



# INVESTIGATING HEAT TRANSFER EFFICIENCY IN PLATE HEAT EXCHANGERS WITH HYBRID NANOFLUIDS

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## ABSTRACT

Plate heat exchangers (PHE) were initially used commercially and have since been used extensively in many industrial applications. Improving PHEs' thermal-hydraulic performance is essential for energy conversion and system economy enhancement by reducing capital expenditure. Using heat transfer (HT) enhancement techniques or adjusting the design of a PHE is two ways to increase its efficiency. The goal of this research is to use hybrid Aluminum oxide with Magnesium oxide (Al<sub>2</sub>O<sub>3</sub>-MgO) nano fluids to increase the HT efficiency of PHEs. It requires examining how concentration, composition, and flow factors affect thermal performance. Key performance indicators of Coefficient of Performance (COP) (5.43), Heat Transfer Area (HTA) (1.92), Energetic Efficiency (EE) (41.7), Performance Index (PI) (225), and Thermal Performance (TP) (1.6) were compared with suggested Al<sub>2</sub>O<sub>3</sub>-MgO with other fluid composites. The findings show that the Al<sub>2</sub>O<sub>3</sub>-MgO nano fluid is a good choice for enhancing heat exchangers' thermal performance. The studies could concentrate on examining the economic viability and long-term stability of employing hybrid nano fluids in industrial settings.



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## 1. INTRODUCTION

Heat transformers (HT) are an essential section of the developed transportation, power generation, and processing sector. The necessity for power conservation with the growing use of renewable power sources has been spurred by environmental concerns over the past few decades over waste disposal, thermal, air, and water pollution (Khodadadi & Sheikholeslami, 2022). More compact heat exchangers have been developed as a

result of these facts, which have also raised the importance of using high-efficiency heat exchangers. Because of their effectiveness, low cost, versatility in design, and compactness, plate heat exchangers (PHEs), which fall at the lesser end of the compression range, are frequently utilized in many industrial applications (Marseglia et al., 2023). Chevron corrugation is one of the plate patterns that have been the most popular over the past few decades, and most manufacturers provide it. Several methods have been used on the structure of

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PHEs with chevron corrugation, wherever the various geometrical characteristics are quite important (Perumal et al., 2022). The findings of these approaches generally show that geometrical parameters have a major impact on PHE performance, and achieving the ideal plate geometrical arrangement is one way to improve performance (Jalili et al., 2022). Research on HT improvement strategies in PHEs has been growing, aiming to employ various enhancement approaches to progress the concert of PHEs instead of concentrating just on the best design for chevron corrugation PHEs (Ajeeb et al., 2023). Increasing the HT coefficient is the standard term for HT enhancement, though it can also mean reducing the approach temperature difference, and increasing the capacity of shrinking the size of the equipment for a given responsibility (Alteneiji et al., 2022). Depending on whether or not exterior power is needed, the HT improvement strategies can be categorized as either active or passive. The application of the unreceptive exterior approach, nano fluids, and other improvement techniques in PHEs has been documented in the literature, demonstrating their significant potential to enhance the PHEs. The background encourages the inclusion of two features in an overview: the geometrical properties of the chevron corrugation and the application of HT enhancement strategies in the PHEs (Luo et al., 2022). Since chevron-corrugated surfaces are the most widely utilized technology on the market at the moment, they must be distinguished from enhancement techniques even if they could also be viewed as a type of submissive exterior approach when contrasted to flat surfaces. Only a handful of previous evaluation techniques addressed the geometrical features of the chevron corrugation and the application of HT improvement techniques (Sheikholeslami et al., 2022). PHE are widely used in industrial applications due to their high thermal efficiency and compact design. They play a crucial role in industries such as power generation, chemical processing, and HVAC systems, where efficient heat transfer is essential for optimal performance and energy savings. Enhancing HT in PHEs is vital for improving overall energy efficiency and reducing operational costs. One promising approach to improving HT in PHEs is the use of hybrid nanofluids. These are engineered fluids that combine two or more types of nanoparticles in a base fluid, leading to enhanced thermal conductivity and improved convective HT. Hybrid nanofluids have demonstrated superior thermophysical properties compared to conventional nanofluids, making them a viable solution for advanced thermal management applications. Analyzing their thermal performance, pressure drop, and overall effectiveness can highlight the potential benefits of hybrid nanofluids in optimizing heat exchanger operations and advancing energy-efficient thermal systems. Understanding these effects can contribute to the development of more efficient and sustainable HT technologies in various industrial applications.

The limitations of investigating HT efficiency in plate HT with hybrid nanofluids include challenges in nanoparticle stability, potential agglomeration, and increased viscosity, which can lead to higher pressure drops. Experimental setups may require precise control of nanoparticle concentration and uniform dispersion. Moreover, the long-term effects of nanofluids on heat exchanger materials, such as corrosion or fouling, remain uncertain. Computational modeling can be complex due to the non-Newtonian behavior of some nanofluids. Additionally, cost and scalability issues may limit real-world applications. Limited standardized data also pose challenges in validating experimental and numerical results for practical implementation. The aim is to enhance the heat transfer efficiency of plate heat exchangers by utilizing hybrid  $\text{Al}_2\text{O}_3$ -MgO nanofluids, optimizing thermal performance while addressing potential limitations.

