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Experimental Investigation On Nanoparticles Suspended Liquid (NSL) As The Heat Transfer Fluid (HTF) For Solar Evacuated Tube Collector

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Abstract: This study investigates the thermal performance of a solar evacuated tube collector (SETC) using nanoparticles suspended liquid (NSL) as the heat transfer fluid (HTF). The NSL is composed of water with different concentration of TiO_2, CuO, Cr_2O_3, TiO_2+CuO+ Cr_2O_3 NSL with average size of ~25 nm. The experimental results show that the use of NSL increase the thermal performance of the SETC to be about 2% higher than that of the SETC without NSL. The enhancement in the thermal performance is mainly attributed to the higher thermal conductivity and specific heat capacity of the NSL. In addition, the effects of NSL concentration, flow rate and temperature on the thermal performance of the SETC with NSL were also studied. It was observed that the thermal performance of the SETC with NSL increases with increasing NSL concentration and flow rate but decreases with rise in the temperature. The results of this study can be used to optimize the design of solar evacuated tube collectors using NSL as the HTF for better thermal performance.

Keywords: Nanoparticles Suspended Liquid (NSL), Heat Transfer Fluid (HTF), nanoparticles, thermophysical properties

1. Introduction

The use of Nanoparticles Suspended Liquid (NSL) as a Heat Transfer Fluid (HTF) in Solar Evacuated Tube Collectors (SETC) has been widely studied in recent years. NSL offers several advantages over traditional HTF including higher thermal conductivity, reduced convective heat losses, and improved efficiency. To illustrate the difference in performance between traditional HTF and NSL consider a SETC with a conventional HTF and a SETC with NSL as the HTF. In the SETC with conventional HTF, the thermal efficiency is limited by the thermal boundary layer, which is the layer of air that forms between the solar collector and the HTF. The size of this thermal boundary layer increases as the temperature of the HTF increases, resulting in increased convective heat losses and decreased efficiency. On the other hand, in the SETC with NSL as the HTF, the small size of the nanoparticles reduces the size of the thermal boundary layer, resulting in reduced convective heat losses and improved efficiency. Additionally, the higher thermal conductivity of NSL allows for more efficient heat transfer between the collector and the HTF, resulting in higher temperatures and better efficiency. By incorporating NSL into SETC, the thermal performance of the system can be significantly improved, leading to more efficient thermal energy production [1].

There are several methods to prepare NSL such as physical mixing, chemical precipitation, and sonication. The

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type of nanoparticles used and their concentration in the liquid can also affect the thermal conductivity of the nanofluid. Common types of nanoparticles used in NSL include metal particles, such as copper and gold with oxide particles, such as alumina and silica.

In terms of applications NSL have been studied for use in industrial cooling systems, solar thermal energy collection and biomedical cooling. For example, in the industrial sector, NSL have been proposed as a more efficient alternative to traditional coolants in processes such as machining and welding. In the field of solar thermal energy, NSL have been studied as a potential working fluid in solar collectors to improve the efficiency of heat transfer. In biomedical applications, NSL have been proposed as a means of cooling medical devices, such as MRI machines, and for localized drug delivery [2].

However, there are also some limitations to the use of NSL in heat transfer. One of the main concerns is the potential for the nanoparticles to aggregate and settle out of suspension, which can negatively impact the fluid's thermal conductivity. Additionally, there are also concerns about the potential toxicity of the nanoparticles and their potential environmental impact. Despite these limitations, ongoing research is being conducted to improve the stability and safety of NSL for heat transfer applications [3].

In above said study, the authors prepared NSL with different volume fractions of alumina nanoparticles suspended in water and measured their thermal conductivity using a transient hot wire method. The nanoparticles were synthesized by a sol-gel method and had an average size of 15 nm. The use of nanoparticles in various fields has gained much attention in recent years, particularly in the field of heat transfer and thermal energy storage. The unique properties of nanoparticles have led to the development of nanofluids which have been shown to have improved thermal conductivity compared to traditional fluids. This introduction summarizes several studies that investigate the impact of nanoparticles on the thermal properties of nanofluids [5].

