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A SHORT SURVEY OF THE THERMOPHYSICAL CHARACTERISTICS OF THE HYBRID NANOFLUIDS

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Abstract. Nanofluids (NFs) are suspensions of nanoparticles in a fluid with improved characteristics at low concentrations, gaining importance in various technical sectors like automotive, healthcare, power plant cooling systems, and computing equipment. Better heat transfer capacities, thermal conductivities, and stability can be counted among the advantages that NFs can provide. Whereas nanoparticle addition may also raise viscosity, albeit increasing thermal conductivity, curbing their thermal advantages. Stability and temperature behavior are crucial issues. Hybrid nanofluids (HNFs) are highly sought after due to their superior thermophysical properties compared to conventional base fluids. To produce these high-performance heat transfer fluids, two or more different nanoparticles are suspended in a base fluid. By highlighting their remarkable characteristics and uses, this research reveals the great potential of HNFs, especially in thermal operations. Binary and ternary thermophysical properties, including heat transfer rate, heat transfer coefficient, friction factor, thermal performance factor, Nusselt number, heat transfer efficiency, zeta potential, stability, thermal efficiency, isobaric heat capacity, and specific heat capacity, have been used to categorize the literature. In addition, the present work scrutinizes studies related to HNFs, particularly those focused on thermal conductivity and viscosity, and covers ingredients such as nanoparticle type, concentration, temperature, and surfactant use for the purpose of preventing sedimentation and agglomeration. Moreover, the paper delivers an improved investigation on NFs' properties, especially involving their physical and rheological aspects in the context of heat transfer enhancement.

Keywords: nanofluids, hybrid nanofluids, heat conductivity, viscosity, rheology

1.Introduction. The rapid technological advancements in today's technology era have led to a need for heat transfer enhancement in the thermal industry. Conventional single-phase fluids are used in real-time heat exchange units, but they struggle to enhance heat transfer coefficient and performance. Researchers have discovered the employment of high thermal conductive fluids, such as NFs, as a promising alternative. NFs are colloidal suspensions at the nanoscale in base fluids like ethylene glycol, ethanol, and water, which facilitate Brownian agitation and increase heat transfer rate. This approach is considered a promising alternative to conventional single-phase fluids. Fig. 1 presents a classification of research trends in HNFs, focusing on thermophysical parameters and HNF types. The figure has three core attention areas as follows: thermal conductivity, dynamic viscosity, and concurrent examinations. Each ingredient's subdivisions distinguish between a binary HNF and a ternary HNF also emphasizing the complication and invention of the NFs being researched. This distinction is crucial in understanding the intricacies of HNF research.

The primary advantage of HNFs is their excellent thermal conductivity and heat transfer

characteristics, which enhance heat transfer efficiency, as highlighted in Figure 2. Conventional NFs have established technology and simplified formulation, indicating maturity, production efficiency, and cost reduction. HNFs offer superior heat transfer capabilities, making them useful in various applications, especially energy storage systems. The usefulness of HNFs can be enhanced through optimizing their characteristics and efficiency.

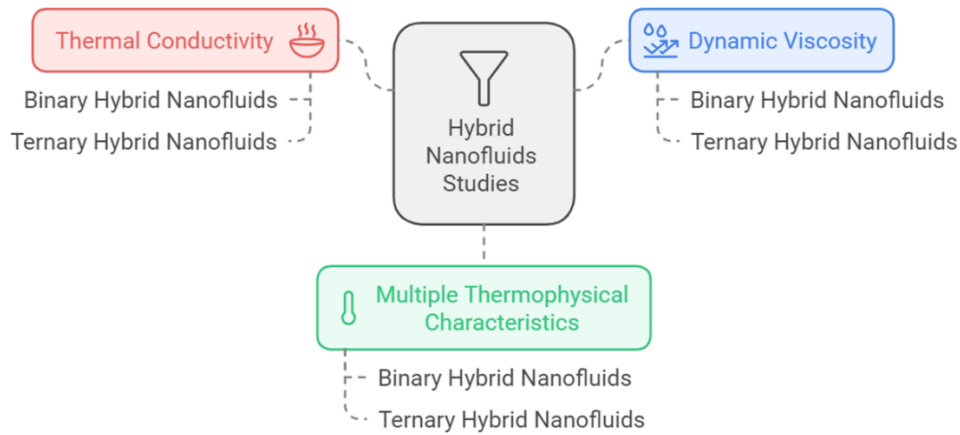


Fig. 1. Sections of the presentation

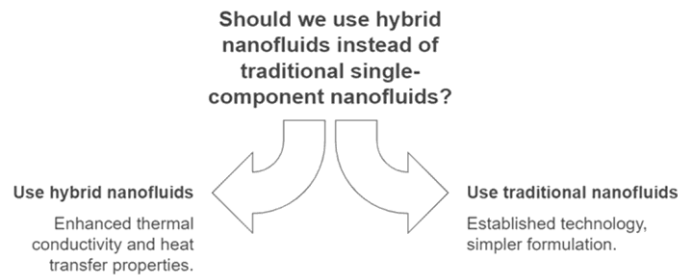


Fig. 2. Main questions about hybrid nanofluids in thermal systems

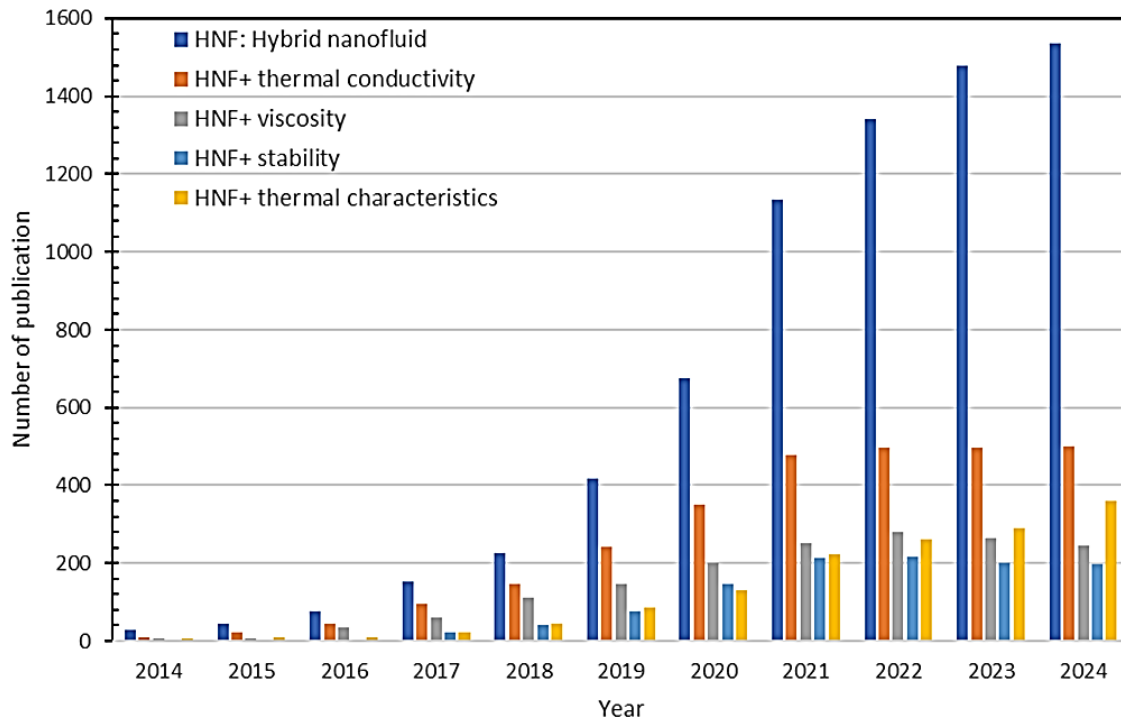


Fig. 3. Number of publications on hybrid NFs by year in WOS database

Even though the studies on NFs were initiated more than three decades, it gained momentum only in the last decade, as shown in Fig. 3. Opportunities and obstacles of NFs in thermal applications are summarized in Table 1. Although NFs hold significant potential for heat transfer applications, their stability issues, which can substantially influence performance, must be carefully addressed.

