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Investigation of Thermodynamic Properties and Stability of Metal Oxide (CuO and Al_2O_3)/Deionized Water Nanofluids for Enhanced Heat Transfer Applications

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ABSTRACT

The potential of nanofluids in improving heat transfer efficiency is well recognized, although there is a lack of clarity regarding the methods for assessing their stability and the influence on thermophysical properties. Moreover, the prevention of nanoparticle aggregation, which is essential for stability, requires further investigation. This study aims to address these issues by investigating the thermodynamic properties and stability of Al_2O_3/deionized water and CuO/deionized water nanofluids, which were prepared using magnetic stirring and ultrasonication. The stability assessment, conducted through standard deviation analysis, revealed that CuO (80 nm)/deionized water nanofluids exhibited greater stability compared to Al_2O_3 (80 nm)/deionized water nanofluids. The research explored the impact of temperature, volume concentration, and nanoparticle type under both static and dynamic conditions. Static tests focused on measuring thermal conductivity, viscosity, and specific heat, while dynamic tests involved a heat exchanger setup to determine heat transfer rates. The findings indicated that CuO nanofluids displayed the highest thermal conductivity and the most significant reduction in specific heat and heat transfer rate. Viscosity was found to increase with nanoparticle concentration and decrease with temperature. This study provides valuable insights into the thermophysical characteristics and stability of nanofluids, emphasizing the advantages of CuO-based nanofluids for heat transfer applications.

1. Introduction

Nanofluids, an innovative category of fluids, are formed by dispersing materials with nanometre-scale dimensions in a base fluid. These fluids exhibit a dual-phase system, consisting of solid and

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liquid phases. They possess exceptional thermophysical properties, such as thermal diffusivity, thermal conductivity, and viscosity, surpassing traditional base fluids. As a result, nanofluids find suitability in a wide range of applications. One of the major challenges in two-phase systems lies in achieving optimal stability in nanofluids. The stability of nanofluids can be influenced by various parameters, including the type of base fluid, the shape and size of nanoparticles, the specific kind of nanoparticles employed, volumetric concentration, surfactants, and the preparation method. Figure 1 and Figure 2 provide visual representations of the stable and unstable colloidal suspension in nanofluid mixtures, as well as the classification of nanofluids' viscosity, respectively. A variety of materials, such as metals (Cu, Ag, Au), metal oxides (Al_2O_3, CuO), carbide ceramics (SiC, TiC), and carbon nanotubes, have been utilised as nanoparticles in nanofluids.

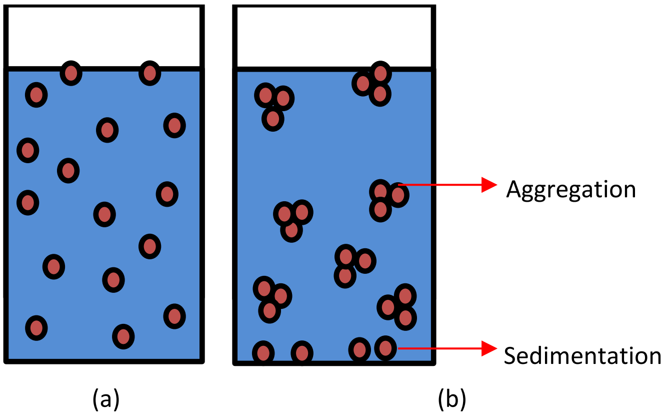


Fig. 1. Colloidal suspension in a nanofluid mixture where (a) stable and (b) unstable

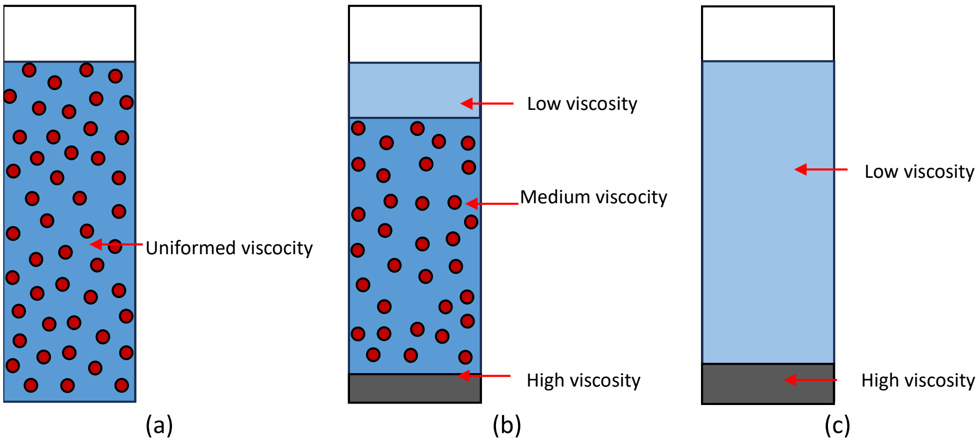
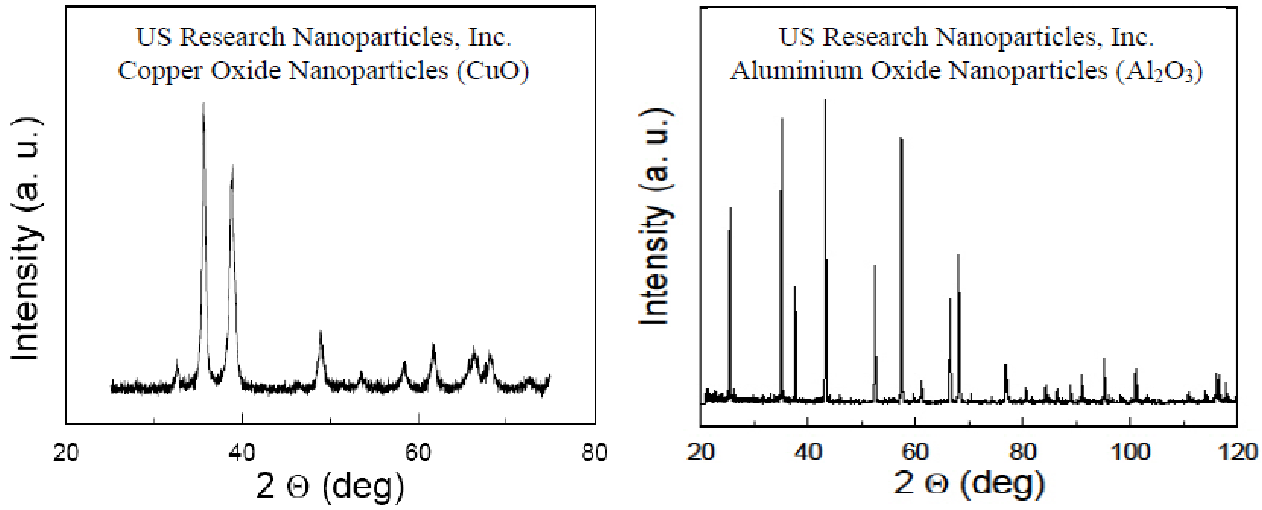


Fig. 2. The nanofluids viscosity classification, where (a) stable, (b) semi-stable and (c) demonstrates the unstable cases of the suspension

Transition metals such as aluminium oxide exhibit distinctive characteristics that render them appropriate for a wide range of uses. Nabgan *et al.,* [1] stated that by utilizing electrochemical anodizing, aluminium oxide can be produced in the form of nanoporous anodic structures, enabling precise regulation of pore attributes such as dimensions and distribution. The utilization of these nanoporous aluminium oxide substances has attracted interest in fields like photoelectrochemical water splitting, owing to their remarkable chemical and mechanical properties. Milikić *et al.,* [2] stated that copper oxide, a type of transition metal oxide, can be found in multiple oxidation states, specifically CuO and Cu_2O. These oxides have widespread applications in various fields, such as catalysis, electronics, and energy storage. Copper oxide materials possess intriguing characteristics, including semiconducting properties, remarkable catalytic activity, and the potential for use in solar cells and gas sensors.

