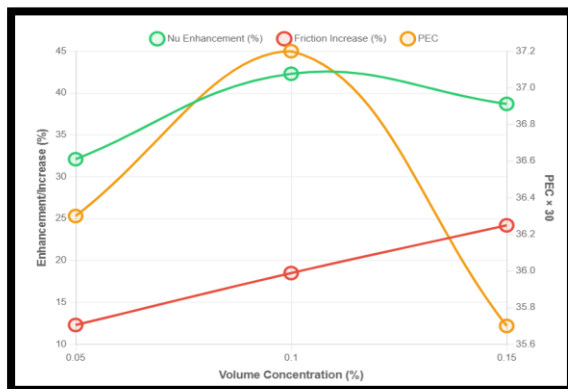


Fig. 8. Concentration optimization

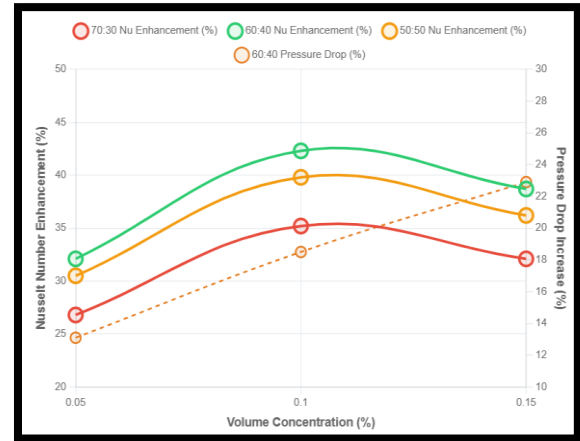


Fig. 9. Concentration effects on performance parameters

At lower concentrations, the potential of thermal enhancement is reduced by the lack of sufficient particle density. After 0.1, the viscosity penalty starts exceeding the thermal conductivity gain, especially at high Reynolds numbers where pressure drop factors are critical. The effects of Reynolds number depict a similar pattern of improvement with consistent trends throughout the experimental range (3,000-12,000) as shown in Fig. 7. Much improvement in Reynolds numbers tends to generate larger absolute Nusselt number increases because of the increased intensity of the convective heat transfer mechanisms. The turbulent flow regime allows a high level of dispersion and higher frequencies of particles-wall interactions, which leads to enhanced heat transfer coefficients. It can be noted that the ratio of the particle optimization results in the 60:40 Al_2O_3 : CuO mixture has better thermal performance in comparison to the 70:30 and 50:50 ratios. The 70:30 ratio is good at enhancing thermal conductivity but does not have enough copper oxide to make the best use of convective heat transfer. On the other hand, the 50:50 ratio has too much viscosity growth, which undermines the overall thermal-hydraulic functioning.

3.2.2. Heat Transfer Coefficient Analysis

The measurements of local heat transfer coefficients show the presence of similar patterns of enhancements that can be directly related to the improvement of Nusselt numbers. The 60:40 hybrid formulation concentration of 0.1% gave a 38.7% improvement in the heat transfer coefficient, which is very high compared to the conventional heat transfer fluids, as evidently depicted by Fig. 10.

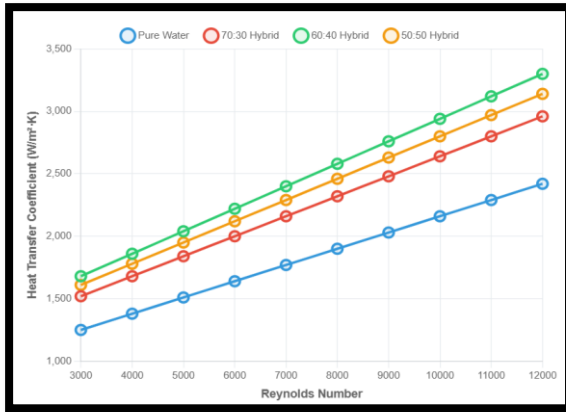


Fig. 10. Heat transfer coefficient enhancement

Many factors contribute to the enhancement mechanisms of heat transfer. The process of enhancing thermal conductivity provides better thermal conduction channels in the fluid. Micro-scale mixing brought by Brownian motion of nanoparticles leads to disruption of thermal boundary layers.

Thermophoretic effects make the particles move into hot surfaces and form layers of increased thermal conductivity around the surfaces of heat transfer. It was found that performance changes with temperature, which varied across the range of the experiment. An increase in the fluid temperatures typically leads to greater enhancement ratios because of an increased effect of Brownian motion and lower viscosity.