Table 1. Potential benefits and limitations of nanofluids in thermal applications

Opportunities	Obstacles
Enhanced heat transfer	Complex formulation
Energy storage benefits	Stability issues
Optimizable performance	Cost of nanoparticles
Versatile application	Compatibility concerns
	Potential environmental and recycling issue

Fig. 4 reveals the connection between these categories and efficiency in heat transfer, thus pointing out the advantages of using HNFs for advancing thermal control. The investigation delivers thorough information on HNFs and their promising aspects. The paper highlights the significance of enhancing viscosity and increasing thermal conductivity, which can also be seen as the core topic of most studies. In addition to these, such factors as viscosity, stability, and general thermal characteristics have also acquired interest. These novel research directions also enable perceptive analysis of HNF production and point out the present issues by carrying out proposed improvements and thus dependability, efficiency, and clarity of HNFs in many fronts of industrial processes.

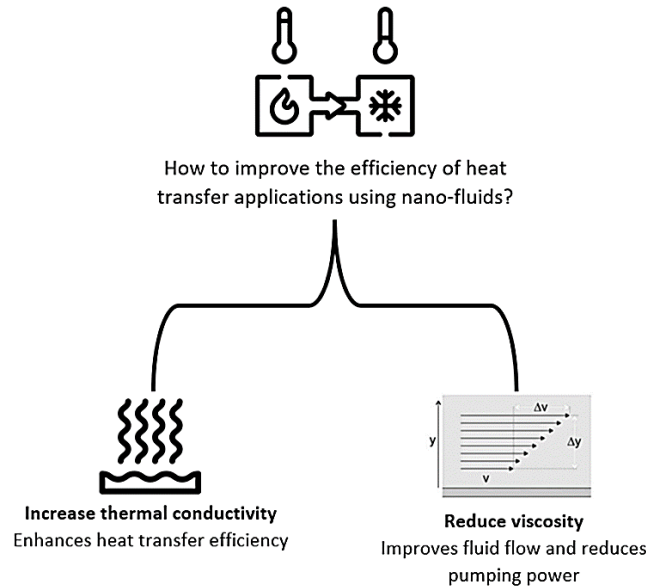


Fig. 4. The efficiency aspect in heat transfer applications with respect to thermal conductivity and viscosity

2.Arrangement of nanofluids. The literature consists of two fundamental techniques: one-step and two-step methods. The one-step method offers long-term stability and a homogeneous structure but is complex and costly. The two-step method, nevertheless, has disadvantages like sedimentation and homogenization requirements. Sedimentation can occur through either method, depending on the reagents and procedures used [2]. Despite these, the two-step method is often preferred due to its cost,

preparation, and practicality [3]. This method was used in this study to formulate NFs.

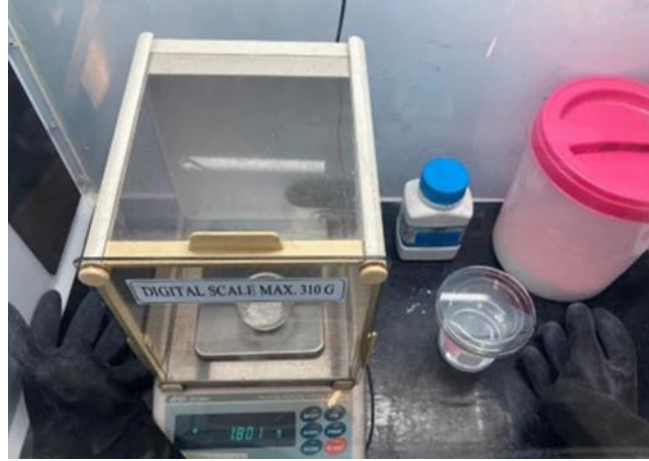


Fig. 5. A typical digital scale

The studies use a digital scale, as shown in Figure 5, to weigh nanoparticles and base fluid, determining the required amounts for different nanofluids. In this figure, the A&D Weighing GF-300 Digital Balance is seen measuring the masses of each substance. The procedure is conducted within an enclosure set up to make up nanofluids. Figure 5 depicts this arrangement and digital balance. For example, to create 1, 2, and 3% NFs, 2.116 g, 4.275 g, and 6.478 g of nanoparticles were needed in 100 g of an ethylene-water-based fluid. The volumetric fraction of nanoparticles was found by Eq. 1, which can be employed in NF and HNF investigations to calculate volumetric concentrations.

$$\phi = \frac{\left(\frac{m_{\text{SiO}_2}}{\rho_{\text{SiO}_2}}\right)}{\left(\frac{m_{\text{SiO}_2}}{\rho_{\text{SiO}_2}}\right) + \left(\frac{m_{\text{EG-w}}}{\rho_{\text{EG-w}}}\right)} \times 100 \quad (1)$$

$$\phi = \frac{\left[\frac{m_{\text{np1}}}{\rho_{\text{np1}}}\right] + \left[\frac{m_{\text{np2}}}{\rho_{\text{np2}}}\right] + \left[\frac{m_{\text{np3}}}{\rho_{\text{np3}}}\right] + \left[\frac{m_{\text{np4}}}{\rho_{\text{np4}}}\right]}{\left[\frac{m_{\text{np1}}}{\rho_{\text{np1}}}\right] + \left[\frac{m_{\text{np2}}}{\rho_{\text{np2}}}\right] + \left[\frac{m_{\text{np3}}}{\rho_{\text{np3}}}\right] + \left[\frac{m_{\text{np4}}}{\rho_{\text{np4}}}\right] + \left[\frac{m_{\text{bf}}}{\rho_{\text{bf}}}\right]} \times 100$$



Fig. 6. An ultrasonic homogenization apparatus [from Atmaca et al. [4] with permission from Springer]

The studies involve adding weighed nanoparticles and surfactants to a base fluid, which is then blended by means of a homogenizer. For example, the samples are homogenized via a Hielscher UP200Ht for 2 hours as shown in Fig. 6, causing a temperature increase and a change in nanoparticle volumetric fraction. Resulting in a uniform dispersion of nanoparticles has been of enormous significance for stability within the production of nanofluids. For this reason, sonication and surfactants were utilized to overcome this problem by adjusting parameters according to information from literature. To impede the nanofluids' evaporation and to hold the ambient temperature comprise great obstacles. A temperature-controlled bath is employed to adjust the temperature within the sonication process to circumvent this obstacle. The NFs are cooled using a chiller to maintain nanoparticle concentrations.