In addition to the thermal conductivity and heat capacity, these studies also examined the stability of nanofluids and the influence of various parameters on their properties. Kaweeteerawat *et al.* (2015) compare the impact of copper nanoparticles, micro sized copper particles, and copper ions on the behavior of Escherichia coli and Lactobacillus brevis, finding that nanoparticles have different effects than their micro sized and ionic analogues [5]. Wang *et al.* (1999) investigate the thermal conductivity of nanoparticle-fluid mixtures [6], while Xie *et al.* (2002) examines the thermal conductivity of suspensions containing nanosized SiC particles [7]. Chieruzzi *et al.* (2013) study the effect of nanoparticles on the heat capacity of nanofluids based on molten salts [8,10], while Hamilton (1962) considers the thermal conductivity of heterogeneous two-component systems [9]. Finally, Asadi *et al.* (2019) reviews the effect of sonication characteristics on the stability, thermophysical properties, and heat transfer of nanofluids [11]. These studies provide valuable insights into the potential of nanoparticles for thermal energy storage and heat transfer applications and highlight the importance of further investigation into the behavior of nanofluids.

These studies continue to explore the potential of nanoparticles for thermal energy storage and heat transfer applications, with a focus on graphene-based and two-dimensional tungsten disulfide-based nanofluids. Pavía *et al.* (2021) provide a critical review of the thermal conductivity enhancement of graphene-based nanofluids, examining the latest developments in this field [12]. Shah *et al.* (2020) investigates two-dimensional tungsten disulfide-based ethylene glycol nanofluids, studying their stability, thermal conductivity, and rheological properties [13]. Liu *et al.* (2011) focus on copper, copper oxide, and carbon nanotube-based nanofluids, examining their effects on thermal conductivities and the potential applications of a water chiller system [14]. These studies provide valuable insights into the potential of nanoparticles for thermal energy storage and heat transfer applications and demonstrate the continued interest in the development of nanofluids with improved thermal properties.

These studies continue to explore the potential of nanoparticles for thermal energy storage and heat transfer applications. Sadri *et al.* (2014) conduct an experimental study on the thermal conductivity and viscosity of nanofluids containing carbon nanotubes [15]. Saterlie *et al.* (2011) examine the particle size effects on the thermal conductivity enhancement of copper-based nanofluids [16]. These studies provide valuable insights into the potential of nanoparticles for thermal energy storage and heat transfer applications and demonstrate the ongoing efforts to develop nanofluids with improved thermal properties.

In the study, prepared NSL with different volume fractions of TiO_2, CuO, Cr_2O_3, TiO_2+CuO+Cr_2O_3 suspended in water, synthesized by a sol-gel method, and had an average size of 15 nm. The results of the study showed that the thermal conductivity of the NSL increased with increasing volume fraction of the nanoparticles, with the highest enhancement observed at a volume fraction of 0.5%. The authors attributed the enhancement in thermal conductivity to the increased heat transfer by the high surface area-to-volume ratio of the nanoparticles.

2. Selection Criteria for Synthesis of Nanoparticles Suspended Liquid (NSL)

The two-step method of NSL synthesis involves two processes; the first process involves mixing nanoparticles with a solvent to form a suspension, and the second process involves the addition of the suspension to the base fluid. This method is advantageous as it can be used to produce NSL suspensions with a wide range of nanoparticles such as oxides and carbon nanotubes. The one-step method is simpler and involving the direct mixing of nanoparticles and base fluid. This method is more suitable for producing NSLs with less stable nanoparticles, however it is important to ensure that the base fluid is of the correct pH and viscosity to ensure a stable suspension. Once the NSL has been synthesized, it is important to ensure that it must be properly stored and handled. NSLs are prone to agglomeration and sedimentation, so it is important to minimize the exposure of NSLs to shear forces or high temperatures. When storing NSLs, it is important to ensure that the container is well sealed to prevent evaporation of the solvent, and to use a dark container to minimize light exposure. Additionally, it is important to be aware of the potential health risks associated with NSLs and wear proper protective equipment when handling them.

2.1 Selection of Nanoparticles

Including NSL preparation, titanium dioxide is widely used in many areas. By production point of view, TiO_2 nanoparticles can be easily obtained as they are readily produced on industrial scales. On the physicochemical profile, they have better stability when dispersed in a base fluid even without the addition of stabilisers. Paraffin oil, Ethylene Glycol (EG) or Propylene Glycol (PG) used as base fluids to improve thermal conductivity for TiO_2 NSL [17-21]. Investigation shows that for CuO NSL preparation the sonication time greatly affects the heat transfer performance & influenced by the nanoparticles concentration. Enhancement of thermal conductivity depends on the particle volume fraction and working temperature of NSL. For 1.2% volume concentration of CuO NSLs, 10.8% to 43.2% increment of NSL thermal conductivity is reported. Above mentioned characteristic is very much helpful in photo-thermal conversion kind of application for solar water heaters.

