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Enhancing Closed System Efficiency through CuO Nanofluids: Investigating Thermophysical Properties and Heat Transfer Performance

Nadhum H. Safir[2,3,5], Zuradzman Mohamad Razlan[1,2,*], Shahriman Abu Bakar[1,2], Muhammmad Hussein Akbar Ali[1,2], Mohd Zulkifly Abdullah[3], Girrimuniswar Ramasamy[1,2], Rodhiyathul Ahyaa Akbar Ali[4]

[1] Centre of Excellence for Automotive & Motorsport, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia
[2] Faculty of Mechanical Engineering & Technology (FKTM), Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia
[3] School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia
[4] Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[5] Forensic DNA Centre for Research and Training,Al-Nahrain University,Jadriya,Baghdad,Iraq

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ABSTRACT

Working fluids play a crucial role in closed systems to ensure efficient performance, particularly in systems for heating, cooling, or power generation, where the heat transfer coefficient is pivotal. This study delves into the thermodynamic properties and stability of copper oxide (CuO) nanofluids as alternative working fluids in closed systems. Investigating colloidal suspensions of CuO nanoparticles, the research aims to enhance heat transfer efficiency. CuO nanoparticles, sized at 40nm and 80nm, were dispersed in base fluids like water, ethylene glycol, and oil sans surfactants. The study, divided into static and dynamic phases, examines key nanofluid properties including viscosity, thermal conductivity, specific heat, and heat transfer rate. Through methodologies such as KD2 Pro for thermal conductivity, rheometer for viscosity, and small heat exchanger for heat transfer rate analysis, the effects of volume concentration, temperature, and nanoparticle size on nanofluid performance were evaluated. Sedimentation analysis employed both quantitative (standard deviation calculations) and qualitative (sediment capture methods) approaches. The findings highlight the superior heat transfer rate of 40nm CuO nanofluid at 0.467% volume concentration which is 9.08 kJ/s, suggesting its potential to optimize system efficiency, particularly in heating, cooling, and power generation applications.

1. Introduction

Nanofluids are characterized as suspensions of nanoparticles, with diameters not exceeding 100 nm, in a base fluid, thereby constituting a two-phase system: a solid phase (nanoparticles) and a liquid phase (base fluid) as stated by Kaggwa and Carson [1]. In this investigation, copper oxide (CuO) nanoparticles of two specific sizes, 40 nm, and 80 nm, are employed to formulate nanofluids. Figure

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[*] *Corresponding author.*
E-mail address: zuradzman@unimap.edu.my

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1 illustrates the process of synthesizing CuO nanofluids by incorporating copper oxide nanoparticles into the base fluid. Subsequently, the properties of the resulting nanofluid are scrutinized under both static and dynamic states as mentioned by Bin-Abdun *et al.,* [2], Manimaran *et al.,* [3], and Ali and Salam [4].

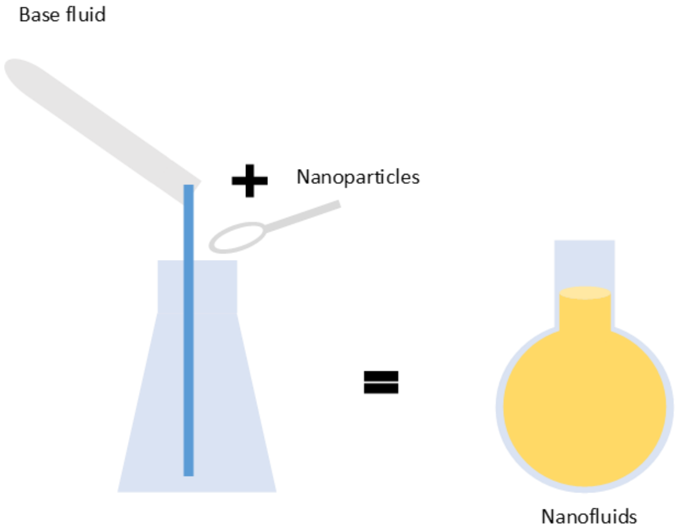


Fig. 1. Example of CuO nanofluid preparation illustration

According to existing research by several authors, nanofluids have the potential to enhance thermophysical parameters, including thermal conductivity, thermal diffusion, viscosity, and the convective heat transfer coefficient, thereby surpassing the performance of fundamental fluids such as oil or water [5-8]. As a result, this study will focus on adjusting parameters such as nanoparticle size, temperature, and volume concentration to optimize the efficacy of nanofluids.