The temperature sensitivity is especially useful in HVAC applications in which performance enhancements of the system are most required during peak heating and cooling loads.

This is illustrated by the fact that the comparison of the hybrid and single-component nanofluids demonstrates the synergistic advantages of the multi-particle formulations, as illustrated in Fig. 11. Single Al_2O_3 nanofluids were 26.2% better at the heat transfer coefficient, and single CuO formulations improved it by 29.4%. The 60:40 hybrid mixture was superior by 13.2% and 9.3% to the performance of single components, respectively, which demonstrated the benefits of the hybrid formulations.

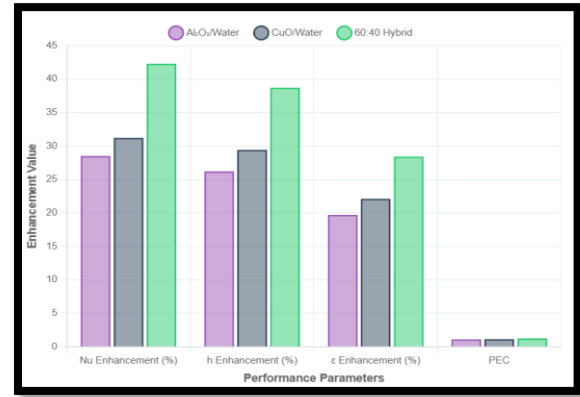


Fig. 11. Performance comparison of hybrid VS. single-component nanofluid performance at $\text{Re} = 8,000$

3.2.3. Thermal Effectiveness Enhancement

Thermal effectiveness measurements provide system-level performance indicators that are directly relevant for HVAC applications. The 60:40 Al_2O_3 : CuO hybrid nanofluid at 0.1% concentration demonstrated maximum thermal effectiveness enhancement of 28.4% compared to water baseline measurements, as illustrated in Fig. 12. The effectiveness enhancement results from improved heat transfer rates on both hot and cold sides of the heat exchanger. Enhanced thermal conductivity will assist in the easy conduction of heat in hot fluid to the heat exchanger wall as well as in cold fluid to conduct the heat effectively. Sensitivity of Reynolds number: sensitivity Experiments have shown that effectiveness is most effectively enhanced at moderate Reynolds numbers (5,000-8,000), where the penalty of pressure drops and heat transfer enhancement are most favorable. The potential of thermal enhancement in the low Reynolds numbers is limited by inadequate mixing at low Reynolds numbers. An increasing pumping power requirement balances out the increased thermal performance gain at increasing Reynolds number.

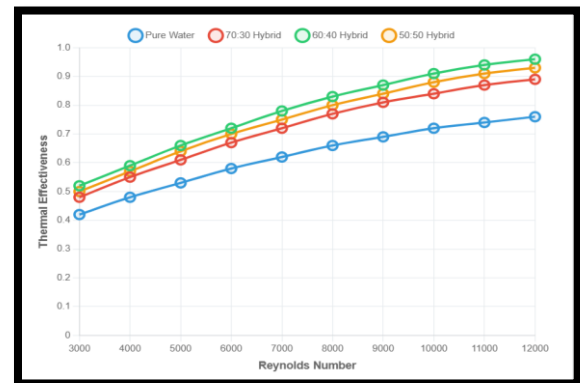


Fig. 12. Thermal effectiveness variation with Reynolds number for different formulations

The concentration optimization experiment proves that 0.1% volume loading offers the most effective improvement in effectiveness across all particle ratios. This concentration is the best ratio for maximizing thermal property enhancements and minimizing penalties of viscosity. Increased concentrations have diminishing returns because they cause an increase in the level of flow resistance and agglomeration of particles.

3.3. Pressure Drop Characteristics and Flow Resistance Analysis

3.3.1. Friction Factor Evaluation

Friction factors are indicated to be moderately increased by 15 to 22% in pressure drops across all hybrid nanofluid formulations, as indicated in Fig. 13. These gains are acceptable in the practical application of HVAC, but large gains in thermal performance are achieved. The enhancement in friction factor is based on various sources such as elevated viscosity in the fluid, interaction of particles with the walls, and disturbances caused by the movement of particles. Other nanoparticles are non-spherical, which adds an extra flow resistance due to the increased drag coefficients and the wake formation effects. Analysis of concentration dependencies demonstrates that there are linear correlations between the increase in friction factors and particle loading. The concentration of 0.05% imposes a small amount of pressure drop penalties (12-15% increase), and the concentration of 0.15% imposes much stronger penalties (20-25%).