2. Measurements of nanofluids' thermophysical properties. Since it impacts the thermal properties, stability is of great significance for nanofluids. To acquire homogenous thermal properties at every point of the mixture, maintaining a uniform structure is required. Waiting time, suspension pH, base fluid type, nanoparticle type, diameter, and nanofluid preparation comprise ingredients influencing stability. In this context, the Malvern Zetasizer Nano ZS has been extensively utilized to measure the stability of nanofluids. For sample volumes within the interval of 150-180 μl , the device can measure Zeta potential along a wide range of particle sizes. The nanofluids are sonicated for 20 minutes before measurements, with each measurement taking around 2 minutes. The average value of three measurements is used as the last outcome.

Lee et al. [5] defined excellent stability as a zeta potential value above 60 mV, physical stability between 60 and 30 mV, and limited stability below 20 mV. In Fig. 7, The zeta potential value of 1% ZnO 0.50-SiO₂ 0.50 NF was measured at Yildiz Technical University's Science and Technology Application and Research Center. The zeta potential value is a measure showing that raising it raises thermal conductivity. The sample has a - 14 mV zeta potential value after preparation. 1% ZnO 0.50-SiO₂ 0.50 nanofluid is considered limited stability, even with a 10% gum Arabic surfactant. Factors such as density, ultrasonication time, nanoparticle shape, and high NF concentration may negatively affect stability. After the NFs are made up, around 100 mL are kept for visual observation as shown in Figure 8. The NFs are replaced in cylindrical bottles cleaned with alcohol and dried afterwards. Bottles of NFs are kept airtight at room temperature. All NFs are snapped at 1, 7, 14, and 28 days after creation for the control of sedimentation by visual observation. The outcomes of visual observation are given in Table 2. Fig. 8 illustrates images of hybrid nanofluids as well [4].

Table 2. Durations for which nanofluids showed no sedimentation

Nanofluid/Vol. concentration	0.1%	0.5%	1%
MWCNT	7 days	1–7 days	1–7 days
SiO ₂	> 28 days	> 28 days	> 28 days
ZnO	1–7 days	1–7 days	1–7 days
TiO ₂	> 28 days	1–7 days	1–7 days
SiO ₂ -TiO ₂	> 28 days	–	–
SiO ₂ -TiO ₂ -MWCNT	> 28 days	–	–
SiO ₂ -TiO ₂ -MWCNT-ZnO	1–7 days	–	–

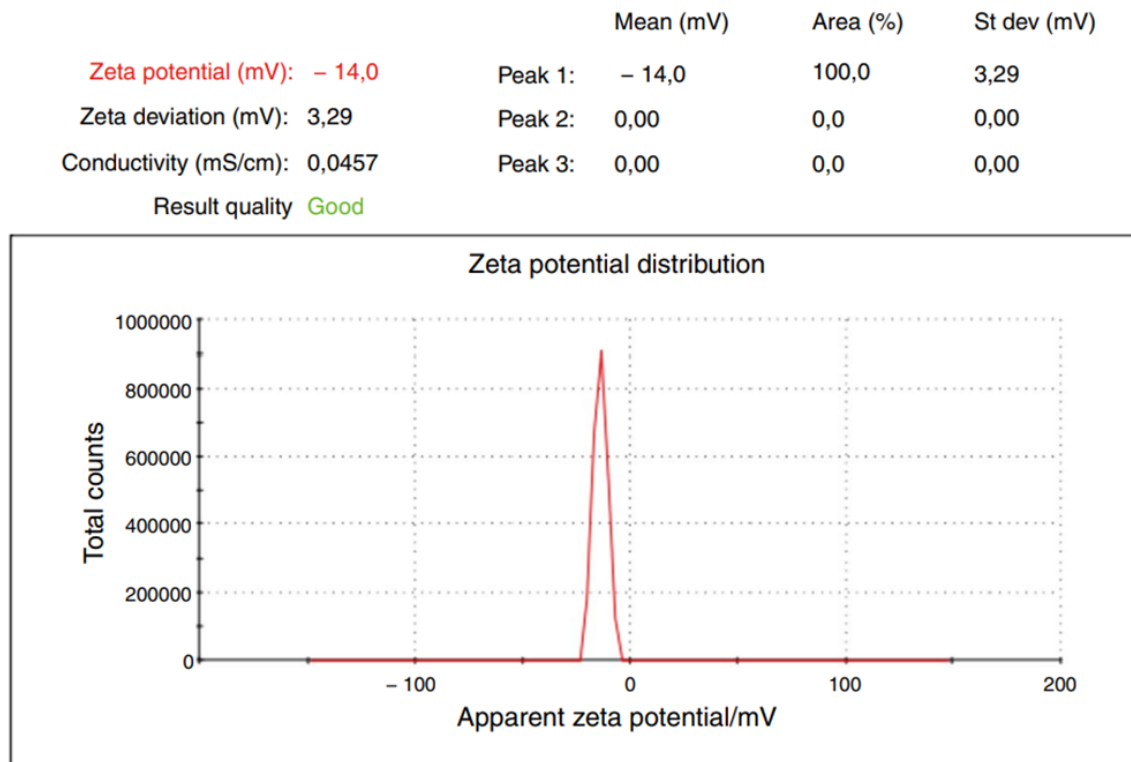


Fig. 7. Zeta potential value of 1% ZnO 0.50-SiO₂ 0.50

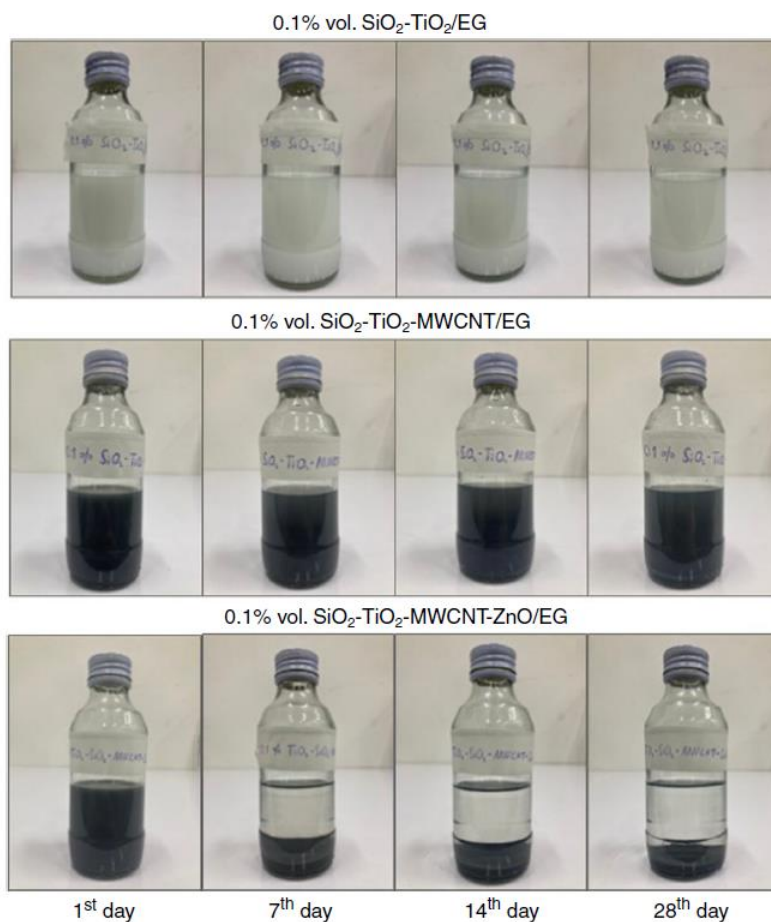


Fig. 8. Visual observation of hybrid nanofluids 1, 7, 14, and 28 days after formulation [from Atmaca et al. [4] with permission from Springer]

These findings in Table 2 have brought literature to the conclusion to produce hybrid nanofluids having a volume concentration of 0.1% to diminish nanoparticle sedimentation. Resembling behavior of SiO_2 and TiO_2 single nanofluids at 0.1% volume concentrations, deterioration was not observed after 28 days for the SiO_2 – TiO_2 /EG nanofluid. After 28 days, the SiO_2 – TiO_2 –MWCNT/EG nanofluid has not deteriorated depicting much better stability. The SiO_2 – TiO_2 –MWCNT–ZnO/EG nanofluid, because of instabilities, has solidified in 7 days. The ZnO nanoparticles were rather great, and the material was dense.