The selection of copper oxide (CuO) in the realm of nanofluids for heat transfer applications is not arbitrary but is rooted in its unique thermophysical properties. CuO nanofluids have been recognized for their high thermal conductivity and stability, which significantly enhance the heat transfer performance in closed systems [9,10]. Factors influencing the selection of nanomaterials like CuO include chemical stability, thermophysical properties, toxicity, availability, compatibility with the base fluid, and cost. Specifically, CuO nanofluids have demonstrated a strong relationship between thermal conductivity and heat transfer levels, offering better thermal conductivity than conventional base fluids [2,9]. The use of CuO nanofluids can significantly enhance the efficiency of heat transfer in closed systems, it can be used in heat exchangers, transportation cooling, refrigeration, and electronic equipment cooling [6].

Nonetheless, the stability of this two-phase system poses a substantial challenge. The pursuit of optimal stability is a significant obstacle, as demonstrated in Figure 2, which contrasts the states of nanofluids under conditions of high and low stability. The stability of nanofluids is vital for enhancing the performance of nanoparticle suspensions in traditional fluids, as it ensures the uniformity of the thermophysical properties of nanofluids, it also has been stated by Mukherjee and Paria [11] and Ali and Salam [12].

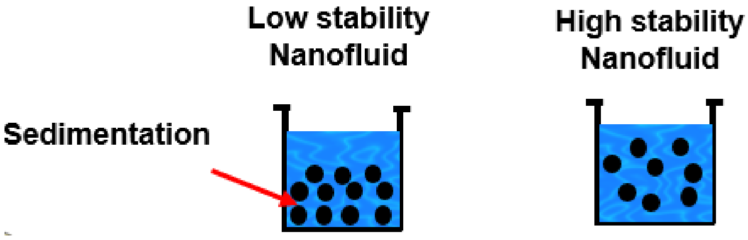


Fig. 2. The illustration of a comparison between the condition of nanofluids in high stability and low stability

This study aims to examine and propose quantitative measurement methods for CuO nanofluids to determine their thermodynamic properties and the stability of the colloidal suspension. The study focuses on the two-step method for nanofluid preparation, given its widespread acceptance in research. Scanning electron microscopy (SEM) scanning is performed to verify the physical properties of the nanoparticles used. The study also introduces quantitative and qualitative methods for analyzing nanofluid sediments, aiming to determine the total sediment percentage. The investigation explores the relationship between temperature, volume concentration, and nanoparticle size on nanofluid properties, tested at three different levels in both static and dynamic conditions using a rheometer, KD2 Pro, and a small heat exchanger. The findings from these experimental works will be evaluated and documented as a guide for future research.

2. Methodology

2.1 Sample of Material

In this study, the primary material used as nanoparticles is copper oxide (CuO). The characteristics of the nanoparticles used are microscopic and light. As a precaution, the package of nanoparticles should be opened in an airtight room that is a room away from wind movements to prevent nanoparticles from being carried into the air.

According to Ravinayagam and Jermy [13] and Baliga and Dean [14], nanoparticles with a size less than 100 nm can enter the lung and then the blood when inhaled, ingested, or touched the skin. Therefore, a researcher should use face masks and gloves to increase safety measures throughout the experimental work of these nanofluids and nanoparticles. Additionally, this study relies on deionized water (often referred to as "DI Water" or "Demineralization") as its principal base fluid because it can provide predictable and repeatable findings which are also mentioned by Manimaran *et al.,* [3] and Sekhar and Sharma [15].

2.2 The Properties of Nanoparticles

In this study, scanning electron microscopy (SEM) analysis is performed on dried CuO nanoparticles to describe this nanoparticle agglomeration, shape, and suspension uniformity. This step is important to ensure that the shape and dispersion of the nanoparticles follow this experiment's requirements.