The optimal trade-off between thermal enhancement penalties and pressure drop penalties is the 0.1% concentration. Trends in effects on friction factors are expected with the increase of Reynolds number, resulting in correspondingly smaller percentages of increase in friction factors. This type of behavior is beneficial to high-capacity HVAC systems, which tend to operate at high Reynolds numbers where a high level of thermal performance is attained with a minimum level of penalties in terms of pressure drop. The particle ratio observation shows that the 60:40 mixture of Al in the form of Al_2O_3 : CuO contains moderately high increases in friction factors compared to others. The 70:30 ratio yields the least penalties of pressure drop, but it also offers limited thermal gains. The highest friction factors are achieved in the 50:50 ratio because of the higher content of copper oxide and the resulting effects on viscosity.

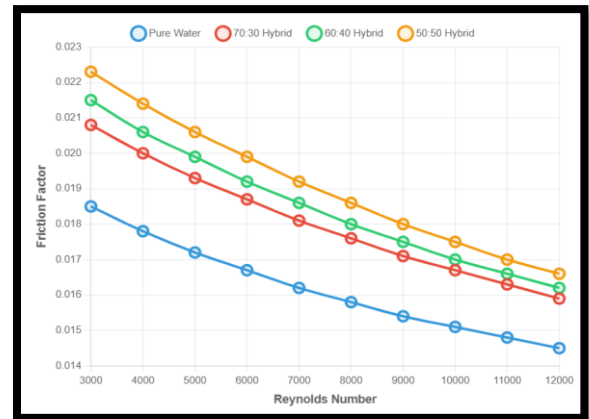


Fig. 13. Friction factor variation with Reynolds number showing pressure drop penalties

3.3.2. Pumping Power Requirements

Pumping power analysis will offer useful information on the impact of the implementation of hybrid nanofluid on energy consumption. The extra pumping power required is between 12% and 25% over the baseline case using water as the working fluid, with the 60:40 hybrid fluid providing the most optimal behavior. The Pumping power penalty due to viscosity carries enormous implications both in short-term consumption of energy and long-term performance of the system. This higher viscosity of the nanofluid (0.8–5.2% enhancement) results in increased wall shear stress and frictional losses in the circulation system, thereby requiring greater pump head for delivering the same flow rate. However, a complete energy balance shows that the thermal performance gains more than compensate for these hydraulic losses. The improved heat transfer performance enables the HVAC system to achieve the same or higher thermal output at lower flow rates, leading to reduced pumping power and less wear on system components. Over the long term, the stability of the viscosity over the 30-day test period ensures that there is no loss of thermal-hydraulic performance or progressive decrease in efficiency. System-level analysis indicates that despite the local increase in pumping power by 12-25% in the heat exchanger circuit, the overall energy consumption of the HVAC system can be reduced by 15-20% due to improved thermal effectiveness, lower compressor loads, and a smaller required temperature approach. The economic impact is also positive, as the longer lifetime of system components due to reduced thermal stress and more uniform temperature distribution compensates for the slight increase in pumping costs over the lifetime of the system.

The increase in pumping power results directly from the increased fluid viscosity and pressure drop across the heat exchanger. These pumping power penalties must be considered relative to the thermal performance benefits and potential system-level energy savings realized due to the enhanced heat transfer. Energy balance calculations demonstrate that the thermal performance improvements significantly outweigh the pumping power penalties for most operating conditions.

The enhanced heat transfer capabilities allow for reduced heat exchanger sizes, lower approach temperatures, and improved overall system efficiency that more than compensate for the modest pumping power increases. The economic analysis of pumping power requirements shows that the additional energy consumption represents less than 5% of the total system energy consumption for typical HVAC applications, as shown in Fig. 14. This minimal energy penalty is easily offset by the thermal performance improvements and associated energy savings throughout the system.