Based on a study by Bin-Abdun *et al.,* [3] Metal oxides have been favoured over pure metallic particles due to their ease of manufacturing and stabilisation. Additionally, Chavali and Nikolova [4] stated that Metal oxide nanoparticles (MONPs) have become essential tools in modern nanotechnology due to their unique properties. These include nonlinear optical behaviour, higher ductility at elevated temperatures compared to coarse-grained ceramics, cold welding properties, superparamagnetic behaviour, and catalytic sensitivity. The melting point of nanosized materials is also lower than that of bulk materials with the same composition. Despite their advantages, nanoparticles exhibit unusual adsorptive properties and fast diffusivities, impacting their stability under critical conditions.

X-ray diffraction (XRD) is the most convenient and widely employed technique for determining the average size and structure of nanoparticles. The CuO and Al_2O_3 nanoparticles were analyzed using an X-ray diffractometer within the range of 20 – 50 °C, and their corresponding reflections in the XRD pattern can be observed in Figure 3. The XRD analysis was conducted at a scan speed of 2 θ/min. The full width at half maximum (FWHM) extracted from the XRD pattern is presented in Figure 3. Consequently, the nanofluids employed in this study consist of aluminium oxide (Al_2O_3/deionized water) and copper oxide (CuO/deionized water), with an average nanoparticle size of 80nm.



(a) (b)

Fig. 3. Powder X-ray diffraction pattern of CuO and Al_2O_3 nanoparticles

The selection of copper oxide (CuO) and aluminium oxide (Al_2O_3) nanoparticles is based on their superior thermal conductivities in comparison to other metal oxides. Al_2O_3 offers high thermal conductivity and chemical inertness, while CuO provides excellent heat transfer enhancement and stability at elevated temperatures. Zahmani *et al.,* [5] found Al_2O_3 and CuO to be effective through experimental analysis of their thermal conductivity, specific heat capacity, and viscosity properties in nanofluid formulations. Additionally, Plant *et al.,* [6] found the potential synergistic effects when these nanoparticles are combined, along with previous research supporting their effectiveness in enhancing heat transfer, further justifies their selection. Moreover, the practicality of working with CuO and Al_2O_3 nanoparticles in experimental setups adds to their appeal. The authors' objective in combining these nanoparticles is to enhance the overall thermal conductivity of the nanofluid and improve heat transfer efficiency in their porous open-cell foam metal system. This, in turn, leads to a significant thermal enhancement when compared to commercial alumina nanofluid.

The objective of this research is to investigate the stability of nanofluids, develop a quantitative method for measuring stability, and assess its impact on heat transfer enhancement, thermal conductivity, and viscosity. These factors play a crucial role in determining the practical applicability of nanofluids.

The present study focuses on the intricate process of preparing nanofluids, which goes beyond simple mixing, especially when it comes to achieving uniform dispersion of nanoparticles in a base fluid. The primary objective of this research is to prevent the aggregation of nanoparticles, thereby enhancing the stability of nanofluids. Despite the existence of numerous studies on the stability of nanoparticle dispersion in base fluids, the methodologies for evaluating nanofluid stability and its impact on thermo-physical properties remain unclear. Wen *et al.,* [7] observed that nanofluids produced without stabilizing materials experience rapid changes in stability over time. In their investigation of an Al_2O_3/water (2.5 weight %) nanofluid, they found that the Al_2O_3 nanoparticles became completely separated after 5 hours, yet the nanofluid mixture still exhibited a higher sedimentation layer. It was affirmed that the degree of aggregation depends on various factors by Ghasemi *et al.,* [8], Dinali *et al.,* [9], and Safiei *et al.,* [10]. This research aims to analyse the stability of Al_2O_3 nanofluids using a quantitative measurement method, compare the stability of nanofluids composed of different materials, and determine the influence of variables such as temperature, volume concentration, and nanoparticle type on the properties of nanofluids under both static and dynamic conditions.

Nanofluids, which consist of nanoparticles or nanofibers with a size smaller than one hundred nanometres dispersed in a liquid medium, have attracted considerable attention due to their improved thermal properties. Experimental studies by Keblinski *et al.,* [11] have shown that even a small volume fraction of Cu nanoparticles (less than 1%) dispersed in ethylene glycol or oil can significantly enhance thermal conductivity by 40% to 150%. However, to effectively utilize nanofluids for heat transfer applications, it is crucial to have a comprehensive understanding of their thermophysical properties, particularly thermal conductivity and viscosity. Various research studies have attempted to estimate these properties using prediction correlations, while others have conducted empirical investigations to verify them. The present study focuses on the stability of nanofluids, the development of a quantitative method for measuring stability, and the impact of stability on heat transfer enhancement, thermal conductivity, and viscosity. These aspects are of utmost importance for the practical implementation of nanofluids. This research area has gained significant attention recently due to the inconsistent results obtained by different researchers when using the same nanoparticles.

1.1 Preparation of Nanofluids

The synthesis of nanofluids, which involves dispersing nanometre-sized particles in a base fluid, is a complex process that aims to enhance the thermal properties of traditional heat transfer fluids. Proper preparation is crucial to prevent nanoparticle aggregation and ensure optimal thermos-physical properties. Additives are often used with base fluids and nanoparticles to enhance nanofluid stability and dispersion properties, as outlined in Figure 4. Two primary methods exist for nanofluid preparation: the one-step and two-step methods. In a study by Eastman *et al.,* [12] The one-step method, which involves simultaneous nanoparticle preparation and dispersion in the base fluid, can reduce nanoparticle aggregation. However, it may leave impurities due to incomplete reactions as highlighted by Tarafdar *et al.,* [13]; necessitating further research to fully understand how to generate stable nanofluids with various volume concentrations based on Buongiorno [14], Saidur *et al.,* [15], and Shah *et al.,* [16]. The two-step method, which is more commonly used due to the wide availability of nanoparticles in various sizes and forms as mentioned by Bin-Abdun *et al.,* [3], involves creating nanoparticles using techniques such as inert-gas condensation, chemical emulsion, mechanical grinding, and chemical vapour deposition, and then dispersing them in a base fluid with the aid of magnetic stirring and ultrasonication. Ensuring nanofluid stability over a longer period presents two major challenges: reducing nanoparticle aggregation and preventing nanoparticle sedimentation in the base fluid. Past analyses and experiments have attempted to address this problem, with several major research papers employing a two-step strategy to investigate nanofluid stability, as summarized in Table 1. However, some authors failed to indicate the solution's length or stability period. The methodologies for nanofluid preparation, including one- and two-step procedures, are summarized in Table 2. There are two main approaches for preparing nanofluids and nanoparticles: the one-step method and the two-step method. The one-step method involves direct preparation using techniques like Vapor Deposition, Laser Ablation, and Chemical Reduction. The two-step method involves first preparing nanoparticles using methods like precipitation and sol-gel synthesis, and then preparing nanofluids using techniques like Magnetic stirring and Ultrasonic agitation. These methods allow researchers to customize the preparation process to meet their specific needs. Both steps of the methods have their advantages and disadvantages, as highlighted in Table 3.