In a nuclear reactor, nanofluids could function as either the primary coolant or the emergency coolant, as discussed by (Borhani et al., 2024). The nanofluid's thermo-hydraulic performance was examined in a high-pressure test loop that can withstand pressures of up to 25 bars. A cosine heat flow pattern was produced by the circular shape of the test section. The cores of nuclear reactors are represented by this flux pattern. Kamsuwan et al. (2023) provided a novel approach to HT employing nanofluid in an HT that combines with traditional progression replication. Furthermore, the sensitivity of the design and rating criteria for heat exchangers was examined. Ain et al. (2024) utilized numerical analysis to examine a horizontal magnetizing field in a new star-shaped enclosure in water as the base fluid. The sustainability of employing a nano composite made of Graphene Nano platelets (GNPs) and multi-walled carbon nanotubes (MWCNTs) for thermal engineering applications was examined by (Tao et al., 2024). Water was used to defer the mixture of nano composites at dissimilar volumetric concentrations. By examining laminar HT in swirling fluid dynamics, Patil et al. (2024) proposed to improve the HT efficiency of heat exchangers using Graphene oxide (GO)-based nano fluids. While hybrid nanofluids were used as a coolant, Alklaibi et al. (2024) proposed to experimentally examine the performance of PHEs. Its hybrid nano fluids based on water were made, and experimental estimates of their thermo physical characteristics were made. To evaluate the potential for improved performance, (Iyer et al., 2022) statistically calculated the friction factors and Nussle numbers in the laminar flow regime to characterize the flow and heat transfer properties based on structures. It was the first to assess the HT. It also contributed to the quantitative information on the thermal and flow characteristics that is currently accessible. Tu et al. (2022) claimed that to improve the energy consumption rate, numerical simulation should be used to examine the flow surrounding the channel of HT. The channel of HT has the finest presentation, according to the results, and nano fluids can enhance an HT's overall performance.

The objective of the research is to assess the HT efficiency of PHEs using hybrid Aluminum oxide with Magnesium oxide ( $\text{Al}_2\text{O}_3\text{-MgO}$ ) nano fluids. To optimize the hybrid nanofluid mixture for increased energy efficiency, it is necessary to determine the flow parameters, concentration, and nanoparticle composition on thermal performance.

The numerically investigates the flow and HT characteristics of pillow-plate HT with hybrid nanofluids was suggested by Roueintan & Fattahi, (2024). It looks at how wave amplitude, the wavelength, Reynolds coefficient, and the nanofluid volume percentage affect hydrodynamic and thermal performance. An artificial neural network model was employed to predict performance efficiently. Using wavy plates and hybrid nanofluids increased the Nusselt number by 12–42% with a minor 10% rise in pressure drop. Performance evaluation criteria (PEC) values exceeded unity, reaching a maximum of 1.8. Alhuyi Nazari et al. (2024) were evaluated the performance improvement of a fin–plate heat exchanger using hybrid nanofluid ( $\text{MWCNT-Fe}_3\text{O}_4/\text{water}$ ) and a winglet vortex generator (VG) at different angles through numerical simulations with SST turbulence models. The findings revealed that nanofluid enhanced HT by increasing thermal conductivity, while VG improved it by reducing the boundary layer and intensifying turbulence. The highest heat transfer improvement was 74.6% when both techniques were combined.

The thermal performance of  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  nanofluids (NFs) in a compact plate heat exchanger (CPHE) through numerical and experimental analyses was investigated by Ajeeb & Murshed (2022). The results indicated that adding nanoparticles enhanced CPHE performance. The maximum variance of 12% at the maximum flow rate, numerical models revealed convection HT coefficients that were lower than experimental data. The numerical model demonstrated acceptable accuracy, improving for lower nanoparticle concentrations and lower flow rates. Aytaç et al. (2023) were enhanced the thermal effectiveness of a concentric U-tube heat exchanger (HE) by investigating the effects of different turbulator modifications and nanofluids, including single and hybrid  $\text{Al}_2\text{O}_3\text{-SiO}_2/\text{water}$  nanofluids. Numerical findings showed that turbulators improved heat transfer but increased pressure drop, with quarter-circular ones causing less resistance. Experimentally, hybrid nanofluid enhanced HT the most, achieving a 58.97% increase in overall heat transfer coefficient compare to distilled water.

## 1.1 Problem Statement

Heat exchangers play a crucial role in industrial applications, and improving their efficiency is essential for energy conservation and performance enhancement. Traditional heat transfer fluids often exhibit limitations in thermal conductivity, reducing overall heat exchanger

efficiency. The combination of more than one nanoparticles in the base fluid results in hybrid nanofluids, which have the latent to improve HT performance and offer better thermal properties. Their use in PHEs, however, is still not well understood.

The heat transfer efficiency of PHEs using hybrid nanofluids, analyzing their thermal performance, pressure drop, and overall effectiveness to optimize heat exchanger design for industrial applications.