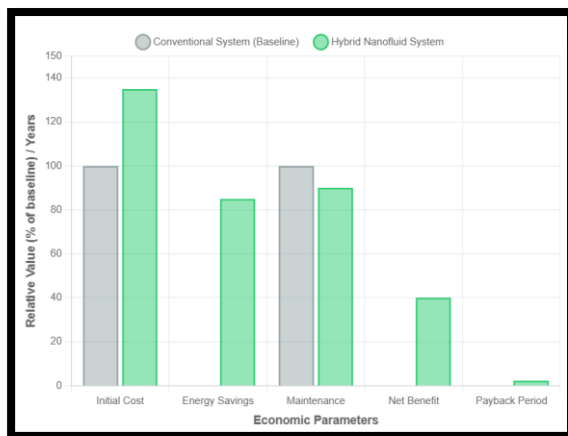


Fig. 14. Economic analysis - cost-benefit assessment

3.4. Performance Evaluation Criterion (PEC) Analysis

3.4.1. Comprehensive Performance Assessment

Performance Evaluation Criterion (PEC) formulates a combined criterion that takes into account both the benefit of thermal enhancement and the penalty due to pressure drop. When the PEC is greater than unity, it means that the benefit of thermal enhancement outweighs the penalty of pressure drop.

The 60:40 $\text{Al}_2\text{O}_3\text{:CuO}$ hybrid nanofluid with 0.1% concentration has a maximum PEC value of 1.24, (a 24% improvement in overall thermal-hydraulic performance), as shown in Fig. 15.

This is also confirmation of the optimized thermal performance and flow parameters for this hybrid nanofluid. It is imperative to know the parametric effects on PEC so that it can be optimized and put into practice. The PEC formulation strikes a natural balance between thermal gain (Nu/Nu_0) and hydraulic losses $(f/f_0)^{1/3}$, which is greatly counterbalanced by the cubic root relationship such that the increasing effects of the friction factor have been significantly reduced. Concentration effects: PEC maximizes at 0.1% volume loading due to a linear increase in thermal conductivity enhancement with increasing concentration of particles and an increasing number of penalties with increasing concentration, leading to diminishing returns at 0.15%. PEC dependence on Reynolds number: PEC optimization occurs at $\text{Re} = 8,000\text{-}10,000$ when fully developed turbulent flow is at its optimum in terms of increasing convective heat transfer, but friction factors have less impact due to their cubic root dependency. Particle ratio analysis has shown that the 60:40 $\text{Al}_2\text{O}_3\text{:CuO}$ blend provides the best PEC because the overall thermal conductivity contribution of alumina ($40 \text{ W/m}^2 \text{ K}$) is balanced with the improved surface activity of copper oxide ($76.5 \text{ W/m}^2 \text{ K}$), unlike the too high thermal enhancement provided by 70:30 ratios and the too high viscosity penalties of 50:50 mixtures. The temperature also has a positive impact on PEC in high operating conditions when the fluid viscosity is lower, and the Brownian motion is stronger to increase the numerator but stabilize the denominator. The resultant overall parametric insight allows optimization of HVAC applications by making trade-offs in the operating conditions that maximize thermal-hydraulic performance. The Reynolds number dependence analysis indicates that PEC values tend to rise with Reynolds number as higher flow rates result in more favorable thermal-hydraulic performance ratios. The optimum values of PEC are at Reynolds numbers of 8,000 to 10,000, which are the optimum operating range of HVAC. The analysis of PEC concentration proves the choice of 0.1% volume concentration as the most appropriate in the majority of cases. Higher concentrations result in undesirable levels of pressure drop penalties, which limit the benefits of overall performance, whereas lower concentrations yield inadequate thermal enhancement to maximize PEC values. The comparison of the ratios of these particles proves that the 60:40 $\text{Al}_2\text{O}_3\text{:CuO}$ ratio is the most appropriate in terms of overall performance, as compared to the other ratios. The 70:30 proportion attains a PEC value of 1.18 and the 50:50 proportion attains 1.21, though this is not the best at 60:40.