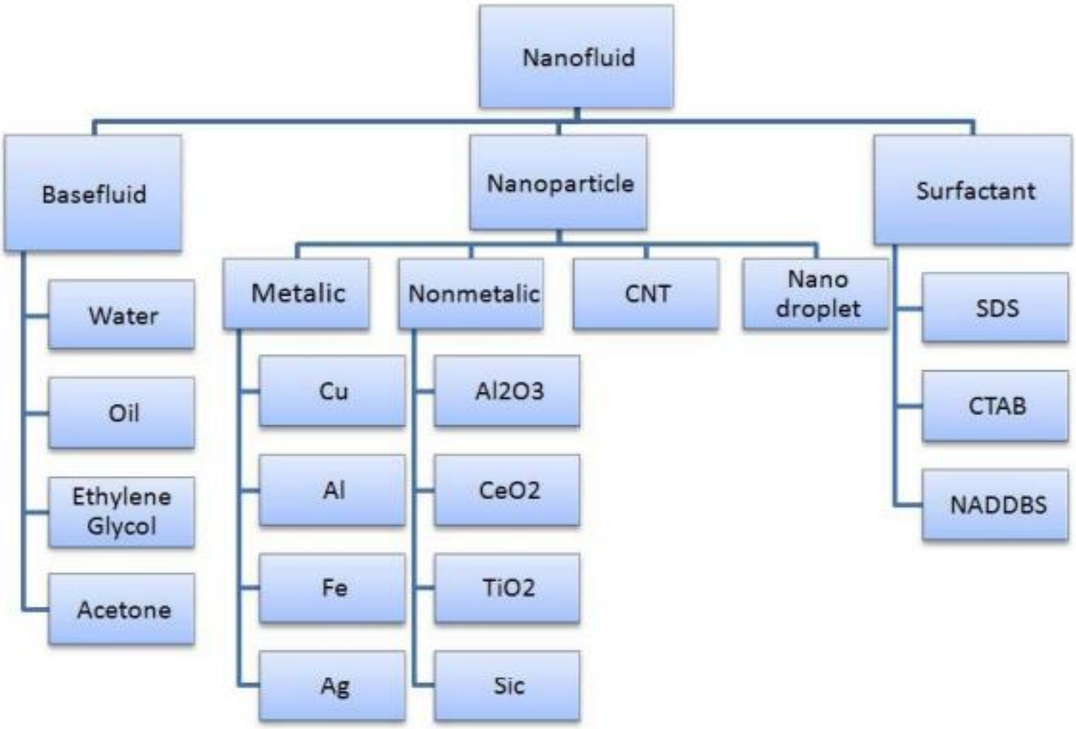


Fig. 4. Outlines of the common synthesizing nanofluids

Table 1
Summary of the preparation of various nanofluids and surfactants in a two-step method

Author	Nanofluids	Surfactants	Sonication time	Remarks on sedimentation
Bin-Abdun *et al.,* [3]	Al_2O_3/DI Water	SDS	12 hr	Sedimentation found after 39days
Bin-Abdun *et al.,* [3]	CuO/DI Water	SDS	12hr	Sedimentation found after 53days
Wen and Ding [17]	Al_2O_3/DI Water	SDBS	16 – 20 hr	Sedimentation was originated for mass concentrations more than 4wt% after 4hr.
dos Santos *et al.,* [18]	Fe_3O_4/Water	Polyethylene glycol	-	-
Fazeli *et al.,* [19]	CuO/Water	SDS and CTAB	4hr	SDS is more stable than CTAB for 7days
Ji *et al.,* [20]	Al_2O_3/DI Water	CTAB and SDBS	15hr	Sedimentation is still stable after 30 days by using CTAB
Singh *et al.,* [21]	CNT/Water	SDS	0 to 180 min.	Less sedimentation on sonication time of 180 min
Wang *et al.,* [22]	Fe_3O_4/Water	SDS, SLS, TMAH	32hr	Less sedimentation by using SDS surfactant

Table 2
Summary preparation method of nanofluids applied by the researchers

Author	Nanoparticles	Base fluid	Concentration	Type of method
Bin-Abdun *et al.,* [3]	CuO	Deionized water	0.40vol%	Two-step
Safiei *et al.,* [10]	Al_2O_3	Deionized water, Ethylene glycol (EG)	0.2-0.6wt%	Two-step
dos Santos *et al.,* [18]	Fe_3O_4	Water, Ethylene glycol (EG)	0.18-0.27vol%	Two-step
Hung *et al.,* [23]	HCNF	Sodium dodecyl sulphate	0.02wt%	One-step
Zhu *et al.,* [24]	$CuSO.5H_2O$	Water	0.15wt%	One-step
Cacua *et al.,* [25]	Al_2O_3	Deionized water	0.1-0.5wt%	Two-step
Wang *et al.,* [26]	Al_2O_3	Palm oil	0.0-4.0wt%	Two-step
Muthusamy *et al.,* [27]	TiO_2	Ethylene glycol (EG)	0.1-1.5vol%	Two-step
Amrita *et al.,* [28]	Nano graphite	Water	0.3wt%	Two-step
Setti *et al.,* [29]	Al_2O_3, CuO	Water	0.05-1.0vol%	Two-step
Wei *et al.,* [30]	SiC/TiO_2	Diathermic oil	1.0vol%	Two-step
Elcioglu *et al.,* [31]	Al_2O_3	Water	1.0-2.0vol%	Two-step
Suresh *et al.,* [32]	Al_2O_3/CuO	Sodium-lauryl sulphate	0.1vol%	Two-step
Suresh *et al.,* [32]	Al_2O_3	Water	0.33–5vol%	Two-step
Zhang *et al.,* [33]	Al_2O_3/SiC	Plant oil	2.0vol%	Two-step
Liu *et al.,* [34]	Al_2O_3/CuO	Water	0.1-1.5wt%	Two-step
Choudhary *et al.,* [35]	Al_2O_3	Water	0.01-0.8vol%	Two-step
Zainith and Mishra [36]	Al_2O_3, CuO, TiO	Deionized water, CMC	0.01-0.04wt%	Two-step
Ali *et al.,* [37]	TiO_2	Water, paraffin oil or ethylene glycol	0.024 vol%	One and two-step

Table 3
Nanofluids preparation methods advantage and disadvantage

Method	Advantage	Disadvantage
One-step (Simultaneous creation and dispersion)	1. Quality is high in terms of stability 2. Decrease in the aggregation of nanoparticles	1. Only able to prepare a lower quantity of nanofluids 2. High price
Two-step (Prepared and dispersed)	1. Able to prepare large quantity of nanofluids 2. Low price	1. Quality is less in terms of stability 2. Difficulty in preparing stable nanofluids

1.2 Techniques for Enhancing the Stability of the Nanofluids

According to Urmi *et al.,* [38] to maintain nanofluid stability and prevent nanoparticle sedimentation, three main techniques have been identified: surfactant addition, pH control, and ultrasonic vibration. Surfactants or dispersants are often used to stabilize nanofluids by reducing surface tension and preventing nanoparticle aggregation. However, according to Ali and Salam [39], and Zainon and Azmi [40] excessive use of dispersants can affect the thermophysical properties of nanofluids, such as chemical stability and thermal conductivity. Therefore, it is important to use the right amount of dispersant. Surfactants, such as SDS, CTAB, PVP, DTAB, and SOCT, can affect the dispersion of particle size as mentioned by Safiei *et al.,* [41]. Ali and Salam [39] conducted a study on Mg(OH)2/water nanofluid stability. They found that surfactants, including SDS, Oleic Acid, and CTAB, are important for enhancing stability. CTAB surfactants had the best results. The stability of nanofluids is linked to their electrokinetic properties, with well-dispersed suspensions being stabilized by strong repulsive forces due to high surface charge density.

In a study by Xie *et al.,* [42], it was found that carbon nanotubes can be stabilized in water using acid treatment, making them hydrophilic instead of hydrophobic. This treatment introduces a hydroxyl group. The surface charge state is important for enhancing the thermal conductivity of nanofluids, but experiments have shown that changing the pH level can affect the particle morphology. Lunardi *et al.,* [43] conducted a study on Al_2O_3 nanofluids to investigate their pH characteristics. The study found that the size of clustered particles decreased by 18% at a pH of 1.7 but increased by 51% at a pH of 7.66. When Al_2O_3 particles are in water, hydroxyl groups form on their surface, and the pH of the solution affects important reactions. The fluctuation in particle diameters due to pH changes is shown in Table 4. The optimal pH level varies depending on the nanoparticle type, with alumina at pH 8, graphite at pH 2.0, and copper at pH 9.5. Temperature differences also influence the pH value of the point of zero charge (PZC), as shown in Table 5.

Different methods have been suggested to change the surface properties of nanoparticles and prevent the formation of particle clusters for stable suspensions. Ultrasonic baths, processors, and homogenizers are more effective than high-shear stirrers and magnetic stirrers for dispersing clusters. However, it is important to be aware that prolonged processing can lead to increased agglomeration and clogging issues, causing rapid sedimentation. Ganguli and Pandit [44] developed a new method using microchannels to create stable suspensions. They used cavitation to break up nanoparticle clusters. When the suspension flows through the microchannel, it increases in velocity and causes cavitation. This process results in a homogeneous dispersion with fewer distinct modules. It is recommended to repeat this process three times for efficient dispersion of nanoparticles.