One more analysis method employed to figure out the disposition of NF is FE-SEM imaging. This technique discloses the properties of NF, such as the shape of nanoparticles, sedimentation and nanoparticle sizes, etc.

As an example, the study [6] utilized FE-SEM imagery using a Nova Nanosem 450 instrument, which can operate under various pressures and achieve magnifications of up to 500,000x. The instrument's beam voltage can be adjusted between 200 V and 30 kV. Sample arrangement involved locating a NF sample onto a copper holder, drying it, and then coating the samples with a gold and palladium alloy to enhance electron transmissibility.

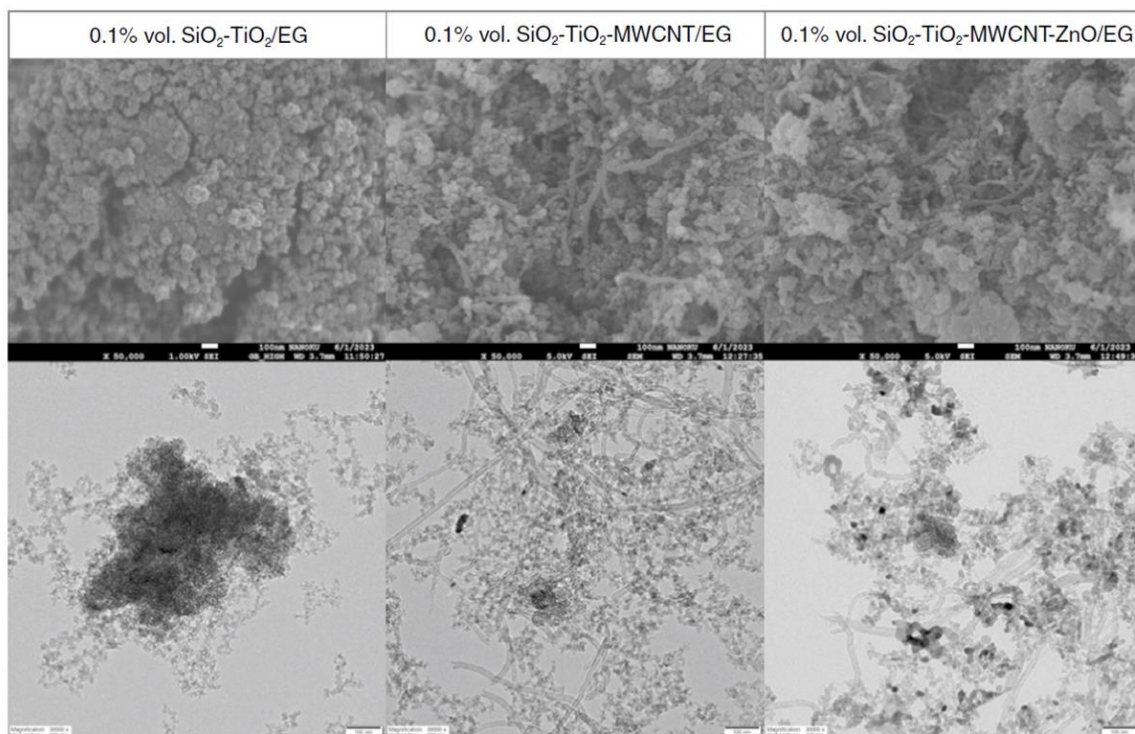


Fig. 9. FE-SEM (top, 50,000 $\times$) and FE-TEM (bottom, 30,000 $\times$) images of hybrid nanofluids [from Atmaca et al. [4] with permission from Elsevier]

As such, there are not any contamination views after drying in FE-SEM images of HNFs. A homogenous spread in two spherical structures is seen for the SiO_2 – TiO_2 nanoparticles, as the SiO_2 – TiO_2 –MWCNT–MWCNT nanoparticles are of cylindrical tubes uniformly scattered between two spherical structures. As can also be observed from Figure 9, all three nanoparticles are of an evenly spread structure. The images have been demonstrated at 50,000 $\times$ magnification.

3.1. Measuring Thermal Conductivity. Thermal conductivity is a crucial property for NFs, commonly measured using the hot wire method in Figure 10. There are several major components to this figure. The sample material has been involved in a 250 mm long; 25 mm diameter cylinder made of polypropylene. The hot wire cell is a Teflon-coated platinum wire of 190 mm and of diameter 76.20 μm . Furthermore, the thickness of the Teflon is 31.75 μm . The KD 2 Pro thermal conductivity analyzer system, shown in Figure 11, is widely used by researchers and used at ambient pressure. Temperatures are controlled by using a heating-cooling water bath within thermal conductivity measurements, dynamic viscosity measurements, and nanofluid sample preparation.

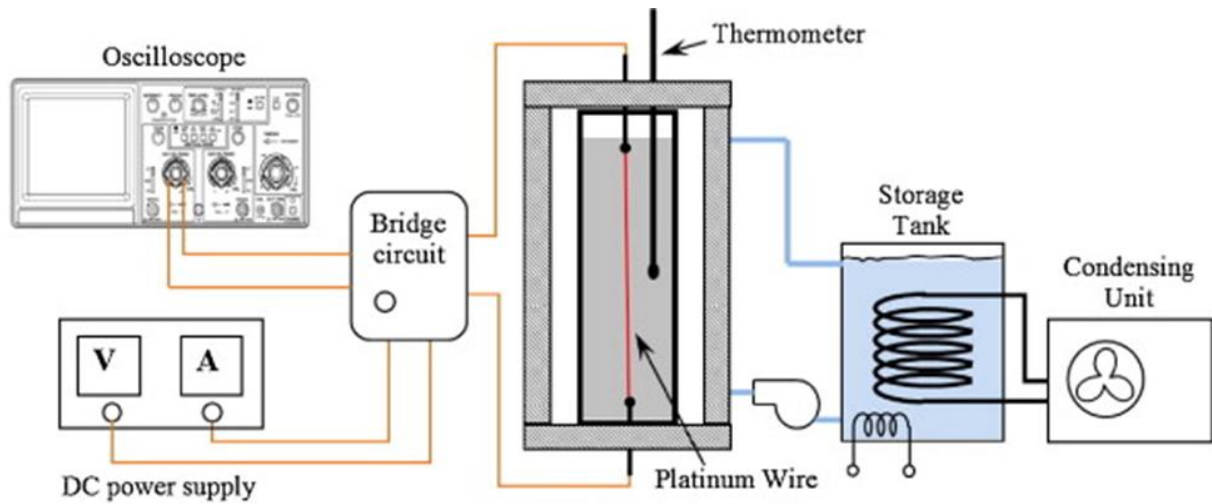


Fig. 10. The transient hot wire apparatus [from Yiamsawasd et al. [7] with permission from Elsevier]