The following structures constitute the study's organization: The study's materials and methodology are included in Part II. The study's results and discussion are presented in Part III, and the conclusions are covered in Part IV.

## 2. METHODOLOGY

$\text{Al}_2\text{O}_3$  (46 nm) and  $\text{MgO}$  (21 nm) nanoparticles are mixed with de-ionized water to create the  $\text{Al}_2\text{O}_3\text{-MgO}$  hybrid nanofluid. To ensure homogeneity, mechanical stirring and ultrasonic agitation are then used. Utilizing Transmission Electron Microscopy (TEM), the size, shape, and dispersion of the particles are examined. In a heat exchanger system, the hybrid nanofluid serves as a coolant. Isothermal baths, flow meters, and manometers are used in hot and cold fluid loops to control temperature and flow. Fluid flow is controlled by a control valve, and pressure drops throughout the system are tracked by differential manometers. Figure 1 represents the methodology flow.

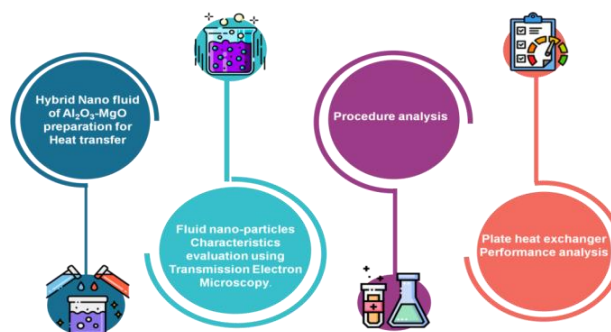


Figure 1. Method flow

### 2.1 Hybrid nanofluid of $\text{Al}_2\text{O}_3\text{-MgO}$ preparation

The two-stage procedure was used to create the hybrid nanofluid, with the first step being the characterization of the nanoparticles. Figure 2 represents the method for a hybrid of  $\text{Al}_2\text{O}_3\text{-MgO}$  fluid preparation. An electronic balance was used to quantify the calculated amounts of  $\text{MgO}$  and  $\text{Al}_2\text{O}_3$  nanoparticles, which were then combined with de-ionized water.  $\text{Al}_2\text{O}_3$  and  $\text{MgO}$  nanoparticles had respective average sizes of 46 and 21 nm. To achieve good stability and homogeneity, the mixture was mechanically swirled for 1.5 hours and then ultrasonically agitated for 3.5 hours at a certain temperature in an ultra-sonication system. A 0.1%

volume concentration of  $\text{Al}_2\text{O}_3$  nanofluids was first created, and then, using the same process, hybrid nanofluids with  $\text{MgO}$  and  $\text{Al}_2\text{O}_3$  nanoparticles in various ratios (5:0, 4:1, 3:2, 2:3, 1:4, and 0:5) were created. Equation (1) can be used to calculate the mass of nanoparticles required to produce the hybrid nanofluid with different particle ratios:

$$mnp = Vf \cdot \phi \cdot \rho np \quad (1)$$

Where  $mnp$  - mass of nanoparticles ( $g$ ),  $Vf$  = volume of the nanofluid ( $L$ ),  $\phi$  = concentration of nanoparticles,  $\rho np$  = density of the nanoparticles ( $g/L$ ). For various ratios, the mass fraction of  $\text{Al}_2\text{O}_3$  - $\text{MgO}$  nanoparticles can be computed using Equation (2) and (3).

$$X\text{Al}_2\text{O}_3 = m\text{Al}_2\text{O}_3 + m\text{MgO}m\text{Al}_2\text{O}_3 \quad (2)$$

$$X\text{MgO} = m\text{Al}_2\text{O}_3 + m\text{MgO}m\text{MgO} \quad (3)$$

Where:

- $X\text{Al}_2\text{O}_3$  = mass fraction of  $\text{Al}_2\text{O}_3$
- $X\text{MgO}$  = mass fraction of  $\text{MgO}$
- $m\text{Al}_2\text{O}_3$  = mass of  $\text{Al}_2\text{O}_3$  ( $g$ )
- $m\text{MgO}$  = mass of  $\text{MgO}$  ( $g$ )

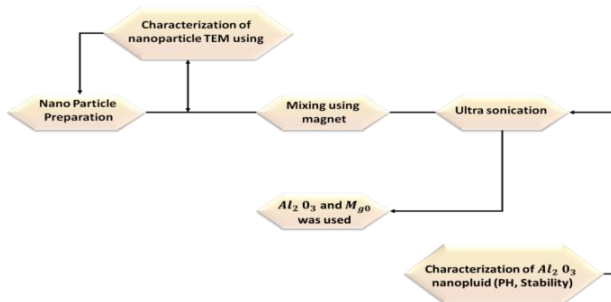


Figure 2. Fluid preparation

## 2.2 Evaluated the fluid nano-particles characteristics using Transmission Electron Microscopy (TEM)

Insights about the size, distribution, and shape of the nanoparticles can be obtained using TEM. Microscopy is the sole method for determining particle size that enables the direct viewing and measurement of individual particles. Particle size analysis can be done manually or automatically. The images display the usual levels of polydispersity and agglomeration that are produced by a thermal plasma procedure. Agglomerates of many primary particles make up typical nanoparticles. It refers to the agglomerates as secondary particles. It is created when strong chemical connections or weak surface forces hold together initial particles. More than 500 particles were counted to gather the particle size data. Data on particle size and size distribution can be shown graphically or tabular. Calculating Particle Size: From

the anticipated area  $A$ , the effective diameter  $D$  of the nanoparticles could be calculated using Equation (4).

$$D = 2\pi A \quad (4)$$

For the purpose of calculating the mean particle size, one might utilize Equation (5):

$$D = N1i = 1\sum NDi \quad (5)$$

Where:  $D$  = mean particle size( $nm$ ),  $Di$  = individual particle size ( $nm$ ),  $N$  = total number of particles counted.