Table 4
Summary of the preparation of various nanofluids and surfactants in a two-step method

Nanofluids	pH	Mean particle (nm)
Al_2O_3/Deionized water	-	170
Al_2O_3/DI/PBS/HCl	1.7	139
Al_2O_3/DI/PBS	7.66	1033

Table 5
Temperature affected the pH value

Temperature (°C)	PH_{PZC}
5	6.62
15	6.39
25	6.17
35	5.97
45	5.78
55	5.61

1.3 Stability Evaluation Methods for Nanofluids

The application of nanofluids heavily relies on their stability, which is frequently hindered by the powerful van der Waals interactions among nanoparticles, resulting in agglomeration. Numerous techniques are utilized to assess the stability of nanofluids, such as zeta potential, UV-Vis spectrophotometer, sediment picture capture, TEM and SEM, sedimentation balancing methods, three omegala, and light scattering. Researchers use various methods to determine the stability of colloidal suspensions in nanofluid mixtures. These methods include analyzing the electrical double-layer repulsive force (EDLRF) and the Van der Waals attractive force. When the EDLRF is greater than the Van der Waals forces, the nanofluid is considered stable, as this prevents particle aggregation and settling. Techniques like Zeta potential measurement and sedimentation photography are employed to evaluate stability, with higher Zeta potential values correlating with improved stability as stated by Ali and Salam [39].

The zeta potential test, as stated by Shnoudeh *et al.,* [45] is an essential technique for assessing the stability of nanofluids by examining their electrophoretic behaviour. Strong electrostatic repulsions between particles, resulting from high zeta potential values, contribute to the formation of stable suspensions, as highlighted by Dastbaz *et al.,* [46]. The zeta potential values and the corresponding stability behaviour are presented in Table 6. The analysis of dispersions in a fluid can be conducted using a UV-Vis spectrophotometer, which can detect liquid absorption within the wavelength range of 200-900 nm. In their studies, Sadeghi *et al.,* [47], and Abdolkarimi-Mahabadi and Mohammadi [48] have proposed the utilization of a UV-Vis spectrophotometer to estimate sedimentation in nanosuspensions. This process involves scanning for the peak absorbency of dispersed nanoparticles in a highly diluted solution, preparing the necessary nanofluid absorption, and continuously monitoring the concentration of the remaining nanoparticles using a UV-Vis spectrophotometer over a period. The technique employed by Bin-Abdun *et al.,* [3] and Pawar *et al.,* [49] to assess sedimentation involves the capture of sedimentation photographs. This method entails taking photographs of a portion of the suspension at specific time intervals after preparation to analyse the sedimentation process. To determine the shape, size, and dispersion of nanoparticles, Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) are utilized. The sedimentation balance method involves submerging a tray in a nano-suspension and monitoring the mass of sediment nanoparticles over time.

Table 6
Zeta potential absolute values

Zeta potential (mV)	Stability behaviour
0 to ±5	Rapid coagulation or flocculation
±10 to ±30	Incipient instability
±30 to ±40	Moderate stability
±40 to ±60	Good stability
>61	Excellent stability

Eq. (1) is used to determine the suspension fraction (Fs) at a specific time, with W_0 representing the total weight of nanoparticles and W representing the weight of sediment nanoparticles. The three-omega technique measures the increase in thermal conductivity caused by the sedimentation of nanoparticles across various volume fractions. Light scattering theory can be used to analyse the structure of polymer particles or suspended particles through single-particle analysis. After sonication stops, the average cluster size is measured multiple times within a minute. These methods, along with surfactants and pH control, provide a comprehensive approach to enhancing and evaluating nanofluid stability.

$$Fs = \frac{W_0}{W} \tag{1}$$

1.4 Stability Evaluation Methods for Nanofluids

Numerous research studies have examined the effectiveness of nanofluids in heat transfer applications, specifically those containing Al_2O_3 and CuO nanoparticles in deionized water. Liu *et al.,* [34] acknowledged the potential of solid nanoparticles with high thermal conductivity to complement nanofluids, addressing their tendency to become unstable over time due to gravitational forces and pressure loss. Porgar and Rahmanian [50] conducted a study on the impact of Ag and Al_2O_3 nanoparticles on viscosity and thermal conductivity, discovering that higher concentrations of these nanoparticles resulted in improved thermal properties. Chiam *et al.,* [51] focused on the influence of surfactant concentration on the thermal conductivity and viscosity of Al_2O_3 nanofluids in ethylene glycol-water mixtures, observing a correlation between temperature and viscosity, as well as between concentration and thermal conductivity. Mohebbi *et al.,* [52] and other researchers explored the effects of various parameters such as temperature, particle concentration, and shape on thermal conductivity and natural convection in nanofluids, emphasizing the significance of optimizing volume concentrations to achieve maximum heat transfer efficiency. These investigations contribute to our understanding of nanofluid behaviour in heat transfer processes, providing valuable insights for engineering applications across diverse industries.

These are the research gaps found based on the literature above

i. Investigation of Synergistic Effects: This involves exploring the combined impact of surfactant concentration and pH control on the stability of Al_2O_3 and CuO nanofluids. By considering their unique surface properties and electrokinetic behaviour, you can develop optimized stabilization strategies.
ii. Nanoparticle Morphology and Stability: This involves analyzing the influence of nanoparticle shape (e.g., spherical vs. rod-shaped) on the stability mechanisms of Al_2O_3 and CuO nanofluids. By elucidating how variations in morphology affect dispersion characteristics and long-term stability under dynamic conditions, you can gain a deeper understanding of the factors influencing nanofluid stability.

iii. Dynamic Stability Assessment: This involves developing dynamic stability evaluation methods tailored to assess the time-dependent behaviour of Al_2O_3 and CuO nanofluids under shear forces and thermal gradients. This will enable a comprehensive understanding of stability dynamics crucial for real-world heat transfer applications.

These research directions could significantly advance our understanding of nanofluid behaviour and stability, leading to more effective and efficient applications in heat transfer and other areas.

2. Methodology

The research employs Scanning Electron Microscopy (SEM) analysis to examine the microstructure and morphology of nanoparticle materials. The experiments conducted aim to measure the thermophysical properties and assess the performance of working fluids in both static and dynamic states. The working fluids used in this research are Aluminium oxide (Al_2O_3/deionised water) and copper oxide (CuO/deionised water) nanofluids, both with a particle size of 80 nm. The research flow, visualized in Figure 5, is divided into two stages. The first part of the experimental work focuses on measuring the thermal conductivity, specific heat, and viscosity of the working fluids in a static condition. The second part involves experimental studies aimed at determining the heat transfer rate in a dynamic condition. All equipment used in the experimental studies was calibrated before the purpose of this experimental investigation was to evaluate the behaviour and characteristics of Al_2O_3 and CuO nanoparticles. We obtained these nanoparticles from US Research Nanomaterials, a well-known and trustworthy business situated in the United States. data collection to ensure accuracy. This comprehensive approach allows for a thorough investigation of the properties and performance of the nanofluids under study.