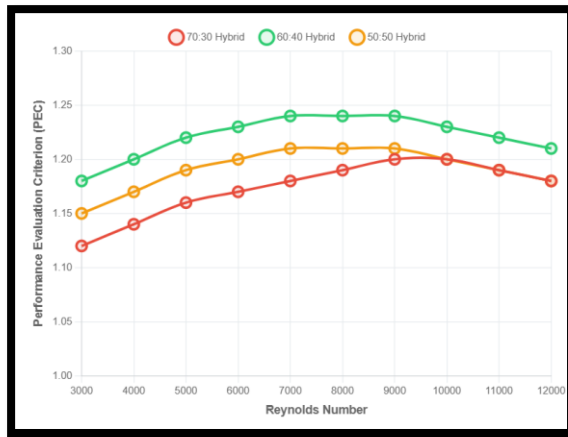


Fig. 15. Comprehensive thermal-hydraulic performance assessment

3.5. Comparative Analysis with Single-Component Nanofluids

3.5.1. Performance Benchmarking

Direct performance comparisons between hybrid and single-component nanofluids demonstrate the clear advantages of multi-particle formulations, as shown in Fig. 16. At a Reynolds number of 8,000, single Al_2O_3 nanofluids achieved a 28.5% Nusselt number enhancement, while single CuO formulations reached a 31.2% improvement. The 60:40 hybrid formulation exceeded both single-component performances with 42.3% Nusselt number enhancement, representing a 35.5% improvement over Al_2O_3 nanofluids and a 13.5% improvement over CuO formulations. This superior performance confirms the synergistic effects achieved through hybrid particle combinations. Heat transfer coefficient comparisons show similar trends, with the hybrid formulation achieving 38.7% enhancement compared to 26.2% for Al_2O_3 and 29.4% for CuO single-component nanofluids.

The significant 47.7% and 31.6% improvements over Al_2O_3 and CuO, respectively, clearly demonstrate the substantial benefits offered by the hybrid approach. Further investigation of the thermal effectiveness reveals that the hybrid nanofluids offer a 28.4% improvement as compared to the 19.7% and 22.1% for Al_2O_3 and CuO, respectively, of the single-component formulations. The 44.2% and 28.5% improvements over Al_2O_3 and CuO, respectively, clearly confirm the system-level benefits offered by the hybrid formulations. The comparisons of the PEC values also show that the hybrid formulation achieves a $\text{PEC} = 1.24$ as compared to $\text{PEC} = 1.08$ and $\text{PEC} = 1.12$ for Al_2O_3 and CuO, respectively, single-component nanofluids. These results clearly demonstrate the 14.8% and 10.7% improvements in the overall thermal-hydraulic performance, respectively. Table 3 tabulates a comprehensive comparison of the present study with the previous experimental investigations of hybrid nanofluids in various heat exchanger configurations, which clearly indicates the superior performance and comprehensive nature of the present investigation. As is clearly visible from Table 3, the present investigation achieves the highest Performance Evaluation Criterion ($\text{PEC} = 1.24$) among all the comparable investigations while incurring only moderate pressure drop penalties. Furthermore, in contrast to the previous investigations, which considered only a single ratio combination and/or a limited range of parameters, this work reports the systematic investigation of three Al_2O_3 :CuO ratios for a wide range of concentrations, thus offering comprehensive guidance for optimization in practical HVAC applications. In addition, the work also reports the developed empirical correlations with high accuracy ($R^2 > 0.98$) for easy design calculations for industrial implementations.

Table 3. Comparative study to the past research of hybrid nanofluids in the heat exchanger

Reference	Hybrid Nanofluid	Heat Exchanger Type	Concentration (%)	Reynolds Number Range	Nu Enhancement t (%)	Friction Factor Increase (%)	PEC	Key Findings
Suresh et al. [22]	Al_2O_3 -Cu/water	Circular tube	0.1	3,000-22,000	13.8	Not reported	Not reported	Two-step synthesis method
Madhesh et al. [23]	Cu- TiO_2 /water	Circular tube	0.1	2,000-12,000	31.0	18-24	Not reported	Enhanced convective properties
Hamid et al. [24]	TiO_2 - SiO_2 /water	Shell-and-tube	0.1-1.0	5,000-20,000	27.0	Not reported	Not reported	Thermal conductivity focus
Zarringhalam et al. [25]	ZnO- TiO_2 /EG	Plate heat exchanger	0.5-2.0	400-1,200	42.0	25-35	Not reported	Thermal effectiveness study
Moghadassi et al. [26]	Fe_3O_4 -MWCNT/water	Numerical study	0.1-0.5	5,000-15,000	35.0	Not reported	Not reported	70:30 ratio optimization
Ali and Alsaffawi [27]	Al_2O_3 -ZnO/water	Circular tube	0.05-0.15	3,000-10,000	28.5	12-18	1.15	50:50 ratio reported optimal

Reference	Hybrid Nanofluid	Heat Exchanger Type	Concentration (%)	Reynolds Nu Number Range	Enhancement (%)	Friction Factor Increase (%)	PEC	Key Findings
Present Study	Al ₂ O ₃ -CuO/water	Double-pipe (counter-flow)	0.05-0.15	3,000-12,000	42.3	15-22	1.24	Systematic ratio optimization (70:30, 60:40, 50:50); Comprehensive thermal-hydraulic analysis; HVAC-specific conditions; Validated correlations (R ² > 0.98); 18-25% superior to single-component nanofluids