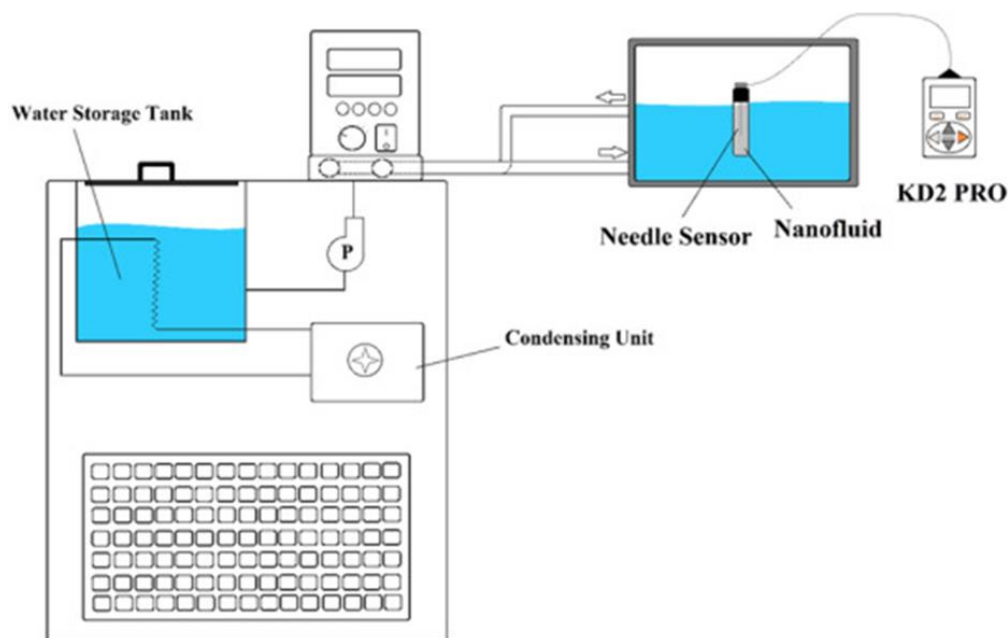


Fig. 11. An example of a typical experimental setup for thermal conductivity research [from Dalkilic et al. [8] with permission from Elsevier]

The experiment apparatus in Figure 11 consists of three discrete key components. Heating-cooling water baths, ultrasonic homogenizer, and thermal conductivity analyzer comprise that apparatus. The heating-cooling water bath can be operated between temperatures $-10\text{ }^{\circ}\text{C}$ and $100\text{ }^{\circ}\text{C}$ and has been used within $25\text{ }^{\circ}\text{C}$ - $60\text{ }^{\circ}\text{C}$ in the work in the literature. Ultrasonic homogenizer (Hielscher UP200Ht) can be utilized between capacities of 0 and 200 W, and from 0 to 26 kHz.

3.2 Measuring Thermal Conductivity. Prior to measurements, KD 2 Pro thermal conductivity analyzer should be calibrated by di-water, and the outcomes of the contrast with reference data [9] are illustrated in Figure 12 as an example. In this figure, a deviation of 2.2% has been noticed between experimental and reference thermal conductivity data [10]. Initially, the necessary amounts of samples (100 mL) are mixed by the homogenizer for one hour. Afterward, samples have been put into the water bath for thermal balance. Then, measurements are drawn and recurred three times by KD 2 Pro thermal conductivity analyzer. The average results have been determined as the results.

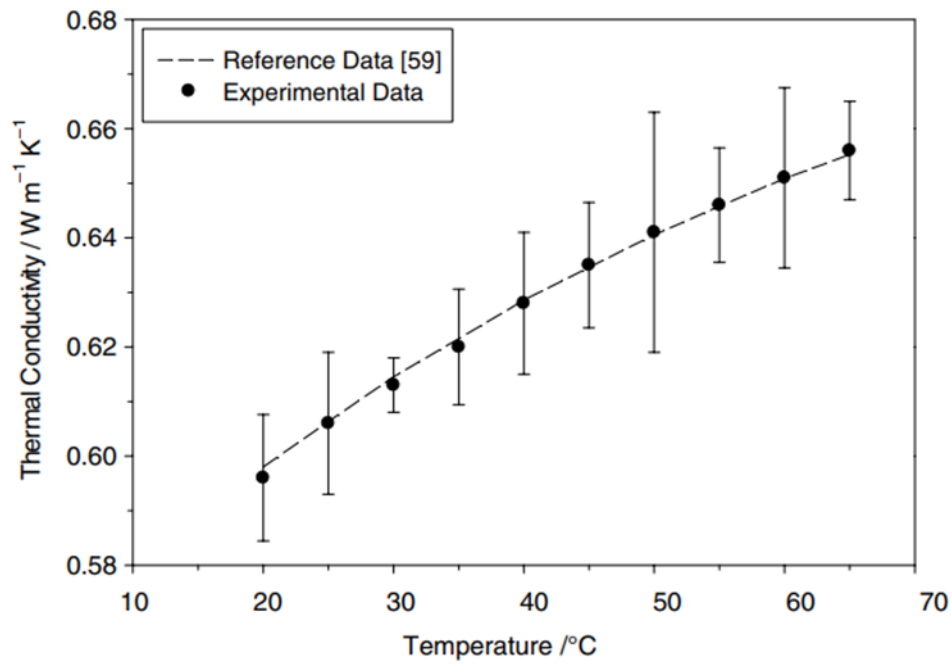
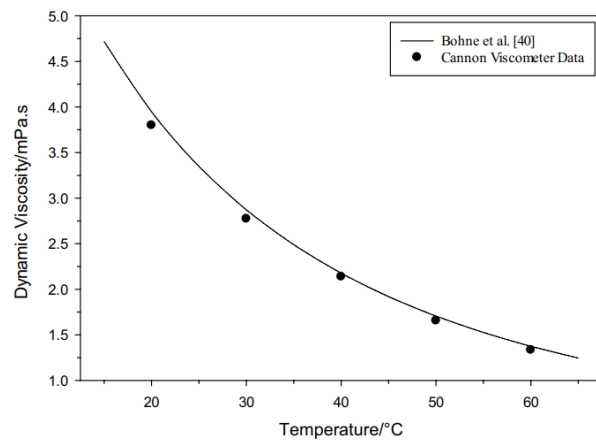


Fig. 12. Comparison of thermal conductivity findings with reference data [9] apparatus [from Yalcin et al. [10] with permission from Elsevier]

For example, a Cannon-Fenske opaque viscometer, as shown in Figure 13a, can be used for accurate measurements of viscosity in nanofluid samples, with an accuracy of $\pm 0.2\%$. Base fluid viscosity measurements are compared with reference data before using nanofluid samples, as shown in Fig. 13b.



a)



b)

Fig. 13. Experimental setup for viscosity measurement [from Dalkilic et al. [11] with permission from Elsevier] (a) and comparison of measured data with reference one [6] (b)