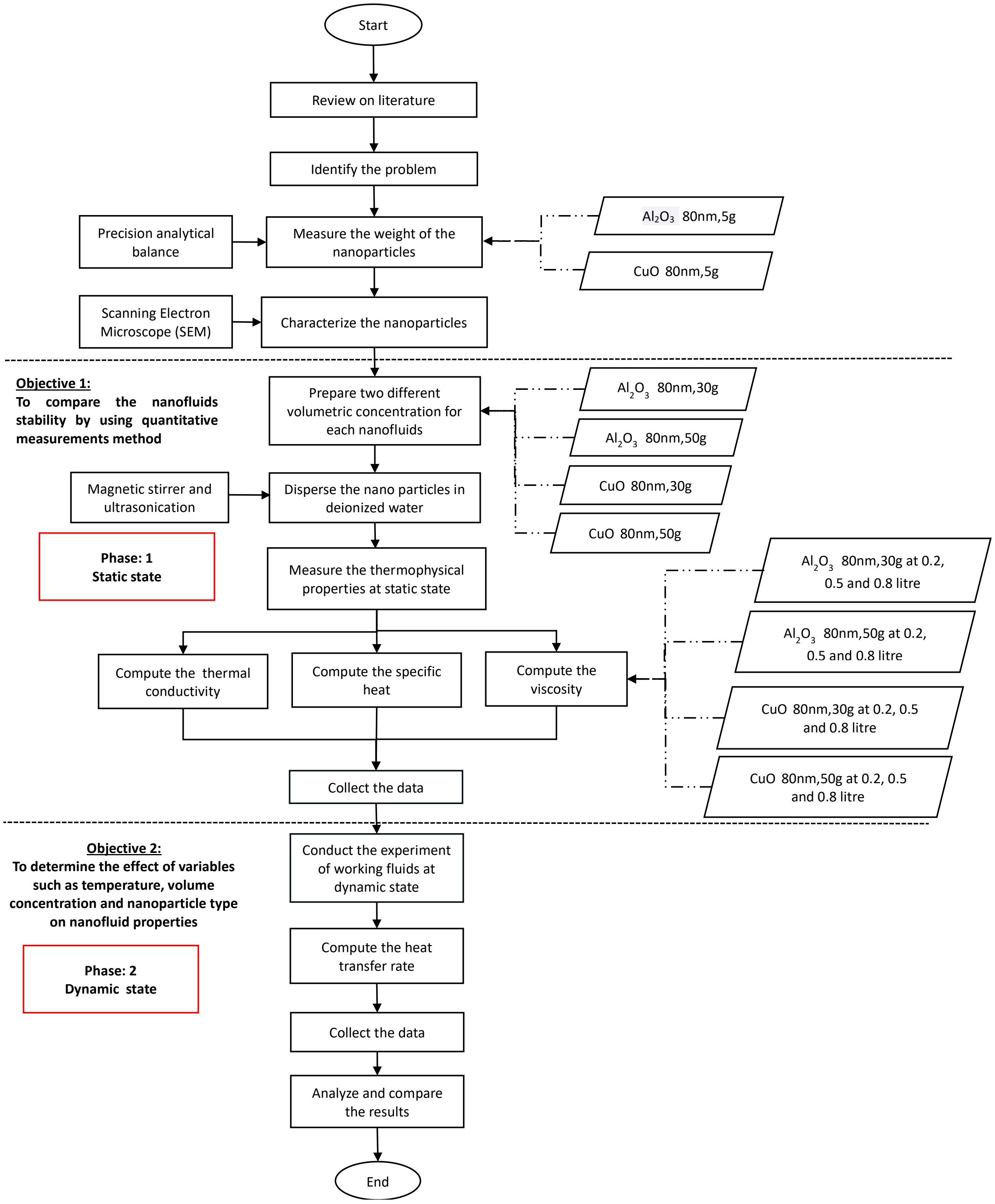


Fig. 5. A detailed flowchart outlining the steps involved in synthesizing and characterizing nanoparticles for CuO and Al_2O_3 nanofluid research

2.1 Selection of Material and Nanofluids Preparation

In this experimental study, we acquired nanoparticles of Al_2O_3 and CuO from US Research Nanomaterials, a reputable company based in the United States. The average diameter of these nanoparticles was measured to be 80 nm. To ensure optimal dispersion and stability, we meticulously dispersed the Al_2O_3 and CuO nanoparticles in deionised water. The weights of the Al_2O_3 and CuO nanoparticles were determined to be 30 g and 50 g, respectively. Using these masses, and referring to past research by Safir *et al.,* [53-55] we calculated the volume concentrations to be 0.75% and 1.25% for the Al_2O_3 (80 nm)/deionised water solution, and 0.47% and 0.79% for the CuO (80 nm)/deionised water solution. These concentrations provide valuable insights into the distribution of nanoparticles within the deionised water medium. Figure 6 visually presents the Al_2O_3 and CuO nanoparticles, offering a clear representation of their physical characteristics and dispersion quality.

(a) (b)

Fig. 6. The photograph of nanopowders (a) Al_2O_3 (80 nm) nanopowder, (b) CuO (80 nm) nanopowder

2.2 Nanofluids Preparation

The researchers have shown a preference for the two-step method of synthesizing nanofluids that contain oxide nanoparticles. This preference is supported by previous studies, which are detailed in Table 2. In this investigation, Al_2O_3/deionised water and CuO/deionised water nanofluids were chosen due to their ease of preparation and cost-effective availability in the commercial market. The two-step procedure was employed to prepare the nanofluid for the experiment. To achieve this, the Al_2O_3 and CuO nanoparticles were individually dispersed in deionised water, each in separate one-litre bottles. To ensure optimal dispersion, the nanofluid mixtures, with varying volume concentrations, were subjected to a magnetic stirrer for five hours per bottle. Following this, the bottles were placed in an ultrasonic bath for three hours, with pure water filled to 70% capacity to prevent any potential damage. This critical step played a crucial role in minimizing the aggregation of Al_2O_3 and CuO nanoparticles in the deionised water, resulting in a homogeneous and stable nanofluid that was suitable for the experiment.

2.3 Thermophysical Test (Static State)

2.3.1 Thermal conductivity test

In these experimental investigations, the thermal conductivity of the working fluids was determined using a thermal property meter called the KD2 Pro, manufactured by Decagon Device, Inc. This device utilizes the transient hot-wire method to measure thermal conductivity and offers a high level of accuracy, with a precision of ± 0.5%. The method involves passing a constant electric current through a platinum wire and monitoring the changes in electrical resistance as the temperature rises. The KD2 Pro starter kit consists of a handheld controller and a sensor needle. The sensor needle, known as model KS-1, is equipped with a thermistor and a heating element and has dimensions of 1.3 mm in diameter and 60 mm in length. It functions as an infinite line heat source, minimizing any disturbances to the sample during measurements. The precision of this sensor is ±0.01 W/m.K. To compute the thermal conductivity, the working fluids used were Al_2O_3/deionised water and CuO/deionised water. These fluids were injected into a vial, and their thermal conductivity was measured at different temperatures and varying nanoparticle volume concentrations. The vial was then placed in a water bath with a temperature range of 5 °C to 30 °C, which could be controlled. For each sample, measurements were taken at six different temperatures, and each temperature measurement was repeated twice to ensure accuracy. To minimize potential errors in the measurements, a 15-minute interval was implemented between successive thermal conductivity tests.

2.3.2 Viscosity and nanofluids stability test

The DVNext Cone/Plate Rheometer from Brookfield was employed to determine the viscosity of the Al_2O_3 and CuO nanofluids. To ensure accurate measurements, the plate was strategically positioned in the sample cup, while the cone was securely attached to the spindle drive. To protect the nanofluid sample from potential contamination and environmental influences, it was appropriately covered. The viscosity of the nanofluid was then measured under controlled temperature conditions. To quantify the viscous drag of the fluid in opposition to the rotation of the spindle, the displacement of the calibrated spring was utilized. The viscometer provided a range of spindle speeds from 0 to 100 rpm, with the shear rate varying from 0 to 750 s^{-1}. Before the measurements, the viscometer was calibrated using deionized water and nanofluids at temperatures ranging from 5 °C to 30 °C, facilitated by a water bath. In this study, three different levels of nanofluid samples were obtained using a dropper. This quantitative analysis method plays a crucial role in evaluating the relationship between the viscosity of the nanofluid mixture and its stability. Figure 7 visually represents the nanofluid mixture at three distinct viscosity measurement levels, with (a) corresponding to 0.8 ℓ, (b) to 0.5 ℓ, and (c) to 0.2 ℓ. To assess the degree of variance or dispersion within the group of values, the standard deviation of the nanofluids was calculated.