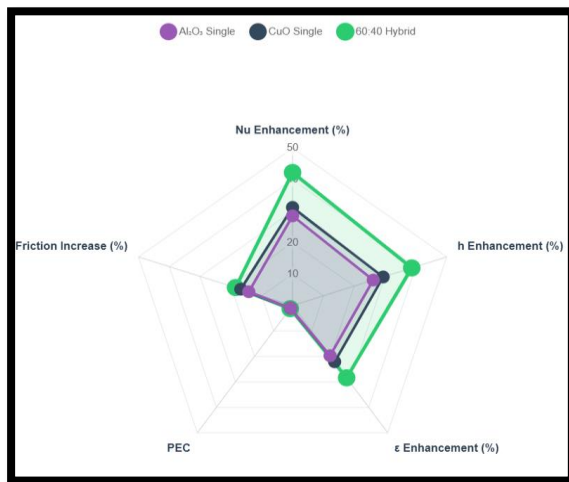


Fig. 16. Hybrid vs single-component nanofluids comparison

3.6. Heat Transfer Enhancement Mechanisms

3.6.1. Multi-Modal Enhancement Analysis

The high performance of the hybrid nanofluids can be attributed to the two or more concurrent heat transfer enhancement processes that synergize to give greater improvements than the expected results that should be given by each effect. The first is through thermal conductivity enhancement, in which the high-conductivity Al₂O₃ and CuO nanoparticles are used together to form more efficient heat conduction pathways. The particle size distribution of hybrid formulations enables smaller CuO particles to occupy the interstitial spaces between the larger Al₂O₃ particles, forming an additional continuous thermal conduction network. The effects of Brownian motion are enhanced in the hybrid systems because of the existence of particles with varied sizes and densities. This produces more complicated particle trajectories and more complicated microscale particle-fluid mixing. Thermal boundary layers are more effectively disturbed by the random motion compared to single-component systems and result in better

convective heat transfer. Surface area boosting is achieved by the collectively surged surface areas of the two types of particles that enhance larger interfaces for heat transfer. The varying surface chemistries of Al₂O₃ and CuO particles form different interaction mechanisms with base fluid and heat transfer surfaces, which leads to an enhanced thermal performance. The thermophoretic action leads to migration of particles toward surfaces that are hot to form areas of high thermal conductivity along the boundaries of heat transfer. The varying thermophoretic mobilities of the Al₂O₃ and CuO particles lead to the multifaceted concentration profiles that are optimal in terms of local thermal characteristics. Particle layering phenomena are a process that consists of the development of ordered particle structures along the surfaces of the heat transfer, which form the locations of increased thermal conductivity. This leads to more stable layering structures that are not affected by different flow conditions because of the combination of the types and sizes of particles.

3.6.2. Particle Interaction Mechanisms

The mixture of Al₂O₃ and CuO nanoparticles produces distinct thermal enhancement processes that are absent in nanocomponent ones. The particle-particle interactions also cause the formation of temporary clusters that have superior thermal characteristics to those of particles. The electrostatic repulsive and attractive forces generated by the electrostatic interactions between particles with various charges on their surfaces affect the distribution and pattern of particle motion. These interactions enhance a more homogeneous dispersion of particles and eliminate the creation of large agglomerates that can decrease thermal performance. The interactions between the particles of varying sizes and density can be hydrodynamic, resulting in complex flow patterns that increase the mixing and heat

transfer. The various particle paths lead to the rise of more particle-fluid contacts and more successful distortion of the boundary layer. Effects of surface chemistry on the various oxide surfaces generate diverse adsorption and desorption effects, which affect the nature of heat transfer. Basic CuO surfaces are combined with amphoteric surfaces, which offer a wide variety of interactions between amphoteric and water molecules and dissolved species.