2.2 Selection of Base Liquid and Size of Nanoparticle

In this experiment of NSL preparation, TiO_2 nanoparticles of an average size of 25 nm with the purity of 99.9%, have been used as purchased from the Nano wings Pvt. Ltd Company, Khamam, India. The size of the nanoparticles supplied from the appropriate supplier and used in this experiment is 20 - 30 nm. In this experiment distilled water is considered as host fluid due to its well-known evaporation characteristics. Favourably the TiO_2 nanoparticles are easily available in the market. During dispersion process of nanoparticles, the buffer was added. To obtain NSL, this mixture has been sonicated with the help of ultrasonic probe almost for 1 hour. Cupric Acetate Monohydrate $(CH_3COO)_2Cu.H_2O$ powder in equal proportion is added in double distilled water for 0.6 molarities. For complete dispersion, the correct proportion of water and Cupric Acetate is a pre-requisite condition. Again, stirring for 35 minutes and heating at 150 °C for the total dispersion of powder. $C_{14}H_{23}Cr_3O_{16}$ (Chromium Acetate) powder for 0.4 molarities added in distilled water. Acetic acid (CH_3COOH) in the same quantity has been mixed up for NSL preparation. Complete mixture is stirred for complete dispersion of nanoparticles. Stirring with heating takes place at 170 °C for 45 minutes [19,20]. At the end of this task, complete dispersion of powder takes location and NSL is prepared.

All above individual NSLs are mixed up with each other in 1:1:1 proportion to prepare a new one. NSL developed in this way for these processes remains stable for about a week and without any agglomeration. The base fluid (distilled water) is taken for the dispersion of nanoparticles. This facility of Oscar ultrasonic machine PR- 1000 was availed by Saurashtra University, Rajkot.

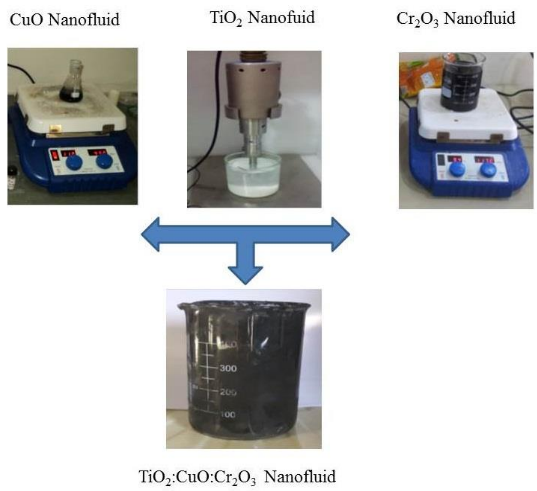

Fig. 1 - Preparation of NSL in ultrasonication

The mixture of nanoparticles and base fluid was carried out in the horn type Oscar ultrasonic reactor. The attached horn to the transducer develops ultrasonic irradiation throughout the mixture. The frequency of is in the range of 25 kHz to 30 kHz. Time ranges from 3 to 30 minutes along with the power supply from 100 W to 1000W in the steps of 100W. The transducer horn was submerged approximately 5 cm in the mixture of nanoparticles and base fluid.

3. Results and Discussion

The stability of the NSL is an important factor that affects the performance of the SETC. The stability of the NSL is affected by the size of the nanoparticles, the type of nanoparticles, and the concentration of the nanoparticles. The size of the nanoparticles affects the suspension of the nanoparticles in the HTF. The type of nanoparticles affects the interaction between the nanoparticles and the HTF. The concentration of the nanoparticles affects the viscosity of the HTF and hence affects the heat transfer rate. Therefore, to ensure the stability of the NSL and improve the performance of the SETC, it is important to optimize the size, type, and concentration of the nanoparticles [25-27].

3.1 Major Properties of TiO_2, CuO, Cr_2O_3 Nanoparticles

Table 1 and Table 2 give all the required properties of the TiO_2, CuO, Cr_2O_3 nanoparticles and double distilled water as the base fluid. The Below given table represents the thermal properties of the NSLs with different nanoparticles.

Table 1 - Major properties of TiO_2, CuO, Cr_2O_3 nanoparticles

Nanoparticles (Powder phase)	Density (gm/cm^3)	Specific Surface Area (m^2/g)	Thermal Conductivity (W/m K)	Specific Heat (kJ/kg K)
TiO_2 (Anatase)	0.2-0.4	60	6	0.69
CuO (Monoclinic)	6.315	140	18	0.540
Cr Powder	0.13	80	42	0.46

Table 1 shows the properties of nanoparticles of TiO_2 (Anatase), CuO (Monoclinic), and Cr Powder. TiO_2 (Anatase) has a density range of 0.2-0.4 g/cm^3 and a high specific surface area of 60 m^2/g. However, its thermal conductivity is relatively low, with a value of 6 W/m K. This is due to its low density and high surface area, which results in lower heat transfer capacity. The specific heat of TiO_2 is 0.69 kJ/kg K [28-30].