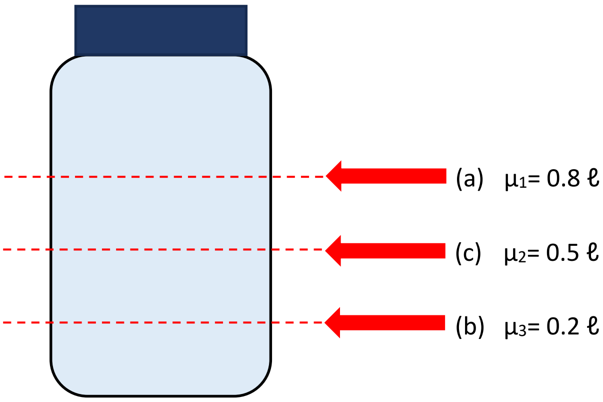


Fig. 7. Quantitative measurement method at 3 different levels

2.4 Specific Heat Test

The heat transfer rate of working fluids is significantly influenced by the thermophysical property known as specific heat. This property was determined in the present study using the specific heat equation, a mathematical model that enables precise calculation. To measure the temperatures and heat flow during thermal transitions of the nanofluids, an Ultrasonic Homogeniser (model JY92-IIDN) was utilized. This device allows for accurate tracking of temperature changes and heat flow, thereby providing valuable data for the analysis of the thermal properties of the nanofluids. The insights obtained from these measurements contribute to a deeper comprehension of the behaviour of nanofluids under different thermal conditions.

2.5 Heat Transfer Performance of Working Fluids Test (Dynamic State)

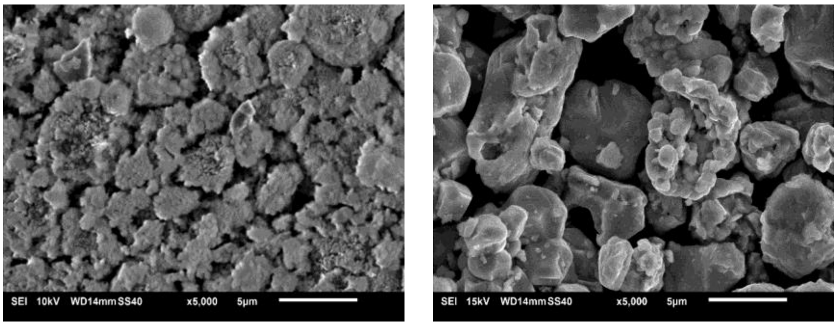
The heat transfer rate for each testing condition was assessed in these experiments through the implementation of a dynamic state test. The experimental setup consisted of two distinct cycles: the primary cycle involved the utilization of tested working fluids such as Al_2O_3/deionised water and CuO/deionised water, while the secondary cycle employed hot water. For the primary cycle, the working fluid tank was filled with 0.18 litres of the tested working fluid. Subsequently, the working fluid was conveyed from the tank to the heat exchanger, which comprised two rows of tubes, employing a gate valve and a pump. To regulate the temperature, a copper coil within the stainless-steel water tank was employed to heat the water. The heat load was maintained at 50 °C using a temperature bath, which constituted the second cycle. To measure the temperature at various points, as well as the bulk fluid temperature of the working fluid, thermocouples of Type-K were installed at the inflow and outflow of the heat exchanger. These thermocouples possessed an accuracy of ± 0.1 ºC. The temperature readings from each thermocouple were captured using a data acquisition device (Agilent 34970A), which could display temperature values up to three decimal places. Subsequently, the temperature data was analysed in a spreadsheet using the BenchLink Data Logger software, enabling a comprehensive analysis of the measurement data.

3. Results

Over the past few decades, a significant amount of research has been conducted to explore the various properties of nanofluids. The focus of the research was to investigate the methodologies for measuring the stability of nanofluids and to understand the impact of stability on their thermo-physical properties. The results obtained from this study can be categorized into two phases: the static state and the dynamic state. In the static state, measurements were conducted on the working fluids to determine their thermophysical properties, such as thermal conductivity, viscosity, and specific heat. On the other hand, the dynamic state experiment aimed to replicate a heat exchanger setup, with the primary goal of identifying the heat transfer rate. To conduct the experiments, desired nanoparticles, namely Al_2O_3 and CuO, were dispersed in deionised water at two different weights: 30 g and 50 g, respectively. Before conducting the systematic tests on the Al_2O_3/deionised water and CuO/deionised water nanofluids, the accuracy and reliability of the experimental measurement approach were validated through equipment calibration. Readings were taken once the equilibrium state was reached, and each experiment was repeated twice to minimize potential errors.

3.1 Results of Scanning Electron Microscopy Analysis (SEM)

SEM analysis was employed to acquire digital photographic data and assess the size measurements of the nanoparticles under investigation. Before the SEM analysis of the nanofluid samples, a platinum coating was applied to 5 g of each nanoparticle. SEM analysis was then conducted, and Figure 8(a) and Figure 8(b) illustrate the morphology analysis of Al_2O_3 and CuO particles, respectively. These figures demonstrate that the nanoparticles display an aggregation phenomenon, with an average particle size of 80 nm, and possess a spherical shape. This morphological information plays a crucial role in comprehending the behaviour and properties of these nanoparticles in diverse applications.



(a) (b)

Fig. 8. SEM images of (a) Al_2O_3 80nm and (b) CuO 80nm

3.2 Thermophysical Results (Static State)

3.2.1 Thermal conductivity

The thermal conductivity of the working fluids was determined by utilizing a KD2 Pro analyser over a temperature range spanning from 5 °C to 30 °C. To ensure accuracy, the measurements were conducted twice, and the resulting thermal conductivity values were averaged. The relationship between thermal conductivity and temperature is depicted in Figure 9, Figure 10, Figure 11 and Figure 12. Figure 9 and Figure 10 specifically illustrate the relationship between thermal conductivities and temperature for nanofluids containing aluminium oxide (Al_2O_3). These nanofluids were prepared with two different weights, namely 30 g and 50 g. As the temperature increases, the thermal conductivity also increases. Notably, the highest thermal conductivity value of 0.547 W/m.K at 30 °C was observed for the nanofluid with a volume concentration of 1.25% Al_2O_3 80 nm/deionized water. Conversely, the lowest thermal conductivity value of 0.338 W/m.K at 5 °C was obtained for the nanofluid with a volume concentration of 0.75% Al_2O_3 80 nm/deionized water. Figure 11 and Figure 12 illustrate a similar pattern, highlighting the relationship between thermal conductivities and temperature for copper oxide (CuO) nanofluids with two different weights of 30 g and 50 g. As the temperature increases, the thermal conductivity also increases. Notably, the highest thermal conductivity of 0.578 W/m.K at 30 °C was observed for the 0.79% CuO 80 nm/deionised water nanofluid. Conversely, the lowest thermal conductivity of 0.343 W/m.K at 5 °C was obtained for the 0.47% CuO 80 nm/deionised water nanofluid. Based on these findings, it can be inferred that the enhancement in thermal conductivity is influenced by both the concentration of nanoparticles and the temperature. The rise in temperature leads to an increase in thermal conductivity. Furthermore, the thermal conductivity of the CuO (80 nm)/deionised water nanofluid was found to be higher than that of the Al_2O_3 (80 nm)/deionised water nanofluid at the highest concentration. These trends align with the conclusions drawn by Asthana *et al.,* [56] and Sandhu *et al.,* [57].