2.3 Preparation Method for Nanofluids CuO

The nanoparticles used are from U.S. Research Nanomaterials, a company based in the U.S. Each packet of these nanoparticles weighs 100 g and has a purity of 99%. Before preparing nanofluids, the first step is analyzing the properties of the nanoparticles, such as size and morphology. After that, start preparing CuO nanofluids. The preparation of nanofluids is a crucial stage and needs to be ready systematically using a two-step method. The two-step method is commonly used for nanofluid preparation. Nanomaterials are produced in powder form through laser ablation processes. This powder is then dispersed into a fluid using techniques such as ultrasonic agitation. Despite the challenge of nano-powder aggregation, surfactants are used to stabilize the nano-powder in fluids. The stability of nanofluids is achieved when the repulsive forces between particles are strong enough to prevent them from clustering and settling.

2.4 The Stability Evaluation Methods for Nanofluids

Nowadays, researchers can assess nanofluids' stability in various ways leading to tremendous improvements. Several other techniques are available to prepare stable nanofluids: zeta potential analysis, sedimentation method, centrifugation method, and spectral analysis method. However, in this study, the sedimentation analysis is preferred.

In this study, the sedimentation analysis is done using two methods which are quantitative and qualitative. For the quantitative approach, the sediment is analyzed by the photo capture method using a digital camera at the same time interval for three consecutive days until the nanofluid has settled, this approach is also used by Ali and Salam [16], Ali and *et al.,* [17], and Aghel *et al.,* [18]. Then, for the quantitative method, the standard deviation for the average viscosity of nanofluid data is calculated to analyze the percentage of nanofluid sediment. This method was also implemented by Barkhordar *et al.,* [19] and Giwa *et al.,* [20].

2.5 Thermophysical Properties Evaluation for Nanofluids (Static Phase)

2.5.1 Measure the viscosity

Then, analyze the viscosity of nanofluids (CuO) using quantitative methods at three levels, namely at 800ml, 500ml, and 200ml. This quantitative method can also determine at which level (800m, 500m, and 200m) nanofluid settles. In addition, the temperature readings tested on the viscosity of nanofluid are 5°C, 10°C, 15°C, 20°C, 25°C, and 30°C.

According to Abbas *et al.,* [21], various instruments are widely used to measure fluid viscosity: capillary viscometer, falling sphere viscometer, vibrating viscometer, rotational viscometer, acoustic rheometer, microfluidic rheometers, and others. This study also uses an instrument to measure the viscosity of nanofluids, namely the DVNext rheometer, which is equipped with a cone and plate.

2.5.2 Measure the thermal conductivity

In the context of prior studies, researchers from previous studies have outlined several methodologies for quantifying the thermal conductivity of nanofluids [3,13]. These encompass transient techniques (including transient hot-wire, thermal constants analyzer, temperature oscillation, and 3w method), steady-state techniques (such as steady-state parallel plate and cylindrical cell), and the thermal comparator technique.

In this study, the thermal conductivity of the working fluids was determined utilizing a thermal property meter (Decagon Device, Inc., KD2 Pro), which employs the transient hot-wire technique. The nanofluids were subjected to testing at a spectrum of temperatures (5°C, 10°C, 15°C, 20°C, 25°C, and 30°C) and varying nanoparticle volume concentrations (0.775% and 0.467%). As per the findings of Ebrahimi *et al.,* [22], the transient hot-wire method is predominantly utilized for the measurement of the thermal conductivity of such fluids in engineering applications.

2.5.3 Measure the heat capacity

One of the most critical aspects of nanofluid characteristics is the specific heat, which can be defined as joules per kilogram per Kelvin (J/kg.K). The specific heat represents a system's thermal storage capacity and computes other related variables, such as dynamic thermal conductivity and diffusivity. The specific heat of nanofluid is defined as follows:

$$Cp_{nf}=\frac{Q}{m\Delta T}=\frac{Q}{m(T_2-T_1)} \tag{1}$$

where Cp_{nf} is the specific heat of nanofluid.

2.6 Thermophysical Properties Evaluation for Nanofluids (Dynamic Phase)

The dynamic thermophysical characteristics of nanofluids are analyzed to estimate their heat transfer and volume flow rates. This study conducts experimental work using a small heat exchanger with a 0.0057 ℓ/s volume flow rate. Before running the heat exchanger, 0.5 liters of CuO nanofluid are first filled into the sample tank, and the temperature water bath is fixed at 50°C.