CuO (Monoclinic) has a higher density of 6.315 g/cm^3 and a relatively high specific surface area of 140 m^2/g. It has a higher thermal conductivity of 18 W/m K, reflecting its greater heat transfer capacity. The specific heat of CuO is 0.540 kJ/kg K. Cr Powder has a low density of 0.13 g/cm^3 and a moderate specific surface area of 80 m^2/g. It has a relatively high thermal conductivity of 42 W/m K, which is higher than the other two nanoparticles, reflecting its strong heat transfer capability. The specific heat of Cr Powder is 0.46 kJ/kg K. These properties have implications for the use of these nanoparticles in thermal management applications and must be considered when choosing the appropriate nanoparticle for a particular application [31-34].

Table 2 - Major properties of double distilled water as a base fluid

Powder phase	Density (kg/l)	Thermal Conductivity (W/m K)	Specific Heat (kJ/kg K)	Viscosity (CST)
Pure Water	1	0.669	4.186	1.79

Table 1 and Table 3 present the properties of three types of nanoparticles: TiO_2, CuO, and Cr_2O_3, as well as their combination (TiO_2+CuO+ Cr_2O_3 NSL) in two different proportions (0.25% and 0.5%). The properties presented are density, kinematic viscosity, thermal conductivity, specific heat, and boiling point. For TiO_2, increasing the proportion to 0.5% results in a slightly higher density (0.9996 g/cm3) compared to 0.25% (0.9990 g/cm^3), as well as a slightly higher thermal conductivity (0.70 W/m K) compared to 0.67 W/m K. The kinematic viscosity and specific heat remain relatively unchanged. The boiling point increases from 377 K to 381 K.

Similarly, for CuO, increasing the proportion to 0.5% results in a higher density (6.920 g/cm^3) compared to 0.25% (6.870 g/cm^3) and a higher thermal conductivity (1.10 W/m K) compared to 1.01 W/m K. The kinematic viscosity and specific heat also increase. The boiling point increases from 250 K to 252 K. For Cr_2O_3, increasing proportion to 0.5% results in a higher density (1.63 g/cm^3) compared to 0.25% (1.52 g/cm^3) and a higher thermal conductivity (15.00 W/m K) compared to 13.00 W/m K. The kinematic viscosity and specific heat also increase. The boiling point increases from 432 K to 436 K.

Table 3 - Properties of prepared NSL with H_2O water as a host fluid

Nanoparticle	Proportion	Density (g/cm^3)	Kinematic Viscosity (CST)	Thermal Conductivity (W/m K)	Specific Heat (kJ/kg K)	Boiling Point (K)
TiO_2	0.25%	0.9990	0.2820	0.67	4.164	377
	0.50%	0.9996	0.2929	0.70	4.154	381

CuO	0.25%	6.870	1.1650	1.01	16.1	250
	0.50%	6.920	1.2869	1.10	18.1	252
Cr_2O_3	0.25%	1.52	0.2356	13.00	5.12	432
	0.50%	1.63	0.2523	15.00	5.23	436
TiO_2+CuO+ Cr_2O_3 NSL	0.25%	2.42	1.91	2.89	10.05	370
TiO_2+CuO+ Cr_2O_3 NSL	0.5%	2.53	1.96	2.97	11.53	383

The combination of TiO_2, CuO, and Cr_2O_3 (NSL) in a 0.25% proportion results in a density of 2.42 g/cm^3, kinematic viscosity of 1.91 CST, thermal conductivity of 2.89 W/m K, specific heat of 10.05 kJ/kg K, and boiling point of 370 K. Increasing the proportion to 0.5% results in a higher density (2.53 g/cm^3), kinematic viscosity (1.96 CST), thermal conductivity (2.97 W/m K), specific heat (11.53 kJ/kg K), and boiling point (383 K). At a concentration of 0.25%, TiO_2 has the lowest density (0.9990 g/cm^3) and the lowest thermal conductivity (0.67 W/m K) among the nanoparticles. However, it has a relatively high specific heat (4.164 kJ/kg K). CuO has a higher density (6.870 g/cm^3) and thermal conductivity (1.01 W/m K) compared to TiO_2, but a lower specific heat (16.1 kJ/ kg K). Cr_2O_3 has the highest density (1.52 g/cm^3) and thermal conductivity (13.00 W/m K) among the nanoparticles, and a moderate specific heat (5.12 kJ/kg K).