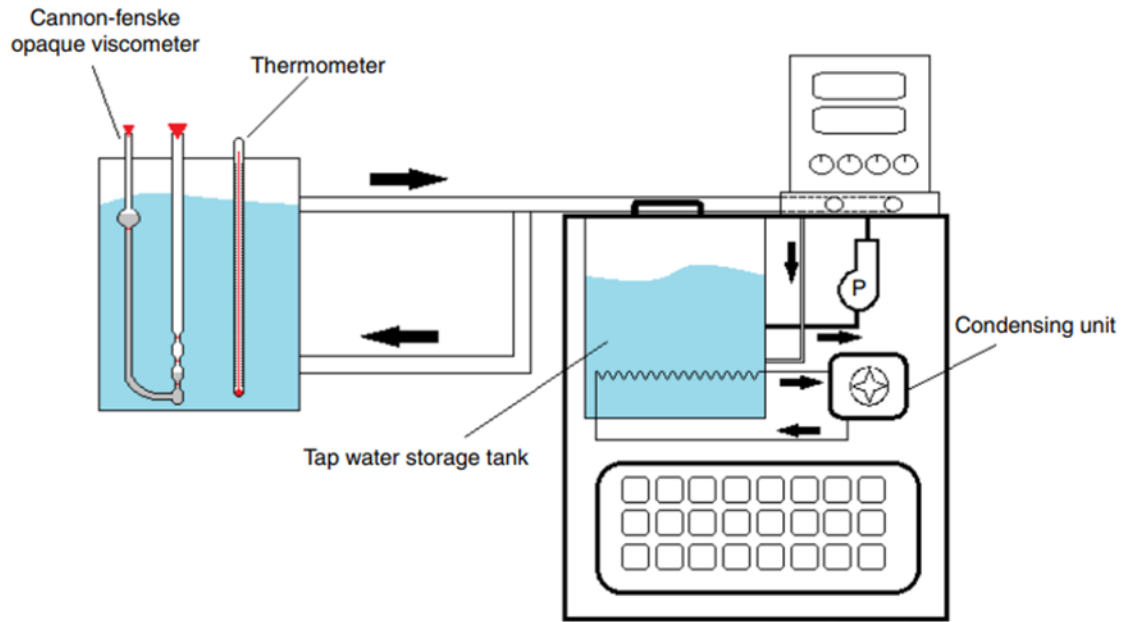


Fig. 14. Experimental setup for viscosity measurements [from Yalcin et al. [6] with permission from Elsevier]

Moreover, the depiction of the experimental apparatus is demonstrated in Figure 14. By means of a Hielscher UP200HT ultrasonic homogenizer adjusted to the highest capacity and frequency, by two hours the samples were homogenized. Eq. (2) is employed to calculate dynamic viscosity.

$$\mu_{nf} = c \times t \times \rho_{nf} \quad (2)$$

where c (cSt/s) is a coefficient that is described by the device producer, and each viscometer has a distinct coefficient. The variable, t , is time in seconds, which is employed to describe the movement of NF in the viscometer tube. ρ (kg/m^3) is the density of the prepared NF sample. Density can be revealed by Pak and Cho's [13] equation.

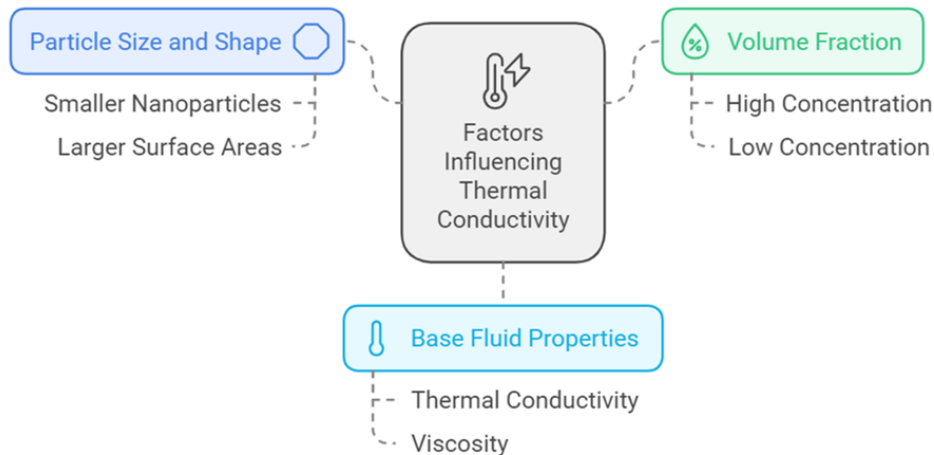


Fig. 15. The factors that influence thermal conductivity of HNFs

Fig. 15 outlines the ingredients impacting the thermal conductivity of HNFs and their influence on thermal transfer applications. It categorizes factors into blue for nanoparticle characteristics, green for volume fraction, and light blue for base fluid properties. The graphic emphasizes the importance of nanoparticle size and shape, with smaller nanoparticles and larger surface areas being critical. The volume percentage of nanoparticles in the base fluid is also crucial, with high and low concentrations suggesting optimal heat conductivity.

4. Studies related to thermal conductivity of hybrid nanofluids

4.1. Binary hybrid nanofluids' thermal conductivity

Although a significant number of studies have been conducted on HNFs thus far, there has still been a blank to be filled in this area. The thermal conductivity of developed NFs is of great significance with respect to heat transfer processes, since higher thermal conductivity results in better heat transfer rates. Mechanism in the interaction between nanoparticles and comprehending internal physics quite matter regarding thermal conductivity. Without conceding in thermal conductivity, in different working conditions the stability of HNFs should be examined. Additionally, alteration of thermal resistance according to parameters such as nanoparticle size, shape, concentration, nanopowder material, and base fluid employment is required as well. Accurate estimation of thermal conductivity through theoretical models can bring about effective design of heat exchangers in industry.

4.2. Ternary hybrid nanofluids' thermal conductivity

Heat transfer characteristics pertaining to HNFs have rendered them an accepted substitution for conventional heat transfer fluids thanks to their enhanced thermophysical properties. Pumping power, flow behavior, and performance of thermal systems are also affected by dynamic viscosity. The study uncovers the effect of base fluid sort, nanofluid concentration, temperature, shear rate, and viscosity over HNFs. In this regard, it is noted that high nanoparticle content advances thermal conductivity but raises viscosity, which may lead to high pressure losses and hence energy consumption rates. Experimental and modelling investigations have mainly been carried out to comprehend these dynamics spanning many nanomaterial combinations and preparation methods. Critical thermal efficiency and flow optimization of HNFs have recently been the core focus of many works. Influencing ingredients and insights suggested for better advancements are emphasized in this section.

Encouraging outcomes have been received from studies associated with ternary HNFs, whereas there have still been gaps to be filled. Owing to causing more complications compared to binary types, three different nanoparticle sorts are assessed to be more challenging in terms of estimating and regulating their configuration in the base fluid. Relations between nanoparticles, the sort of nanoparticles, and the base fluid comprise the factors determining the thermal performance. In this regard, figuring out the thermal resistance on heterogeneous interfaces is significant. The stability of HNFs is dependent on optimizing the size, arrangement, and proportions of nanoparticles. Because of HNFs' composition, size, and thermal characteristics, the selection of nanoparticles is quite challenging. More attention is needed in the future to improve HNF stability.

Figure 16 presents experimental observations of dynamic viscosity from the work of Yalcin et al. [10]. The dynamic viscosity outcomes had an uncertainty interval of $\pm 3.6\%$. In line with the dynamic viscosity results, the lowest dynamic viscosity variation was found to be 7.29% , corresponding to 0.5% ZnO 0.66-SiO_2 0.33 at the temperature of 50°C , as the maximum dynamic viscosity alteration was observed to be 13.6% , which was referring to 1% ZnO 0.33-SiO_2 0.66 at 50°C .