## 2.3 Procedure description

This hybrid nanofluid comprising  $\text{Al}_2\text{O}_3$ - $\text{MgO}$  acts as a coolant. The precise flow loops of hybrid nanofluids and Deionizer water (DI) have a cold stream and a hot stream. Ten plates make up the heat exchanger, which has a surface area of  $0.4 \text{ m}^2$ , port diameter of  $32 \text{ mm}$ , plate thickness of  $0.6 \text{ mm}$ , perpendicular detachment involving a center of  $355.6 \text{ mm}$ , and parallel remoteness involving a center of  $60.9 \text{ mm}$ . The coolant loop includes a float-type flow meter, a manometer, and an isothermal bath. The fluid is maintained with chilled in a 10-liter isothermal wash to maintain a steady intake temperature. It then makes its way to the heat exchanger via a flow meter. A differential manometer is used to assess the hybrid nanofluid's pressure drop, and a manage valve is installed to adjust the fluid's flow rate. An on-off temperature controller keeps the hot water input at the proper temperature. HT Equation (6) can be utilized to analyze the heat transmit rate ( $Q'$ ) through the HT:

$$Q' = U \cdot A \cdot \Delta Tlm \quad (6)$$

Where:

$Q' = \text{HT rate}(W)$ , = overall HT coefficient ( $W/m^2 \cdot K$ ),

$A$  = surface area of the heat exchanger ( $m^2$ ),

$\Delta Tlm$  = log mean temperature difference( $K$ ).

Log Mean Temperature Difference Calculation: Equation (7), which calculates the pressure drop, can be used. Using Equation (8), the pressure drop ( $\Delta P$ ) across the heat exchanger can be calculated.

$$\Delta Tlm = \ln \left( \frac{Th, out - Tc, in}{Th, in - Tc, out} \right) \frac{(Th, in - Tc, out) - (Th, out - Tc, in)}{(Th, in - Tc, out) - (Th, out - Tc, in)} \quad (7)$$

$$\Delta P = f \cdot DhL \cdot 2\rho v^2 \quad (8)$$

Where  $f$  = friction factor (dimensionless),  $L$  = length of the HT ( $m$ ),  $\rho$  = compactness of the fluid ( $kg/m^3$ ),  $v$  = flow rapidity ( $m/s$ ). Reynolds Number Calculation: Equation (9), Overall HTCoefficient Calculation, evaluates the Reynolds number for the fluid flow. Equation (10) can be utilized to calculate  $U$ .

$$Re = \mu \rho v Dh \quad (9)$$

$$U1 = hh1 + hc1 + Rf \quad (10)$$

Where,  $Re$  = Reynolds number,  $\mu$  = dynamic viscosity of the fluid,  $hh$  = convective HTcoefficient for hot fluid ( $W/m^2 \cdot K$ ),  $hc$  = convective HTcoefficient for cold fluid ( $W/m^2 \cdot K$ ),  $Rf$  = thermal resistance due to fouling ( $m^2 \cdot K/W$ ).

### 3. RESULTS AND DISCUSSIONS

The objective of this investigation is to use hybrid  $Al_2O_3$ -MgO nanofluids to assess the HT efficiency of PHEs. It requires ascertaining consider that flow parameters, concentration, and nanoparticle composition affect thermal performance and, optimizing the hybrid nanofluid mixture for improved energy efficiency.

#### 3.1 Performance evaluation

Key performance indicators were used to compare this investigation's hybrid nanofluid ( $Al_2O_3$ -MgO) to calcium chloride with copper oxide ( $CaCl_2$ -CuO), potassium acetate (KAC), ethylene glycol with hybrid nanofluid (EG- HyNf), and propylene glycol (PG-HyNf). While the Coefficient of Performance (COP) evaluates system efficiency under various circumstances, the Heat Transfer Area (HTA) establishes the exchanger's capacity to transport heat effectively. Energetic Efficiency (EE) measures how well the system transforms available energy into usable employment, whereas the Performance Index (PI) evaluates total performance increases in comparison to baseline fluids. Furthermore, the relationship between nanoparticle size and HT optimization throughout the studied fluids is revealed by the outcome of atom volume on Thermal Performance (TP).