3.2 Stability of NSLs with Ultrasonic Probe Process

At a concentration of 0.5%, the density and thermal conductivity of all the nanoparticles have increased, while their specific heat has decreased slightly. The nanofluid TiO_2+CuO+Cr_2O_3 NSL has the highest density (2.53 g/cm^3) and thermal conductivity (2.97 W/m K) among the nanoparticles at this concentration, but a relatively low specific heat (11.53 kJ/kg K). At a frequency of 25 kHz, 500-Watt power and mechanical stirrer method with 400 rpm. In Tables 4 & 5 the stability period of nanoparticles in the host fluid is mentioned.

Table 4 shows the stability period of a nanofluid containing TiO_2, CuO, and Cr_2O_3 nanoparticles in the host fluid after sonication at a frequency of 25 kHz and with a power of 500 Watts. The stability period of the nanofluid was measured after different time intervals of sonication (15, 30, 45, and 60 minutes). The stability period of the nanofluid increased as the sonication time increased, both for 0.25% and 0.5% concentrations. The stability period of the nanofluid was longer for a concentration of 0.5% compared to 0.25%. The longest stability period was observed for a sonication time of 60 minutes and a concentration of 0.5% (29 days) [35,36].

Table 4 - Stability of NSLs with ultrasonic probe process

For 0.25% TiO_2+CuO+ Cr_2O_3 NSL			For 0.5% TiO_2+CuO+ Cr_2O_3 NSL		
Sr. No.	**Time of sonication**	**Stability period**	**Sr. No.**	**Time of sonication**	**Stability period**
1	15 min.	19 days	1	15 min.	15 days
2	30 min.	21 days	2	30 min.	17 days
3	45 min.	24 days	3	45 min.	21 days
4	60 min.	29 days	4	60 min.	27 days

3.3 Stability of NSLs with Mechanical Stirrer Process

Table 5 compares the stability period of 0.25% and 0.5% TiO_2+CuO+ Cr_2O_3 NSLs with different stirring times (15, 30, 45, and 60 minutes). The results show that the stability period of the nanofluids increases with the stirring time, with a higher concentration of the nanofluids (0.5%) having a longer stability period compared to a lower concentration (0.25%). For 0.5% TiO_2+CuO+ Cr_2O_3 NSL, the stability period ranges from 1.6 hours to 9.4 hours, whereas for 0.25% TiO_2+CuO+ Cr_2O_3 NSL, the stability period ranges from 2.1 hours to 12.5 hours.

It can be said that the time of sonication is increased for mixing of nanoparticles and the base fluid, the stability period of nanoparticles increased. Similarly, in mechanical stirrer method, as the stirring time increased the stability time also increased, but for the ultrasonic sonication method stability is much more than the mechanical stirrer method.

Table 5 - Stability of NSLs with mechanical stirrer process

For 0.25% TiO_2+CuO+ Cr_2O_3 NSL			For 0.5% TiO_2+CuO+ Cr_2O_3 NSL		
Sr. No.	**Time of stirrer**	**Stability period**	**Sr. No.**	**Time of stirrer**	**Stability period**
1	15 min.	2.1 hrs.	1	15 min.	1.6 hrs.
2	30 min.	5.2 hrs.	2	30 min.	3.7 hrs.
3	45 min.	8.5 hrs.	3	45 min.	6.3 hrs.
4	60 min.	12.5 hrs.	4	60 min.	9.4 hrs.

3.4 Sonication & Stirrer Time Effect on the Stability of Nanoparticles

It has been from the above-given results that in all methods the stability period increases with a lesser % proportion of nanoparticles. Moreover, as the % proportion of the nanoparticles increase separation of nanoparticles from a base fluid occurs rapidly. The stability of the nanoparticles suspension in the host fluid is an important aspect that influences the performance of nanofluids in various applications. In this study, the stability of 0.25% and 0.5% TiO_2+CuO+Cr_2O_3 NSL suspensions was evaluated under ultrasonication and mechanical stirring conditions.

Under ultrasonication conditions, the stability period of the 0.25% NSL suspension increased from 19 days for 15 minutes of sonication to 29 days for 60 minutes of sonication. Similarly, for the 0.5% NSL suspension, the stability period increased from 15 days for 15 minutes of sonication to 27 days for 60 minutes of sonication. Under mechanical stirring conditions, the stability period of the 0.25% NSL suspension increased from 2.1 hours for 15 minutes of stirring to 12.5 hours for 60 minutes of stirring. For the 0.5% NSL suspension, the stability period increased from 1.6 hours for 15 minutes of stirring to 9.4 hours for 60 minutes of stirring.

Ultrasonication appears to be more effective in enhancing the stability of the NSL suspensions compared to mechanical stirring. The longer stability periods observed under ultrasonication conditions may be due to the higher frequency and power of the ultrasonic waves, leading to more efficient mixing and dispersion of the nanoparticles in the host fluid.