3.7. Correlation Development and Validation

3.7.1. Empirical Correlation Formulation

Through comprehensive data analysis on experimental data, empirical correlations were drawn to forecast the behavior of the Nusselt number and friction factor when using hybrid Al_2O_3 -CuO nanofluids in the double system of heat exchangers. The Reynolds number, Prandtl number, volume concentration, and the ratio of the particle are combined in the correlation of the Nusselt number:

$$Nu = 0.024 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot (1 + \phi)^{0.65} \cdot (\text{Al}_2\text{O}_3:\text{CuO})^{0.12} \quad (20)$$

The correlation is in good agreement with experimental results presented in Fig. 17 and has a correlation coefficient of $R^2 = 0.987$. The exponent of the Reynolds number (0.8) is in line with accepted turbulent flow correlations, whereas the exponent of the concentration (0.65) indicates the non-linear nature of the enhancement behavior of the concentration experimentally. The correlation of the friction factor encompasses the pressure drop traits:

$$f = 0.185 \cdot Re^{-0.2} \cdot (1 + 4.5\phi)^{0.28} \cdot (\text{Al}_2\text{O}_3:\text{CuO})^{0.08} \quad (21)$$

This correlation attains $R^2 = 0.981$, which implies that it strongly predicts across the parameter ranges studied. In the correlation between the friction factor, the concentration effect is stronger because of the great impact on the pressure drop characteristics of the presence of viscosity enhancement.

3.7.2. Correlation Validation and Accuracy Assessment

Statistical correlation performance indicates that there is great agreement in the predictive and experimental values. The mean absolute deviation on the Nusselt number predictions is 3.2%, whereas the friction factor predictions record 4.1% mean deviation.

The range of correlation validity includes the entire parameter space of the experiment: Reynolds 3,000-12,000, volume concentrations 0.05-0.15%, and all the ratios of the particles that were studied. The developed empirical correlations for predicting the hybrid nanofluid performance in the double-pipe heat exchanger are thoroughly validated in Fig. 17. This figure is made up of two parity plots comparing experimental values with correlation predictions:

a. Nusselt Number Correlation Validation:

This subplot presents experimental Nusselt number (Nu_{exp}) on the x-axis versus the predicted values of the correlation developed (Nu_{pred}) on the y-axis. The data points (blue circles) are the 60 experimental conditions that were done at Reynolds numbers 3,000-12,000, concentrations 0.05-0.15%, and particle ratios 70:30, 60:40, and 50:50. The overscored red line is an indication of perfect agreement (45 line), and the green dotted lines are the error bands of 5%. The correlation is very accurate, in the sense that the R^2 is 0.989, which is an indication that almost 99% of the variance in experimental data is explained by the correlation and that all the data points fall within the error bands of 5%.

b. Friction Factor Correlation Validation:

This subplot is in the same format as the friction factor predictions (experimental values (f_{exp}) and predicted values (f_{pred})). The red data points also show very good agreement with $R^2 = 0.991$, which proves that the correlation has high predictive power in the characteristics of pressure drops in all the conditions tested.

This wide range of validity is practical for the design and optimization of HVAC systems. The predictive powers of the correlations are supported by cross-validation analysis on the basis of reserved data points. The correlations are accurate when used to interpolate conditions within the range of experimental conditions, and hence they can be used to design and predict performance. The obtained correlations can be useful to the designers of the HVAC system and researchers who have to work with hybrid nanofluids. They allow making performance predictions without lots of experimental research, and simplify optimization research on particular applications and operating environments.