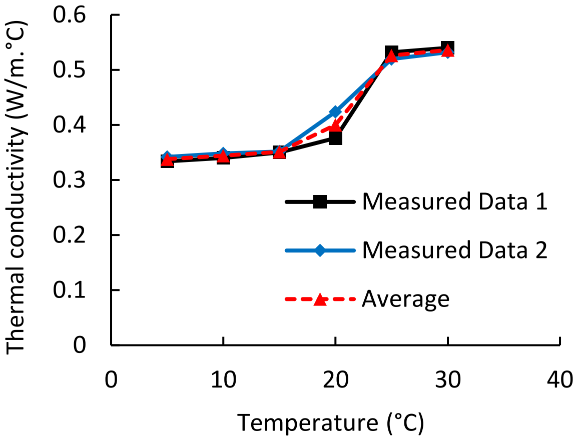


Fig. 9. Thermal conductivity of Al_2O_3 (80 nm-30 g)/deionised water) (0.75%)

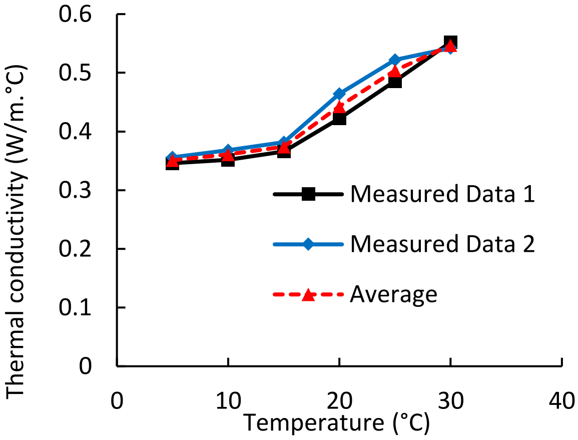


Fig. 10. Thermal conductivity of Al_2O_3 (80 nm-50 g)/deionised water) (1.25%)

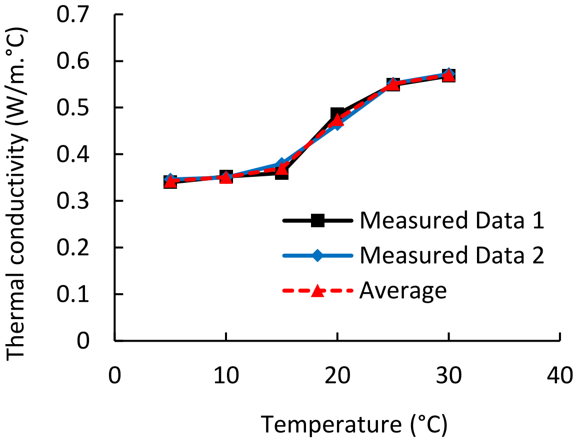


Fig. 11. Thermal conductivity of CuO (80 nm-30 g)/deionised water (0.47%)

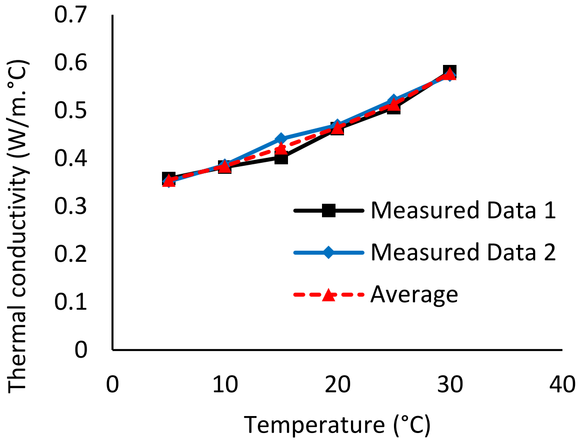


Fig. 12. Thermal conductivity of CuO (80 nm-50 g)/deionised water (0.79%)

3.2.2 Viscosity and nanofluids stability

The results obtained from the viscosity measurements revealed that, under the given conditions of temperature, volume concentration, and viscosity measurement level, the viscosity of all types of nanofluids decreased as the temperature increased. However, it was observed that the viscosity of CuO 80 nm/deionised water nanofluids was higher than that of Al_2O_3 80 nm/deionised water. This increase in viscosity with temperature can be attributed to the presence of an excessive amount of counter ions in the cationic surfactant solution, as supported by previous studies by Sandhu *et al.,* [57] and Abdullah *et al.,* [58]. Additionally, the viscosity of the nanofluids was found to be influenced by the measurement level, with the lowest level (0.2 litre) exhibiting the highest viscosity compared to the highest level (0.8 litre). This variation in viscosity levels can be attributed to the sedimentation of the nanofluid mixture, which leads to differences in viscosity throughout the fluid.

The results from the experiment indicate that as the number of days of sedimentation increases, the standard deviation of the nanofluids also increases significantly. Specifically, the standard deviation of the 0.47% CuO 80 nm/deionised water nanofluid is smaller compared to the standard deviations of the 0.75% Al_2O_3 80 nm/deionised water and 0.79% CuO 80 nm/deionised water nanofluids. This suggests that the distribution of CuO particles in the liquid is more uniform than that of Al_2O_3 particles. A larger standard deviation indicates a wider dispersion of data, indicating less stability, while a smaller standard deviation indicates data that is closely grouped around the mean, indicating greater stability as mentioned by Wenhao [59]. The instability of the nanofluid mixture is caused by various forces, including the Van der Waals attractive force, gravitational force, buoyancy force, and electrostatic repulsive force, which result in the formation of sediment as mentioned by Adewumi *et al.,* [60]. In conclusion, the nanofluids with the lowest volume concentration of CuO 80 nm/deionised water exhibit greater stability compared to Al_2O_3 80 nm/deionised water nanofluids. Table 7 shows the summary data of Al_2O_3/deionised water and CuO/deionised water standard variation from day 1 until day 3. Figure 13 displays the relationship between standard deviation and day of sedimentation.

Table 7
The standard deviation data of Al_2O_3/deionised water and CuO/deionised water

Day	0.75 % Al_2O_3 80nm/deionised water	1.25 % Al_2O_3 80nm/deionised water	0.47 % CuO 80nm/deionised water	0.79 % CuO 80nm/deionised water
1	0.00001414	0.00001886	0.00000816	0.00001633
2	0.00002160	0.00002449	0.00001247	0.00002944
3	0.00003091	0.00004028	0.00002055	0.00004028

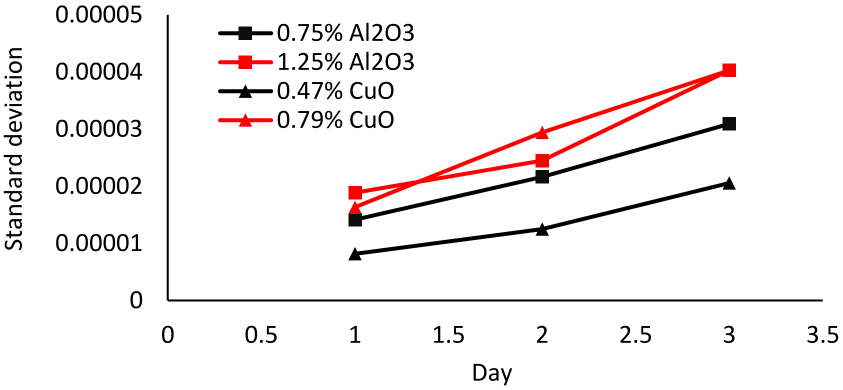


Fig. 13. Thermal conductivity of CuO (80 nm-50 g)/deionised water

3.2.3 Specific heat

The specific heat of the nanofluids was determined by utilizing an Ultrasonic Homogeniser (JY92-IIDN) during thermal transitions. To ensure accuracy, the measurements were performed twice, and the average specific heat value was subsequently analysed. Eq. (2) was employed to calculate the specific heat of the working fluids, assuming a constant heat energy. The relationship between specific heat and volume concentration is illustrated in Figure 14 and Figure 15. The results indicate that as the volume concentration increases, the specific heat of Al_2O_3 (80 nm)/deionised water and CuO (80 nm)/deionised water decreases. The highest specific heat was observed for 0.75% Al_2O_3 80 nm/deionised water (473,684 J/kg.°C), while the lowest was for 0.79% CuO 80 nm/deionised water (337,500 J/kg.°C). Furthermore, it was noted that the specific heat of 0.75% Al_2O_3 80 nm/deionised water nanofluids was the highest among all the nanofluids evaluated in this study. This decline can be attributed to the greater number of particles per unit volume that need to be heated. These findings align with previous results, which also observed a noticeable decrease in the specific heat of Al_2O_3/deionised water nanofluids with increasing volume concentration. Based on these observations, it can be concluded that the reduction in specific heat is dependent on the volume concentration of the nanofluids. At the minimum concentration, the specific heat of Al_2O_3 (80 nm)/deionised water nanofluid was found to be higher than that of CuO (80 nm)/deionised water nanofluid. This can be attributed to the fact that although copper has better heat conductivity than aluminium, aluminium's lower density allows it to dissipate heat more effectively into the surrounding air compared to copper as mentioned by Chakraborty and Panigrahi [61].