Then, connect a heater coil with a single aluminum pipe (heat exchanger part) to transfer high temperature (heat from water bath) to low temperature (heat from nanofluids). Lastly, all the data obtained from this analysis is used to calculate the heat transfer rate by using the following formula:

$$Q=\dot{m}C_P\Delta T=\dot{m}C_P(T_{out}-T_{in}) \tag{2}$$

where Q is the heat transfer rate of nanofluid, and $\dot{m}$ is the mass flow rate of nanofluid.

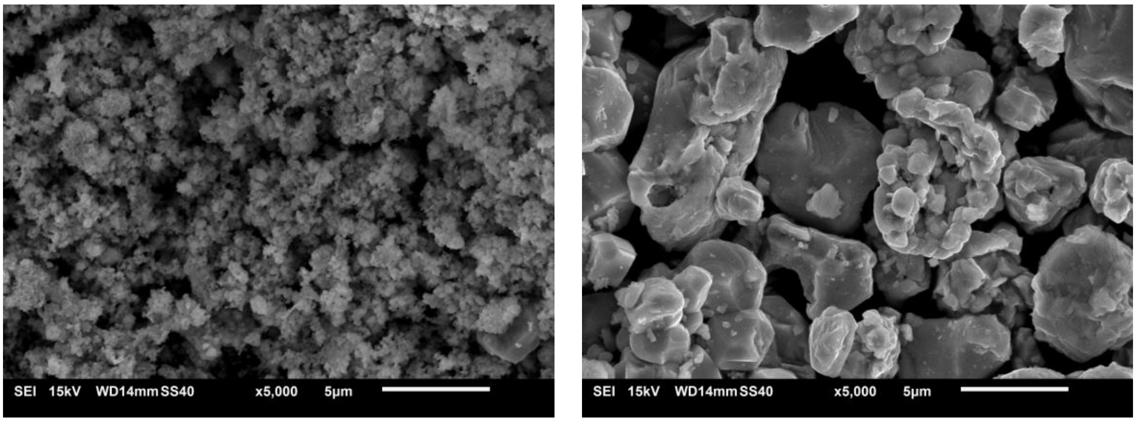
3. Results

3.1 Sedimentation

The sediment capture method is a qualitative approach that employs photographs to analyze the sedimentation of nanofluids. This analysis is conducted at predetermined intervals until the nanofluids have completely settled. However, for this study, the nanofluid was examined over three days, as depicted in Figure 3, due to the short settling time of these nanofluids. The results indicate that the CuO nanofluid/deionized water mixture settled on the first-day post-preparation.

Fig. 3. Sedimentation process for nanofluids CuO

Upon examining Figure 4 at magnifications of x5000 and x7500, it is evident that the diameter of the CuO nanoparticles at 40nm is indeed smaller than those at 80nm. Furthermore, both nanoparticle samples exhibit a nearly spherical shape, aligning with theoretical expectations and corroborating previous research findings. This observation underscores the consistency in the morphological characteristics of CuO nanoparticles.

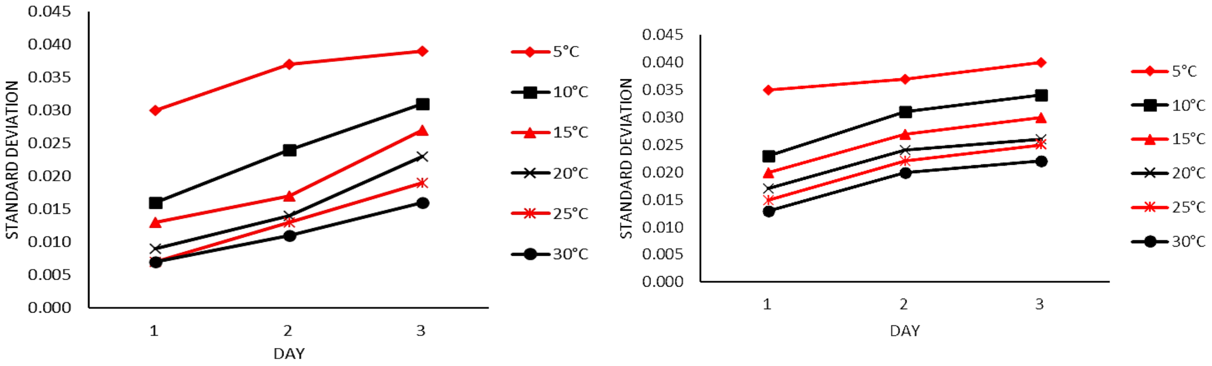


(a) (b)