Fig. 2 indicates that the ultrasonic mixing of nanoparticles in base fluid shows greater stability than with the mechanical stirrer method. Furthermore, stability of newly prepared NSL is more as compared to all individual NSLs.

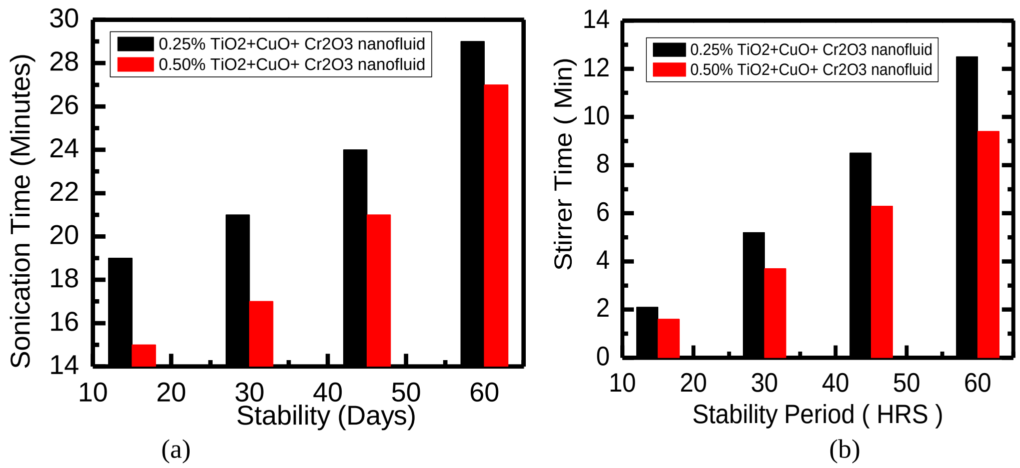

Fig. 2 - Effect on stability of nanoparticles (a) sonication time; (b) mechanical stirring time

3.5 Effects of Nanoparticles Concentration On Mechanical Properties

Fig. 3 shows the variation of different physical and thermal properties of NSL with the proportion of nanoparticles. At last, it is concluded from the above results that thermal conductivity can be enhanced with the increase of nanoparticles percentage.

A little decrease in the specific heat of NSL is observed with the rise in nanoparticles concentration. By increasing the volume fraction of nanoparticles, the two critical properties-kinematic viscosity and density are also increasing. With the addition of nanoparticles in the base liquid, the boiling temperature of NSL also rises.

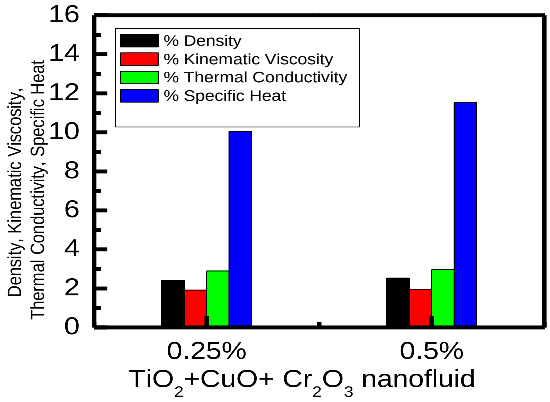

Fig. 3 - Effects of nanoparticles concentration on mechanical properties

4. Conclusion

This study investigated the stability of 0.25% and 0.5% TiO_2+CuO+Cr_2O_3 nano slurry (NSL) suspensions under ultrasonication and mechanical stirring conditions. The results shown that the stability period of the nanofluids increased with the stirring time (up to 60hrs for 13 minutes of stirring time) and the longest stability period was observed for a sonication time of 60 minutes and a concentration of 0.5% (29 days). Ultrasonication was found to be more effective in enhancing the stability (27 days) of the NSL suspensions compared to mechanical stirring (9.4 hours). The increase in stability observed under ultrasonication conditions may be due to the higher frequency and power of the ultrasonic waves, leading to more efficient mixing and dispersion of the nanoparticles in the host fluid. Moreover, the stability of the NSL suspension was found to increase with a lesser % proportion of nanoparticles. Additionally, it was found that thermal conductivity can be enhanced from 2.89 to 2.97 W/m K with the increase of nanoparticles percentage, at the same time specific heat of NSL also increased from 10.05 to 11.53 kJ/ kg K observed with the rise in nanoparticles concentration. With the addition of nanoparticles in the base liquid, the boiling temperature, the most important parameter to be observed increased from 370 to 383 K of NSL. Overall, the findings of this study provide valuable insights into the optimization of nanofluid properties for various applications.