5. Hybrid nanofluids hybrid nanofluids' dynamic viscosity studies

5.1. Studies related to dynamic viscosity of binary hybrid nanofluids. As depicted in Figure 17, by scrutinizing features such as base fluid preference, temperature, and nanoparticle concentration and their impacts on their characteristics, dynamic viscosity of HNFs is explored. The figure emphasizes the compromise between thermal performance and viscosity, such that growing nanoparticle concentration by and large is enhancing thermal conductivity while growing viscosity which causes higher pressure drops and thus work to transfer the fluid and operating costs.

The dynamic viscosity of HNFs remains underexplored, necessitating a comprehensive rheological investigation across various shear rates, temperatures, and pressures. Techniques like TEM, SEM, DLS, and SANS can be used to examine the binary HNF microstructure and nanoparticle distribution, which directly affect viscosity. However, current theories may not be applicable to binary HNFs, necessitating the development of innovative models to accurately measure these systems' interrelations and microstructure. Such knowledge is crucial for determining pressure loss in flow systems and assessing pumping power requirements.

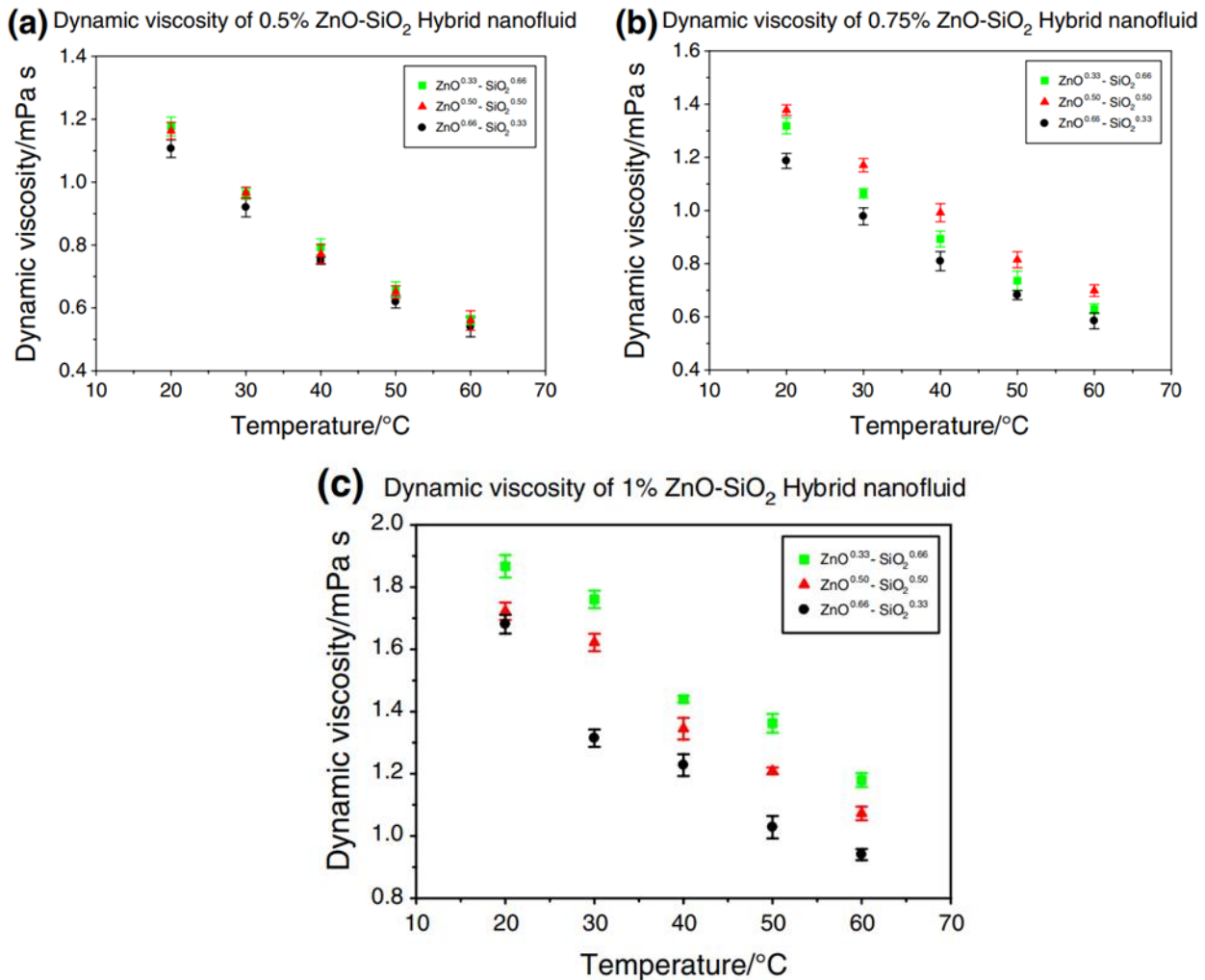


Fig. 16. Dynamic viscosity alteration of ZnO-SiO₂ [from Yalcin et al. [10] with permission from Elsevier]

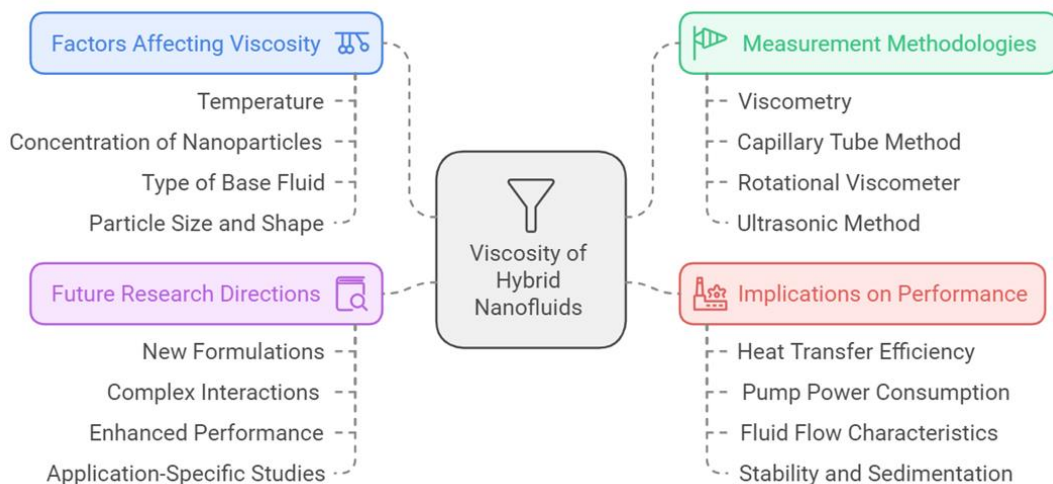


Fig. 17. The affecting factors, future research directions, measurement methods, and performance implications of viscosity of HNFs

5.2. Dynamic viscosity studies of ternary hybrid nanofluids. This section indicates the dynamic viscosity of ternary HNFs and the impact of nanoparticle combinations, temperature, and concentration

on these fluids. Unlike simple Newtonian fluids, ternary nanofluids often have non-Newtonian properties, complicating viscosity behavior. Multi-objective optimization techniques are required owing to the interaction between the base fluid and nanoparticle surfaces generating complex lubricating layers. The distribution and form of nanoparticles considerably affect the viscosity, which also influences the reachable highest concentration prior to getting maximum limits of viscosity. A method integrating engineering, material science, and computer modelling while considering viscosity, thermal conductivity, and pressure drop is necessary for optimized ternary NFs.