Fig. 4. Analysis of CuO nanoparticle (a) 40nm and (b) 80nm at x5000 magnification using a scanning electron microscope (SEM)

Subsequently, standard deviation calculations, which are quantitative studies, were conducted to focus on the average viscosity of nanofluids throughout the analysis (day 1, day 2, and day 3). Figure 5 shows the graphs illustrating the relationship between the standard deviation of the mean viscosity and the day on which the sedimentation analysis was performed. The figure displays an increasing standard deviation trend, signifying the nanofluid sediment percentage over three days. Figure 6 shows a decreasing trend in the average viscosity corresponding to an increase in nanofluid sedimentation.

In the subsequent phase of our study, we conducted standard deviation calculations as part of our quantitative analysis, focusing specifically on the average viscosity of nanofluids over three days. As depicted in Figure 5, there is a clear relationship between the standard deviation of the mean viscosity and the day of sedimentation analysis. The graph reveals an upward trend in standard deviation, which indicates an increase in the variability of nanofluid viscosity over the three days. This increase in variability is a direct reflection of the growing percentage of nanofluid sedimentation. Conversely, Figure 6 presents a downward trend in the average viscosity, which correlates with the increase in nanofluid sedimentation. This inverse relationship suggests that as sedimentation increases, the average viscosity of the nanofluid decreases. This could be due to the settling of nanoparticles, which reduces the effective volume of the nanofluid, thereby decreasing its viscosity. These findings provide valuable insights into the behaviour of nanofluids under varying conditions and have significant implications for their practical applications.



(a) (b)

Fig. 5. Standard deviation of (a) CuO (40nm) with a concentration of 0.467% and (b) CuO (80nm) with a concentration of 0.467%

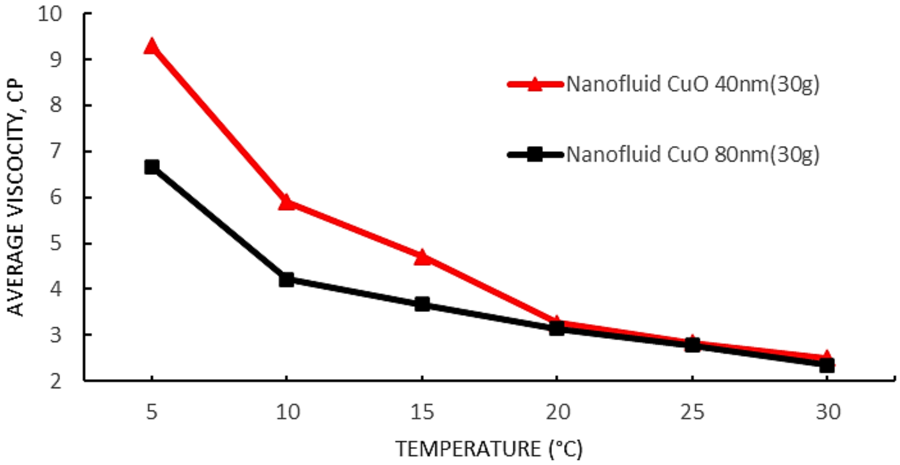


Fig. 6. Average viscosity of CuO 40nm (30g) and CuO 80nm (30g)

3.2 Thermophysical Properties

Figure 7 and Figure 8 display the thermal conductivity and average viscosity results for CuO nanofluids with nanoparticle sizes of 40nm and 80nm, and volume concentrations of 0.775% and 0.467%, in comparison to deionized water (DI). The figures demonstrate a direct relationship between temperature and thermal conductivity, with the latter increasing as the temperature rises. This happens likely due to the increased kinetic energy of the particles, enhancing heat transfer. Conversely, as the temperature decreases from 30°C to 5°C, the viscosity of the nanofluids increases, possibly due to the reduced kinetic energy of the particles, which hinders their movement and increases the fluid's resistance to flow. Furthermore, nanofluids with a higher volume concentration (0.775%) display higher thermal conductivity and viscosity than those with a lower volume concentration (0.467%). This could be attributed to the increased number of nanoparticles providing more pathways for heat transfer and more particle-particle interactions, respectively.