#### Heat transfer Area (HTA) and Thermal performance (TP)

Compared to water or single nanofluids, the hybrid nanofluid reduces the necessary HTA by increasing thermal conductivity, which leads to more effective heat transmission. The HTA values for several nanofluids utilized in heat exchange applications are shown in Figure 3. In comparison to other nanofluids, the suggested  $Al_2O_3$ -MgO hybrid nanofluid shows the greatest HTA at  $1.92 \text{ m}^2$ , indicating higher thermal performance. With an HTA of  $1.75 \text{ m}^2$ , PG-HyNf comes in second, but  $CaCl_2$ -CuO has a lower value of  $1.65 \text{ m}^2$ . These results collectively imply that the  $Al_2O_3$ -MgO hybrid nanofluid holds great promise for improving heat exchanger HT efficiency.

**Table 1.** Overall performance.

| Nanofluids                | HTA/ $\text{m}^2$ | TP   |
|---------------------------|-------------------|------|
| EG-HyNf                   | 1.7               | 0.9  |
| PG-HyNf                   | 1.75              | 0.91 |
| $CaCl_2$ -CuO             | 1.65              | 0.98 |
| KAC                       | 1.68              | 1    |
| $Al_2O_3$ -MgO [Proposed] | 1.92              | 1.6  |

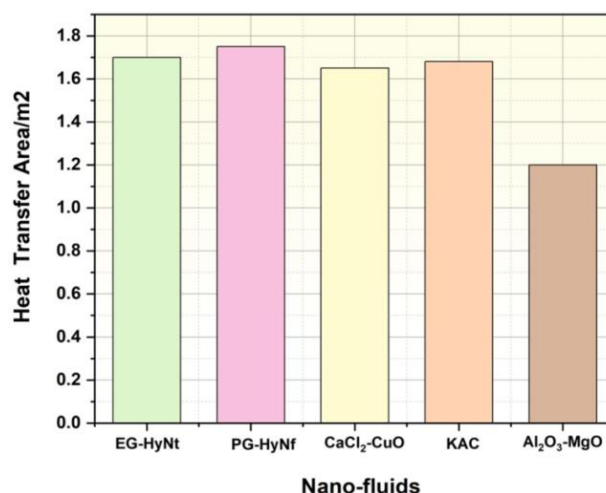


**Figure 3.** Performance of Heat Transfer Area

The efficiency of hybrid nanofluids in enhancing HT in PHEs is assessed by TP. It calculates how well a variety of nanoparticle combinations improve TP in comparison to established fluids by exploratory TP. The values of numerous nanofluids utilized in HT applications are shown in Figure 4. With a TP of 1.6, the recommended  $Al_2O_3$ -MgO outperforms other fluids like EG-HyNf and PG-HyNf, which contain TP values of 0.9 with 0.91, correspondingly. This illustrates the  $Al_2O_3$ -MgO hybrid nanofluid's enhanced HT property, which makes it a viable option for raising heat exchanger thermal efficiency. Table 1 represents the overall efficiency of HTA and TP.

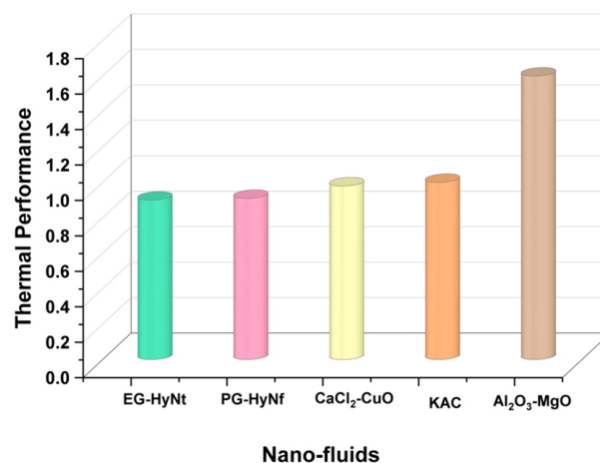


**Figure 4.** Thermal performance analysis

#### Coefficient of Performance (COP) and Energetic Efficiency (EE)

By comparing the utilizable HT attains to the required energy input, the COP is used to evaluate the hybrid nanofluid's effectiveness in HT. Figure 5 illustrates the COP values for dissimilar nanofluids, emphasizing how effective they are in HT applications. The  $Al_2O_3$ -MgO hybrid nanofluid performs better than the other fluids tested among

them, as evidenced by its greatest COP of 5.43. PG-HyNf has a COP of 4.84, whereas the EG-HyNf displays a COP of 4.847. The improved efficiency of the suggested  $\text{Al}_2\text{O}_3$ -MgO nanofluid is highlighted by the somewhat lower COP values of 4.834 and 4.837, respectively, of other formulations, such as  $\text{CaCl}_2$ -CuO and KAC.