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References

[1] Wole-Osho, I., Okonkwo, E. C., Abbasoglu, S., & Kavaz, D. (2020). Nanofluids in solar thermal collectors: review and limitations. *International Journal of Thermophysics*, *41*, 1-74.

[2] Shamsul Azha, N. I., Hussin, H., Nasif, M. S., & Hussain, T. (2020). Thermal performance enhancement in flat plate solar collector solar water heater: A review. *Processes*, *8*(7), 756.

[3] Jamshed, W., Baleanu, D., Nasir, N. A. A. M., Shahzad, F., Nisar, K. S., Shoaib, M., ... & Ismail, K. A. (2021). The improved thermal efficiency of Prandtl-Eyring hybrid nanofluid via classical Keller box technique. *Scientific Reports*, *11*(1), 23535.

[4] Yu, W., & Xie, H. (2012). A review on nanofluids: preparation, stability mechanisms, and applications. *Journal of Nanomaterials*, *2012*, 1-17.

[5] Kaweeteerawat, C., Chang, C. H., Roy, K. R., Liu, R., Li, R., Toso, D., ... & Godwin, H. A. (2015). Cu nanoparticles have different impacts in Escherichia coli and Lactobacillus brevis than their microsized and ionic analogues. *ACS Nano*, *9*(7), 7215-7225.

[6] Wang, X., Xu, X., & Choi, S. U. (1999). Thermal conductivity of nanoparticle-fluid mixture. *Journal of Thermophysics and Heat Transfer*, *13*(4), 474-480.

[7] Xie, H. Q., Wang, J. C., Xi, T. G., & Liu, Y. (2002). Thermal conductivity of suspensions containing nanosized SiC particles. *International Journal of Thermophysics*, *23*, 571-580.

[8] Chieruzzi, M., Cerritelli, G. F., Miliozzi, A., & Kenny, J. M. (2013). Effect of nanoparticles on heat capacity of nanofluids based on molten salts as PCM for thermal energy storage. *Nanoscale Research Letters*, *8*(1), 1-9.

[9] Hamilton, R. L., & Crosser, O. K. (1962). Thermal conductivity of heterogeneous two-component systems. *Industrial & Engineering Chemistry Fundamentals*, *1*(3), 187-191.

[10] Chieruzzi, M., Miliozzi, A., Crescenzi, T., Torre, L., & Kenny, J. M. (2015). A new phase change material based on potassium nitrate with silica and alumina nanoparticles for thermal energy storage. *Nanoscale Research Letters*, *10*, 1-10.

[11] Asadi, A., Pourfattah, F., Szilágyi, I. M., Afrand, M., Żyła, G., Ahn, H. S., ... & Mahian, O. (2019). Effect of sonication characteristics on stability, thermophysical properties, and heat transfer of nanofluids: A comprehensive review. *Ultrasonics Sonochemistry*, *58*, 104701.

[12] Pavía, M., Alajami, K., Estellé, P., Desforges, A., & Vigolo, B. (2021). A critical review on thermal conductivity enhancement of graphene-based nanofluids. *Advances in Colloid and Interface Science*, *294*, 102452.

[13] Shah, S. N. A., Shahabuddin, S., Mohd Sabri, M. F., Mohd Salleh, M. F., Mohd Said, S., Khedher, K. M., & Sridewi, N. (2020). Two-dimensional tungsten disulfide-based ethylene glycol nanofluids: stability, thermal conductivity, and rheological properties. *Nanomaterials*, *10*(7), 1340.

[14] Liu, M., Lin, M. C., & Wang, C. (2011). Enhancements of thermal conductivities with Cu, CuO, and carbon nanotube nanofluids and application of MWNT/water nanofluid on a water chiller system. *Nanoscale Research Letters*, *6*(1), 1-13.

[15] Sadri, R., Ahmadi, G., Togun, H., Dahari, M., Kazi, S. N., Sadeghinezhad, E., & Zubir, N. (2014). An experimental study on thermal conductivity and viscosity of nanofluids containing carbon nanotubes. *Nanoscale Research Letters*, *9*(1), 1-16.