$$\text{Standard Deviation} = \sqrt{\frac{\sum (xi-\mu)^2}{N}} \tag{2}$$

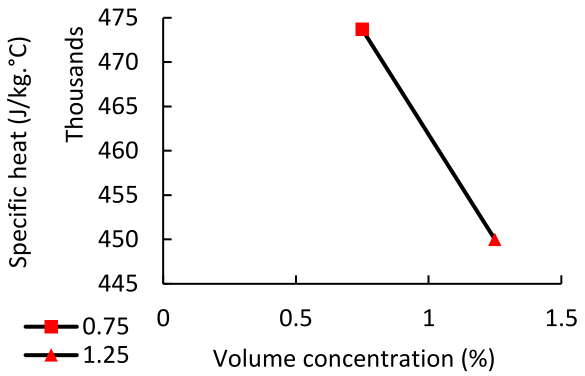


Fig. 14. Specific heat of Al_2O_3 (80 nm)/deionised water

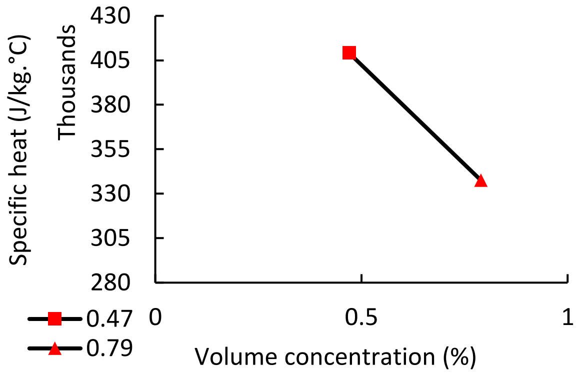


Fig. 15. Specific heat of CuO (80 nm)/deionised water

3.3 Heat transfer Performance of Working Fluids Result (Dynamic State)

The experimental setup aimed to replicate a heat exchanger configuration to determine the amount of heat gained or lost. Initially, the experiment was conducted using Al_2O_3 (80 nm)/deionised water, followed by CuO (80 nm)/deionised water nanofluids. The volumetric flow rate, mass flow rate, and temperature of the experiment were then recorded. Figure 16 and Figure 17 depict the relationship between heat transfer rate and volume concentration. The results indicate that as the volume concentration increases, the heat transfer rate of Al_2O_3 (80 nm)/deionised water and CuO (80 nm)/deionised water decreases. The highest heat transfer rate was observed for 0.75% Al_2O_3 80 nm/deionised water (21,326 J/s), while the lowest was for 0.79% CuO 80 nm/deionised water (10,724 J/s). Furthermore, it was noted that the heat capacity of 0.75% Al_2O_3 80 nm/deionised water nanofluids was the highest among all the nanofluids evaluated in this study. This can be attributed to the fact that Al_2O_3 can dissipate heat more effectively into the air compared to CuO, due to its lower density, resulting in reduced pressure drop. These findings align with previous research conducted by Bin-Abdun *et al.,* [3], Naseema *et al.,* [62], and Al-Araji *et al.,* [63].

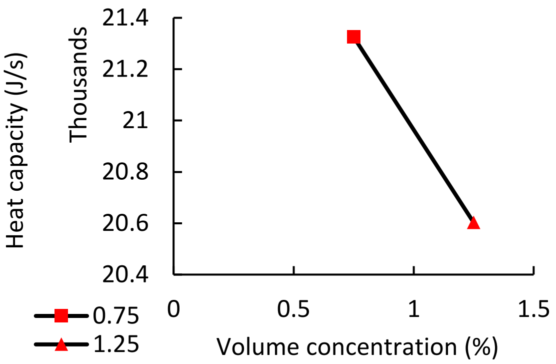


Fig. 16. Specific heat of CuO (80 nm)/deionised water

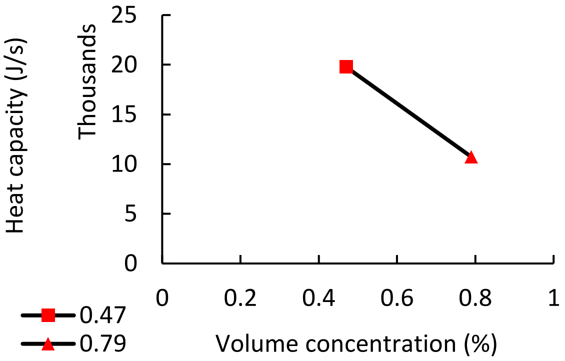


Fig. 17. Specific heat of CuO (80 nm)/deionised water

4. Conclusions

This article is centred around the assessment of stability, thermophysical properties, and heat transfer performance of two different types of nanofluids: Al_2O_3/deionised water and CuO/deionised water. The evaluation considers various factors such as nanoparticle size, nanoparticle type, and volume concentrations. The quantitative findings of this study are categorized into two phases: static state and dynamic state. During the static state, the thermophysical parameters including thermal conductivity, viscosity, and specific heat were measured for the nanofluids. On the other hand, the dynamic state aimed to replicate a heat exchanger setup to determine the heat transfer rate. By adopting this comprehensive approach, a thorough comprehension of the behaviour and properties of these nanofluids under different conditions can be achieved.

4.1 Conclusions

The initial objective was achieved through the comparison of nanofluids' stability, which were prepared using a two-step method and had varying nanoparticle volume concentrations ranging from 0.47% to 1.25%, without the use of any surfactant. The results indicated that the nanofluids with the lowest standard deviation, specifically the 0.47% CuO 80 nm/deionised water nanofluids, demonstrated the highest level of stability. The second objective was accomplished by investigating the impact of various variables, such as temperature, volume concentration, and nanoparticle type, on the properties of the nanofluid under both static and dynamic conditions. Noteworthy findings include

i. The thermal conductivity of the nanofluid is influenced by temperature, volume concentration, and nanoparticle size. Specifically, the CuO (80 nm)/deionised water nanofluid exhibited the highest thermal conductivity among the tested conditions.
ii. The viscosity of the nanofluid is affected by the working temperature, volume concentration, and nanoparticle size. Notably, the 0.79% CuO 80 nm/deionised water nanofluids demonstrated the highest viscosity among the tested conditions.
iii. The specific heat of the nanofluid is dependent on the volume concentration. The greatest decrease in specific heat was observed in the CuO 80 nm/deionised water nanofluid, while the 0.75% Al_2O_3, 80 nm/deionised water nanofluid exhibited the highest specific heat value of 473,684 J/kg.°C.
iv. The heat transfer rate of the nanofluid is influenced by the volume concentration. The greatest decrease in specific heat was observed in the CuO 80 nm/deionised water nanofluid, while the 0.75% Al_2O_3, 80 nm/deionised water nanofluid exhibited the highest heat transfer rate value of 21,326 J/s.

4.2 Recommendations

In addition, the recommendations as below

i. Due to the lack of consistency among experimental data from different researchers, it is imperative to conduct further experimental and theoretical research to identify the primary parameters that determine the performance of nanofluids. This will help in establishing a more comprehensive understanding of their behaviour and properties.
ii. The properties of nanofluids are significantly influenced by the shape of the additives present in them. Therefore, it would be intriguing to explore new production procedures that allow for the development of nanofluids with a controllable microscopic structure. This research project could potentially lead to the enhancement of nanofluid properties and open new avenues for their applications.
iii. The stability of nanofluids is of utmost importance for both scientific research and practical applications. It is crucial to place greater emphasis on studying the stability of nanofluids, particularly in terms of long-term stability, stability under practical conditions, and stability after multiple heat cycles. This will ensure their reliability and effectiveness in various applications.
iv. There seems to be a limited amount of research conducted on the thermal performance of nanofluids at high temperatures. Exploring the behaviour and performance of nanofluids under high-temperature conditions could expand their application scope and unlock their potential in various industries.
v. It is worth noting that high temperatures can accelerate the degradation of surfactants used as dispersants in nanofluids, leading to increased foam formation. Future studies should consider these aspects to gain a comprehensive understanding of nanofluids and their potential applications. By adopting a comprehensive approach, researchers can contribute to the advancement of knowledge in this field and pave the way for practical implementation of nanofluids.

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