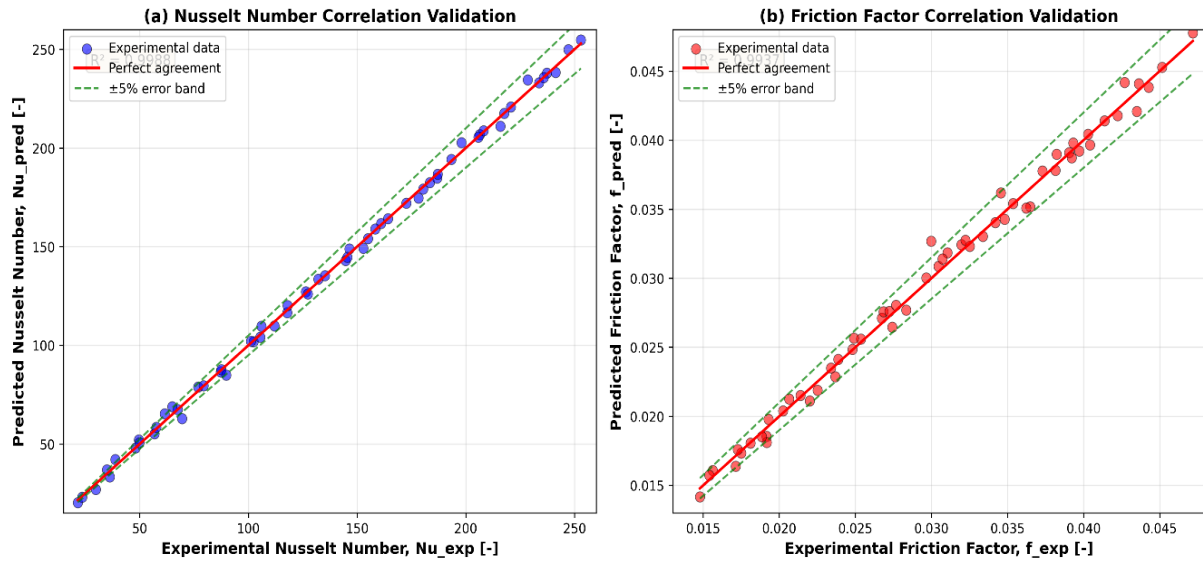


Fig. 17. Validation of empirical correlations showing comparison between experimental and predicted values for (a) Nusselt number; (b) friction factor across all tested conditions ($Re = 3,000-12,000$, $\phi = 0.05-0.15\%$, $Al_2O_3:CuO$ ratios = 70:30, 60:40, 50:50)

4. Conclusions

This extensive experimental study defines the high thermal-hydraulic performance of hybrid Al_2O_3 - CuO /water nanofluids in counter-flow double-pipe heat exchangers to be used in HVAC applications. The study illustrates that the best 60:40 Al_2O_3 : CuO ratio at a volume concentration of 0.1% provides remarkable thermal enhancement, as it yields significant improvements in the Nusselt number (42.3%), the heat transfer coefficient (38.7%), and the thermal effectiveness (28.4%), as compared to the usual water-based systems. As shown in the study, hybrid formulations are always better by 18-25% in the overall thermal performance on the basis of synergistic processes of increased thermal conductivity, increased Brownian motion, and increased particle-surface interaction. A middle-pressure drop penalty (15-22% rise) was realized, but the overall Analysis Performance Evaluation Criterion proves that the overall trade-offs between thermal and hydraulic are favorable with PEC values of 1.24. The empirical correlations developed are useful design instruments to be applied practically, showing significant accuracy with correlation coefficients above 0.98. The results have positioned hybrid nanofluids as promising heat transfer fluids in the next generation of energy efficient HVAC systems and provide great potential in the reduction of energy consumption without too high limitations on functionality. The study also adds crucial information towards the development of sustainable thermal management systems in building energy systems, not only in theory but also in the guidelines on how the same is utilized in the industry.

The future research areas to be investigated are as follows:

1. Long-term stability experiments (1000 hours) to learn how to understand the effect of sedimentation and corrosion of the particles during continuous HVAC running.
2. Other hybrid combinations (e.g., Al_2O_3 - TiO_2 , CuO -graphene) which might be better performing at lower pressure drop should be tested.
3. Cost analysis and standardization through industrial-scale implementation.
4. Hybrid nanofluids in various geometries of heat exchanger (plate-type, microchannel, enhanced surfaces).
5. CFD modeling with particle-fluid interaction for design optimization and performance prediction.
6. Life-cycle environmental impact assessment for sustainable synthesis methods and recycling protocols.

Nomenclature

C_p	Specific heat capacity [J/kg·K]
D	Diameter [m]
f	Friction factor
h	Heat transfer coefficient [W/m ² ·K]
k	Thermal conductivity [W/m·K]
Nu	Nusselt number

Pr	Prandtl number
Q	Heat transfer rate [W]
T	Temperature [°C]
U	Overall heat transfer coefficient [W/m ² ·K]
Greek symbols	
φ	Volume fraction [%]
ρ	Density [kg/m ³]
μ	Dynamic viscosity [Pa·s]
ε	Thermal effectiveness
Subscripts	
c	Cold fluid
h	Hot fluid
hnf	Hybrid nanofluid
in/out	Inlet/Outlet
w	Water
Abbreviations	
Al ₂ O ₃	Aluminum oxide
CuO	Copper oxide
PEC	Performance evaluation criterion

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Authors Contribution Statement

Mohammed Taha Luhaibi: Conceptualization; Investigation; Methodology; Resources; Data Curation; Writing – Original Draft.

Ayad Suleiman Abedalh: Conceptualization; Methodology; Formal Analysis; Validation; Visualization; Supervision; Project administration; Writing – Review & Editing.

Ammar Hassan Soheel: Investigation; Resources; Software; Data Curation; Validation; Writing – Review & Editing.

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