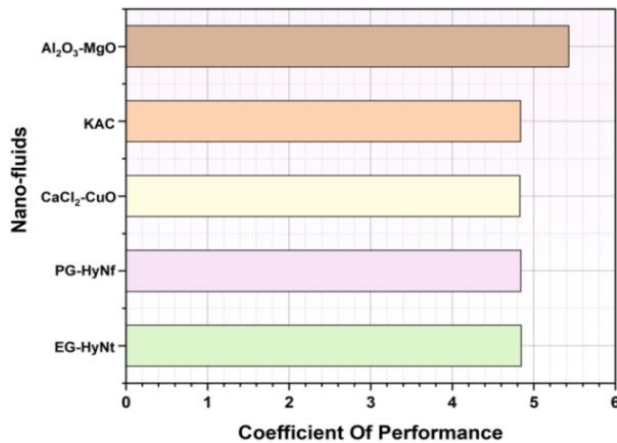


Figure 5. Outcomes of Coefficient of Performance

To assess how effectively hybrid nanofluids transform available thermal energy into useful work during the HT process, EE is being examined. The coefficients of EE for different nanofluids utilized in HT applications are shown in Figure 6 and table 2. By the maximum EE of 41.7% with the mentioned fluids,  $\text{Al}_2\text{O}_3$ -MgO performs improved at transforming thermal force into exploitable employment. The efficiencies of the other nanofluids, including EG-HyNf and PG-HyNf, vary from 38.2% to 39.2% in dissimilarity. This represents that the  $\text{Al}_2\text{O}_3$ -MgO is an added resourceful preference for the HT system due to its enhanced thermal performance.

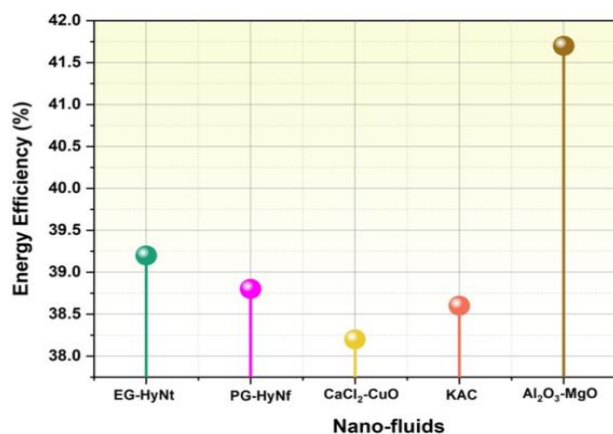


Figure 6. Analysis of Energetic Efficiency

Table 2. Performance evaluation.

| Nanofluids                              | CoP   | EE (%) |
|-----------------------------------------|-------|--------|
| EG-HyNf                                 | 4.847 | 39.2   |
| PG-HyNf                                 | 4.84  | 38.8   |
| $\text{CaCl}_2$ -CuO                    | 4.834 | 38.2   |
| KAC                                     | 4.837 | 38.6   |
| $\text{Al}_2\text{O}_3$ -MgO [Proposed] | 5.43  | 41.7   |

### Performance Index (PI)

To evaluate how well different nanofluids progress HT competence in PHEs, the PI is a considerable measurement in this investigation. The PI values for some nanofluids utilized in this analysis are shown in Table 3 and Figure 7. In the evaluation of other fluids, the recommended  $\text{Al}_2\text{O}_3$ -MgO shows the maximum PI value of 225, demonstrating better thermal effectiveness. The PI values of PG-HyNf,  $\text{CaCl}_2$ -CuO, and KAC are lesser at 210, 198, and 205, correspondingly, but EG-HyNf has a PI of 220. These outcomes display how  $\text{Al}_2\text{O}_3$ -MgO nanofluid can be used to exploit HT in PHEs.

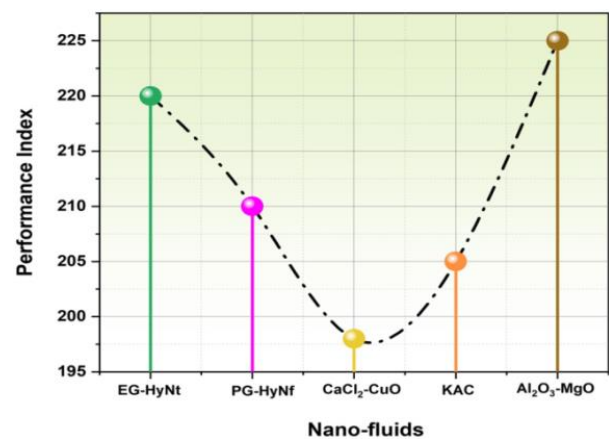


Figure 7. Performance Index

Table 3. Analysis of performance.

| Nanofluids                              | PI  |
|-----------------------------------------|-----|
| EG-HyNf                                 | 220 |
| PG-HyNf                                 | 210 |
| $\text{CaCl}_2$ -CuO                    | 198 |
| KAC                                     | 205 |
| $\text{Al}_2\text{O}_3$ -MgO [Proposed] | 225 |

### 3.2 Discussion

The significant impact of  $\text{Al}_2\text{O}_3$ -MgO hybrid nanofluid on HT efficiency in PHE. Compared to conventional HT fluids, the hybrid nanofluid exhibit superior thermal properties, resulting in enhanced HT effectiveness. With the highest recorded heat transfer area (HTA) of  $1.92 \text{ m}^2$  and a thermal performance factor of 1.6,  $\text{Al}_2\text{O}_3$ -MgO surpasses other tested fluids in terms of thermal conductivity and overall efficiency. These results confirm that the synergistic effects of  $\text{Al}_2\text{O}_3$  and MgO nanoparticles contribute to improved convective HT rates and minimized thermal resistance. The coefficient of performance (COP) of 5.43 and a performance index (PI) of 225 further demonstrate the energy-efficient nature of  $\text{Al}_2\text{O}_3$ -MgO hybrid nanofluid. These metrics indicate that the hybrid nanofluid effectively converts input energy into heat transfer processes, making it a viable option for industrial applications where energy efficiency is paramount.