For example, Figure 18 shows that all NF concentrations, except for the one with SiO₂ nanoparticles, precipitated during stability tests. HNFs of 0.1% concentration were utilized in following tests. An initial binary HNF was created using SiO₂ and TiO₂ nanoparticles. After 28 days, a viscosity measurement was carried out on the fractions, employing a setting ratio of SiO₂–TiO₂ (1:1). Figure 18a contrasts the binary nanofluid with the base fluid and single nanofluids, encompassing SiO₂ and TiO₂. In comparison to ethylene glycol and single nanofluids, the binary hybrid nanofluid resulted in a lower dynamic viscosity. In addition to SiO₂ and TiO₂ nanoparticles, to generate ternary nanofluids, MWCNT nanoparticles were also employed. Since MWCNT nanoparticles are of a lower viscosity than ZnO, for the ternary nanofluid generation process, they were preferred.

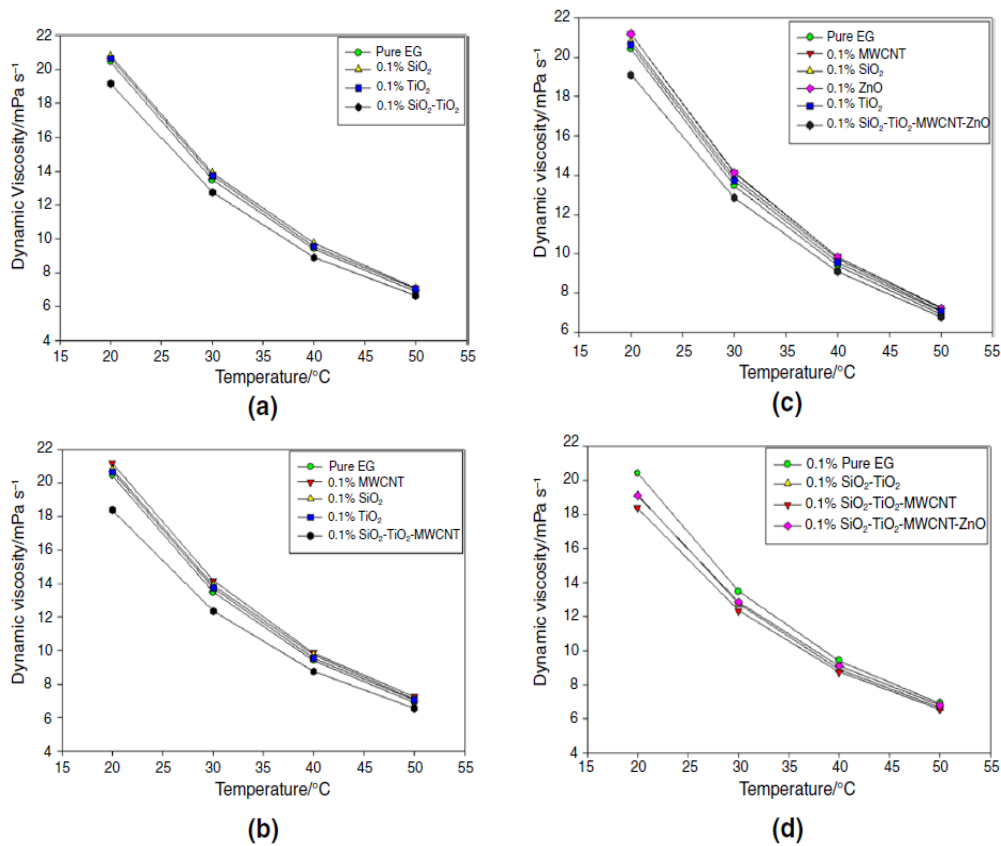


Fig. 18. Comparison of dynamic viscosities of a binary, b ternary, and c quaternary nanofluids with their components, and comparison of dynamic viscosities of hybrid nanofluids [from Atmaca et al. [4] with permission from Elsevier]

6. Multiple thermophysical characteristics studies of hybrid nanofluids. This part explores the thermophysical properties of HNFs, including viscosity, thermal conductivity, density, heat transfer rate, heat transfer coefficient, friction factor, thermal performance factor, Nusselt number, and heat transfer efficiency. It also tracks stability-related metrics like zeta potential and thermal efficiency to ensure long-term suitability in various thermal settings. The study examines the relationship between these thermophysical characteristics and their impact on operating conditions, temperature, base fluid type, nanoparticle concentration, and shape. By comparing the efficiency of HNFs to binary and mono

equivalents, the influence of different nanoparticle groupings and concentrations has been reported in the literature. HNF was created by Kishore et al. [14] using CTAB and distilled water to produce copper-graphene hybrid nanoparticles. Although no stabilizer has been employed, nanofluids have kept their stabilities, and their thermophysical properties have been observed. Contrary to the distilled water, an HNF of 0.02% has raised density, viscosity, and thermal conductivity approximately by 9.95%, 13.5%, and 12.5%, respectively.

7.Conclusion. This paper unveils the strong potential of HNFs particularly in thermal processes, by highlighting their exceptional traits and applications. The literature has been classified by binary and ternary thermophysical properties also referring to their heat transfer rate, heat transfer coefficient, friction factor, thermal performance factor, Nusselt number, heat transfer efficiency, zeta potential, stability, thermal efficiency, isobaric heat capacity, and specific heat capacity. HNFs are recognized for their better thermophysical properties and increased stability, making them a suitable candidate for a solution for single NFs. The findings suggest that strategically combining multiple nanoparticles within a base fluid can improve viscosity, thermal conductivity, and other performance aspects. Resurrection studies indicate that specific HNF compositions can increase the efficiency of thermal systems, particularly in heat exchangers, thermal solar collectors, cooling photovoltaic panels, and electronics cooling systems. Even though there is extensive literature published on the thermal properties of HNFs, there are still gaps that need to be addressed, such as

- a. A favorable synthesis being generated, which is both profitable and reasonable for examining the thermophysical properties of HNFs.
- b. Especially to render them appropriate for electronic cooling applications, comprehending the heat transfer and flow mechanism of HNFs in microchannels.
- c. Single phase flow visualization study of HNFs at different flow conditions would be beneficial for the present industries that focus on thermal management.
- d. Development of generalized or specific theoretical models and development of correlations to calculate the thermophysical properties of HNFs.
- e. Usage of suitable surfactants, by maintaining a good balance between stability and effective thermal conductivity of HNFs.
- f. Possibilities of employing these HNFs in heat pipes and thermosyphons, which work particularly in two-phase and optimize their usage with a reasonable trade-off between nanoparticle settlement and heat transfer.

Lastly, this paper offers a thorough overview of current research on the thermo-physical properties of NFs and how they enhance heat transport in a variety of applications. Although HNFs have a bright future, industrial deployment is still a way off due to stability issues, which are the main problem facing NFs. Their uses are anticipated to grow as research into these complex fluids deepens our understanding of them, resulting in more sustainable and effective thermal management solutions across a range of sectors.

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Declaration of generative ai and ai-assisted technologies in the writing process. During the preparation of this work, the authors used QuillBot to improve the writing and English of some sections. After using this tool/service, the authors reviewed and edited the content as needed, and they take full responsibility for the content of the publication.

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