[16] Saterlie, M., Sahin, H., Kavlicoglu, B., Liu, Y., & Graeve, O. (2011). Particle size effects in the thermal conductivity enhancement of copper-based nanofluids. *Nanoscale Research Letters*, *6*(1), 1-7.
[17] Zehri, A. H., Nylander, A., Ye, L., & Liu, J. (2019). Graphene-coated copper nanoparticles for thermal conductivity enhancement in water-based nanofluid. *2019 22nd European Microelectronics and Packaging Conference & Exhibition (EMPC)*, pp. 1-7.
[18] Garg, J., Poudel, B., Chiesa, M., Gordon, J. B., Ma, J. J., Wang, J. B., ... & Chen, G. J. (2008). Enhanced thermal conductivity and viscosity of copper nanoparticles in ethylene glycol nanofluid. *Journal of Applied Physics*, *103*(7), 074301.
[19] Jalal, M., Meisami, H., & Pouyagohar, M. (2013). Experimental study of CuO/water nanofluid effect on convective heat transfer of a heat sink. *Middle-East Journal of Scientific Research*, *13*(5), 606-611.
[20] Ramani, R. V., Ramani, B. M., Saparia, A. D., Dhruv, D., & Markna, J. (2016). Synthesis and optical characterization of CuO nanoparticles on solar borosilicate glass. *Journal of Nano Research*, 37, pp. 68-73.
[21] Ebadi-Dehaghani, H., & Nazempour, M. (2012). Thermal conductivity of nanoparticles filled polymers. *Smart Nanoparticles Technology*.
[22] Mohamed, L. Z., Eid, A. I., Eessaa, A. K., & Esmail, S. A. (2019). Studying of physico-mechanical and electrical properties of polypropylene/nano-copper composites for industrial applications. *Egyptian Journal of Chemistry*, *62*(5), 913-920.
[23] Park, H. J., Badakhsh, A., Im, I. T., Kim, M. S., & Park, C. W. (2016). Experimental study on the thermal and mechanical properties of MWCNT/polymer and Cu/polymer composites. *Applied Thermal Engineering*, *107*, 907-917.
[24] Huang, C., Qian, X., & Yang, R. (2018). Thermal conductivity of polymers and polymer nanocomposites. *Materials Science and Engineering: R: Reports*, *132*, 1-22.
[25] Chen, W., Wang, Z., Zhi, C., & Zhang, W. (2016). High thermal conductivity and temperature probing of copper nanowire/upconversion nanoparticles/epoxy composite. *Composites Science and Technology*, *130*, 63-69.
[26] Hansen, D., & Bernier, G. A. (1972). Thermal conductivity of polyethylene: The effects of crystal size, density and orientation on the thermal conductivity. *Polymer Engineering & Science*, *12*(3), 204-208.
[27] Shahrokh, A., & Fakhrabadi, M. M. S. (2021). Effects of copper nanoparticles on elastic and thermal properties of conductive polymer nanocomposites. *Mechanics of Materials*, *160*, 103958.
[28] Saterlie, M., Sahin, H., Kavlicoglu, B., Liu, Y., & Graeve, O. (2011). Particle size effects in the thermal conductivity enhancement of copper-based nanofluids. *Nanoscale Research Letters*, *6*(1), 1-7.
[29] Demirpolat, A. B., & Daş, M. (2018). (Cuo) copper oxide nanoparticle production and determination of heat transfer coefficient. *American Journal of Engineering Research (AJER)*, *7*(11), 74-80.
[30] Mirzaei, M. (2019). Experimental investigation of CuO nanofluid in the thermal characteristics of a flat plate solar collector. *Environmental Progress & Sustainable Energy*, *38*(1), 260-267.
[31] Zhu, D., Wang, L., Yu, W., & Xie, H. (2018). Intriguingly high thermal conductivity increment for CuO nanowires contained nanofluids with low viscosity. *Scientific Reports*, *8*(1), 1-12.
[32] Guangbin, Y., Dejun, G., Juhui, C., Bing, D., Di, L., Ye, S., & Xi, C. (2016). Experimental research on heat transfer characteristics of CuO nanofluid in adiabatic condition. *Journal of Nanomaterials*, 7, 1-7.
[33] Sahooli, M., & Sabbaghi, S. (2012). CuO nanofluids: the synthesis and investigation of stability and thermal conductivity. *Journal of Nanofluids*, *1*(2), 155-160.
[34] Nasrin, R., & Alim, M. A. (2013). Performance of nanofluids on heat transfer in a wavy solar collector. *International Journal of Engineering, Science and Technology*, *5*(3), 58-77.
[35] Savaliya, C., Rathod, K. N., Dhruv, D., & Markna, J. H. (2015). Preparation of nanostructured copper oxide rods using advanced sonication method. *International Journal of Nanoscience and Nanoengineering*, *2*(4), 27-31.
[36] Phiwdang, K., Suphankij, S., Mekprasart, W., & Pecharapa, W. (2013). Synthesis of CuO nanoparticles by precipitation method using different precursors. *Energy Procedia*, *34*, 740-745.