Additionally, the 41.7% energy efficiency (EE) signifies its ability to optimize power consumption, ultimately reducing operational costs and enhancing sustainability in thermal management systems. One of the primary reasons for this enhanced performance is the hybrid nanofluid, which ensures effective heat dissipation. The optimized concentration of nanoparticles further contributes to superior stability and uniform dispersion, which prevents sedimentation and maintains efficiency over extended operational periods. This aspect is crucial for industrial applications that require consistent performance and long-term reliability in heat exchanger operations. Overall, the exceptional properties of Al<sub>2</sub>O<sub>3</sub>-MgO hybrid nanofluids make them a promising alternative to traditional fluids in heat exchanger systems. Their ability to improve reduce energy losses, heat transfer rates and enhance efficiency underscores their potential in advancing heat exchanger design and energy-saving technologies, paving the way for more effective thermal management solutions in various industrial sectors. The use of hybrid nanofluids in plate heat exchangers encounters various operational hurdles including expensive preparation approaches along with precipitation of nanoparticles which affects longevity and difficulties in making particles homogenously dispersed. High viscosity in such systems would possibly increase pump power needs which might decrease operational efficiency. Fluctuations in experimental results compared to theoretical models occur because of flow-related complications. The existing heat exchanger materials encounter compatibility problems and long-term corrosion continues to be a concern. Boosting findings from laboratory tests to industrial use encounters multiple obstacles.

## References:

- Ain, Q. U., Shah, I. A., & Alzahrani, S. M. (2024). Enhanced heat transfer in novel star-shaped enclosure with hybrid nanofluids: a neural network-assisted study. *Case Studies in Thermal Engineering*, 61, 105065. doi: 10.1016/j.csite.2024.105065
- Ajeeb, W., da Silva, R. R. T., & Murshed, S. S. (2023). Experimental investigation of heat transfer performance of Al<sub>2</sub>O<sub>3</sub> nanofluids in a compact plate heat exchanger. *Applied Thermal Engineering*, 218, 119321. doi: 10.1016/j.applthermaleng.2022.119321
- Ajeeb, W., & Murshed, S. S. (2022). Comparisons of numerical and experimental investigations of the thermal performance of Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> nanofluids in a compact plate heat exchanger. *Nanomaterials*, 12(20), 3634. <https://doi.org/10.3390/nano12203634>.
- Alhuyi Nazari, M., Mukhtar, A., Mehrabi, A., Ahmadi, M. H., Sharifpur, M., & Luong, T. N. L. (2024). Effect of using hybrid nanofluid and vortex generator on thermal performance of plate-fin heat exchanger: numerical investigation. *Journal of Thermal Analysis and Calorimetry*, 149(9), 4227-4237. <https://doi.org/10.1007/s10973-024-12928-9>.
- Aytaç, İ., Badali, Y., & Tuncer, A. D. (2023). Numerical and experimental investigation for enhancing thermal performance of a concentric heat exchanger using different scenarios. *International Journal of Numerical Methods for Heat & Fluid Flow*, 33(6), 2100-2127. <http://dx.doi.org/10.1108/HFF-10-2022-0588>.
- Alklaibi, A. M., Mouli, K. V. C., & Sundar, L. S. (2024). Heat transfer, and friction factor of Fe<sub>3</sub>O<sub>4</sub>-SiO<sub>2</sub>/water hybrid nanofluids in a plate heat exchanger: experimental and ANN predictions. *International Journal of Thermal Sciences*, 195, 108608. doi: 10.1016/j.ijthermalsci.2023.108608

## 4. CONCLUSION

In comparison to other nanofluids with predictable fluids, the Al<sub>2</sub>O<sub>3</sub>-MgO hybrid nanofluid provided better HT effectiveness in PHEs, based on the outcomes. Its advanced thermal conductivity is established by its significant 1.92 m<sup>2</sup> HTA with 1.6 TP. Its effectiveness in maximizing power employed during the HT progression is established by its COP of 5.43, EE of 41.7%, and PI of 225, compared to the other fluids of EG-HyNf, PG-HyNf, and CaCl<sub>2</sub>-CuO with KAC. The result illustrates that the Al<sub>2</sub>O<sub>3</sub>-MgO nanofluid is a high-quality preference for improving HT thermal performance. The study is constrained by the particular operating parameters that were employed in the tests, which could not accurately represent a range of industrial applications. Furthermore, possible problems with particle agglomeration and sedimentation over time could have an impact on the hybrid nanofluids' long-term performance. To evaluate the feasibility of Al<sub>2</sub>O<sub>3</sub>-MgO hybrid nanofluids for long-term applications, future investigations should concentrate on investigating their long-term stability and endurance in actual production settings. It is also critical to look at the economic viability of increasing production and integrating these nanofluids into already-existing heat exchanger systems. The HT efficiency in plate heat exchangers using hybrid nanofluids is limited by factors such as nanoparticle stability, potential clogging, and high preparation costs. Additionally, variations in flow conditions and long-term effects on exchanger materials require further investigation. Future scope can focus on optimizing nanofluid compositions, enhancing stability, and exploring eco-friendly alternatives. Advanced computational models and experimental studies under diverse operating conditions can improve practical applications in industrial heat exchange systems.