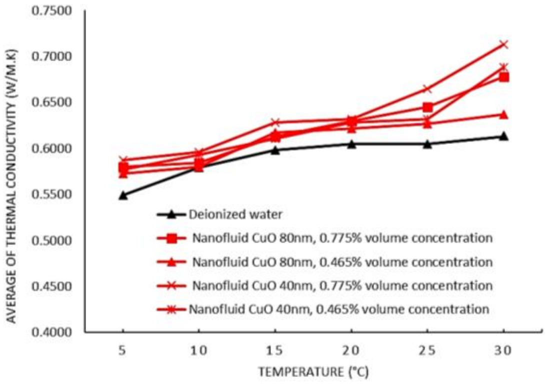


Fig. 7. Result of thermal conductivity

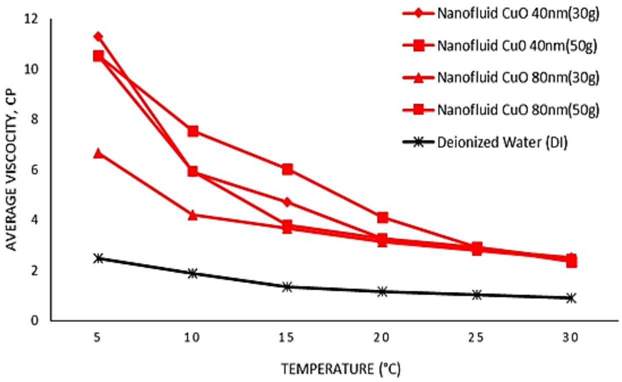


Fig. 8. Viscosity for nanofluids and deionized water (DI)

3.3 Heat Transfer Rate

Table 1 shows that a CuO nanofluid, with a nanoparticle size of 40nm and a volume concentration of 0.467%, demonstrates a superior heat transfer rate of 9.08 kJ/s, outperforming other working fluids. This enhanced heat transfer rate can be attributed to the smaller nanoparticle size, which increases the surface area available for heat transfer, thereby improving the efficiency. On the contrary, larger nanoparticles are found to have a lower heat transfer rate, likely due to their reduced surface area per unit volume, which limits the heat transfer potential. Furthermore, the concentration of nanofluids is observed to significantly impact the overall heat transfer rate. Higher concentrations increase the number of nanoparticles, which can enhance the heat transfer rate by providing more pathways for heat transfer. These findings underscore the critical role of nanoparticle size and concentration in optimizing the heat transfer performance of nanofluids.

Table 1
Result of heat transfer rate values of nanofluid

Type	Volume Concentration, ϕ (%)	Temperature Inlet, T_{in}(˚C)	Temperature Outlet, T_{out}(°C)	Mass Flow Rate, ṁ(kg/s)	Heat Transfer Rate, Q(kJ/s)
CuO	0.467	27.7	29.2	0.00336	9.08
40nm	0.775	29.5	30.8	0.00348	2.038
CuO	0.467	22.7	24.5	0.00336	6.81
80nm	0.775	28.3	29.1	0.00348	1.003

4. Conclusions

This study presents a comprehensive exploration of the thermal properties and heat transfer capabilities of CuO nanofluids, with a particular emphasis on the effects of nanoparticle size, temperature, and volume concentration. Our findings reveal distinct variations in viscosity across different nanofluid levels, a phenomenon attributed to the rapid sedimentation processes influenced by the aforementioned variables. The study included an in-depth qualitative and quantitative analysis of nanofluid sedimentation, reinforcing the necessity for precision in nanofluid applications. Through meticulous examination of thermal properties such as viscosity, and thermal conductivity under static conditions, we discovered that both temperature and volume concentration positively correlate with thermal conductivity, while smaller nanoparticles yield higher thermal conductivity values. Our study revealed that under dynamic conditions, compact heat exchangers demonstrated superior heat transfer performance with CuO nanofluids at a lower concentration volume of 0.467%, achieving an impressive heat transfer rate of 9.08 kJ/s. In conclusion, our investigation illuminates the potential of CuO nanofluids as high-efficiency working fluids in a variety of thermal systems, providing valuable insights for future research and practical applications in the field of heat exchange and beyond. This study, therefore, serves as a significant steppingstone toward the optimization of nanofluid usage in thermal systems.

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