- Alteneiji, M., Ali, M. I. H., Khan, K. A., & Al-Rub, R. K. A. (2022). Heat transfer effectiveness characteristics maps for additively manufactured TPMS compact heat exchangers. *Energy Storage and Saving*, 1(3), 153-161. doi: 10.1016/j.enss.2022.04.005
- Borhani, M. A., Shirani, A. S., Talebi, M., & Mokhtari, J. (2024). Heat transfer evaluation of combined nanofluids in vertical annulus: An experimental and artificial neural network approach. *Progress in Nuclear Energy*, 175, 105339. doi: 10.1016/j.pnucene.2024.105339
- Iyer, J., Moore, T., Nguyen, D., Roy, P., & Stolaroff, J. (2022). Heat transfer and pressure drop characteristics of heat exchangers based on triply periodic minimal and periodic nodal surfaces. *Applied Thermal Engineering*, 209, 118192. doi: 10.1016/j.applthermaleng.2022.118192
- Jalili, B., Aghaee, N., Jalili, P., & Ganji, D. D. (2022). Novel usage of the curved rectangular fin on the heat transfer of a double-pipe heat exchanger with a nanofluid. *Case Studies in Thermal Engineering*, 35, 102086. doi: 10.1016/j.csite.2022.102086
- Kamsuwan, C., Wang, X., Piumsomboon, P., Pratumwal, Y., Otarawanna, S., & Chalermssinsuwan, B. (2023). Artificial neural network prediction models for nanofluid properties and their applications with heat exchanger design and rating simulation. *International Journal of Thermal Sciences*, 184, 107995. doi: 10.1016/j.ijthermalsci.2022.107995
- Khodadadi, M., & Sheikholeslami, M. (2022). Heat transfer efficiency and electrical performance evaluation of photovoltaic unit under influence of NEPCM. *International Journal of Heat and Mass Transfer*, 183, 122232. doi: 10.1016/j.ijheatmasstransfer.2021.122232
- Luo, X., Gu, J., Ma, H., Xie, Y., Li, A., Wang, J., & Ding, R. (2022). Numerical study on enhanced melting heat transfer of PCM by the combined fractal fins. *Journal of Energy Storage*, 45, 103780. doi: 10.1016/j.est.2021.103780
- Marseglia, G., De Giorgi, M. G., Pontes, P., Solipa, R., Souza, R. R., Moreira, A. L. N., & Moita, A. S. (2023). Enhancement of microchannel heat sink heat transfer: Comparison between different heat transfer enhancement strategies. *Experimental Thermal and Fluid Science*, 111052. DOI: 10.1016/j.expthermflusci.2023.111052
- Patil, S. M., Radhakrishnan, A., Pawar, S. R., Railis, D. J., & Barmavatu, P. (2024). Prediction of heat exchanger efficiency using laminar heat transfer in swirling flow of radiated graphene oxide with nano fluid additives using machine learning technique. *Numerical Heat Transfer, Part B: Fundamentals*, 1-19. doi: 10.1080/10407790.2024.2377792
- Perumal, S., Venkatraman, V., Sivanraju, R., Mekonnen, A., Thanikodi, S., & Chinnappan, R. (2022). Effects of Nanofluids on heat transfer characteristics in shell and tube heat exchanger. *Thermal science*, 26(2 Part A), 835-841. doi: 10.2298/TSCI200426076P
- Roueintan, H., & Fattahi, A. (2024). On the pillow-plate heat exchanger with wavy walls and filled with a hybrid nanofluid: Numerical simulation and data-assisted prediction. *Case Studies in Thermal Engineering*, 64, 105495. <https://doi.org/10.1016/j.csite.2024.105495>.
- Sheikholeslami, M., Farshad, S. A., Gerdroodbary, M. B., & Alavi, A. H. (2022). Impact of new multiple twisted tapes on treatment of solar heat exchanger. *The European Physical Journal Plus*, 137(1), 86. doi: 10.1140/epjp/s13360-021-02157-6
- Tao, H., Aldlemy, M. S., Homod, R. Z., Aksoy, M., Mohammed, M. K., Alawi, O. A., ... & Yaseen, Z. M. (2024). Hybrid nanocomposites impact on heat transfer efficiency and pressure drop in turbulent flow systems: application of numerical and machine learning insights. *Scientific Reports*, 14(1), 19882. doi: 10.1038/s41598-024-69648-1
- Tu, J., Qi, C., Li, K., & Tang, Z. (2022). Numerical analysis of flow and heat characteristic around micro-ribbed tube in heat exchanger system. *Powder Technology*, 395, 562-583. doi: 10.1016/j.powtec.2021.10.009

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