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Comparative Analysis of Thermal Conductivity of the Hybrid Nanoparticles Based Sunflower and Jatropha Vegetable Oil

Amol J. Asalekar[1,2] *, D.V. A. Rama Sastry[3]

Abstract

Vegetable oil gained much more interest towards sustainable manufacturing as coolant due to its inherent properties. In this present study, the thermal conductivity of hybrid nanoparticles based sunflower and Jatropha vegetable oil are measured. ZnO-Ag Hybrid nanoparticles were mixed with sunflower and Jatropha vegetable oil in four different volume concentrations of nanofluids ranges from 0.05 to 0.20%. The thermophysical properties viz, thermal conductivity and Stability of prepared hybrid nanoparticles-based vegetable oil were measured by varying the concentrations. The obtained results demonstrate that the thermal conductivity of both the nanofluids are increase with increase in the volume concentration and temperature. Also, comparative experimental values showed that a maximum of 5% enhancement of thermal conductivity was observed more in sunflower based nanofluid for 0.2% particle volume concentration than jatropha based hybrid nanofluid. Both nanofluids further be utilized for the manufacturing process as coolant for a better surface finish.

Keywords: Thermal conductivity, hybrid nanofluid, Vegetable oil

INTRODUCTION

Machining is a broad term encompassing various material removal techniques employed to achieve specific shapes and forms. It constitutes a fundamental industrial process widely applied in sectors such as automotive, aerospace, and small-scale tool and die manufacturing. While machining operations, heat is inevitably produced as a result of friction occurring at the interfaces of the cutting tool with both the workpiece and the chip, as well as within the shear zone itself. This thermal effect can lead to the degradation of the cutting tool's performance. To mitigate tool wear and minimize power consumption, it becomes imperative to introduce cooling and lubrication mechanisms into the cutting zone, effectively managing the machining process [1]. However, the conventional coolant solutions often employed in industrial settings come with a host of challenges related to both environmental impact and operational efficiency.

Traditional coolant formulations, often oil-based or water-based, have served manufacturing processes well for decades. Yet, they present a range of issues that warrant careful consideration. For instance, mineral oil-based coolants contribute to the accumulation of non-biodegradable waste and release potentially harmful substances into the environment. Water-based coolants, while less

*Author for Correspondence
Amol J. Asalekar

[1]Research Scholar, Department of Mechanical Engineering, Koneru Lakshmaiah Educational Foundation, Green Fields, Vaddeswaram, Guntur, Andhra Pradesh, India
[2]Assistant Professor, School of Mechanical Engineering, MIT Academy of Engineering, Alandi Pune, Maharashtra, India
[3]Associate Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Educational Foundation, Green Fields, Vaddeswaram, Guntur, Andhra Pradesh, India

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environmentally detrimental, necessitate complex disposal procedures due to potential contamination [2]. Furthermore, the energy-intensive manufacturing and transportation processes associated with conventional coolants add to their overall carbon footprint.

Utilizing cutting fluids based on vegetable oil presents a viable substitute for conventional cutting fluids (VBCFs). The adoption of VBCFs has the potential to reduce the incidence of chronic diseases, including lung cancer, respiratory ailments, hereditary conditions, and other health issues. Previous studies have explored the enhancement of performance metrics through the utilization of various vegetable oils, including castor oil, soybean oil, coconut oil, sunflower oil, palm oil, among others [3].

The utilization of vegetable oils in machining poses challenges due to their lower thermal conductivity, hindering effective cooling between the tool and the work surface. However, this limitation can be overcome by incorporating nanoparticles into vegetable oils, thereby augmenting their thermal properties, and enhancing the cooling effect. To mitigate the impact of hazardous cutting oils, innovative techniques like Minimum Quantity Lubrication (MQL) with vegetable oils have emerged. Yet, the addition of nanoparticles to vegetable oils surpasses the effectiveness of MQL alone, resulting in what is known as nanofluid or nanoparticle-based cutting fluid. When applied in MQL, this process is termed Nanofluids based MQL (NFMQL) assisted machining. For instance, Sharma et al. [4] utilized SiO_2 nanoparticles in vegetable oil as a cutting fluid, demonstrating superior performance in terms of cutting force, surface quality, tool wear, and chip morphology during wet/MQL and dry machining. Nanoparticle-based vegetable oil is injected into the cutting zone as an oil mist or aerosol with the assistance of pressurized air, significantly improving tribological properties by enhancing heat conductivity [5].

Nevertheless, the use of individual nanoparticles in vegetable oil may limit thermal conductivity due to stability issues, prompting researchers to explore metal oxide nanoparticles. Recent developments have introduced hybrid nanoparticles as a potential solution. These hybrid nanomaterials combine the unique characteristics of their component materials through mixing or similar methods. When these hybrid nanoparticles are introduced into a base fluid, such as water, ethylene glycol, vegetable oil, or engine oil, they enhance thermophysical properties. Despite promising outcomes in previous research, the utilization of hybrid nanoparticles in sunflower oil as a cutting fluid remains an ongoing area of investigation.

Typically, the formulation of hybrid nanoparticles-based vegetable oil involves blending and subjecting two distinct nanoparticles to sonication, with varying weight or volume percentages. Unfortunately, the existing challenge lies in the inadequate stability and suboptimal dispersion of these nanoparticles within the base fluid, hindering advancements in thermal conductivity. Notably, Jadhav et al. introduced a novel approach to enhance the thermal conductivity of nanoparticles, favoring those with lower thermal conductivity (specifically ZnO-Ag) [6–7]. Recently, promising results have emerged regarding the remarkable enhancement of thermal conductivity using ZnO-Ag nanofluids at lower concentrations in water or glycol-based nanofluids [8]. Leveraging vegetable oils like sunflower and jatropha in combination with ZnO-Ag nanoparticles holds great potential for significantly elevating thermal conductivity. Such nanofluids play a crucial role in enhancing the performance of machining operations assisted by NFMQL (nanofluid-based minimum quantity lubrication). Therefore, this work aims to prepare and characterize the ZnO-Ag based hybrid nanofluid. Also, comparative analysis of the nanofluids was reported in detailed manner.

METHODOLOGY

In this study, initially the nanoparticle was synthesized and for the nanofluid preparation two step methods were used. prepared hybrid nanoparticle-based vegetable oil was characterized for thermal conductivity and stability.

Preparation of Hybrid Nanoparticles-based Vegetable Oil

The synthesis of ZnO-Ag hybrid nanoparticles involved a meticulous process. The detailed synthesis process is expired in previous research. [9, 10] Initially, pure ZnO precursor nanoparticles were prepared and then ZnO precursor powder was mixed with water and combined with a silver nitrate solution, resulting in the formation of a thin and uniform Ag shell layer on the recrystallized ZnO nanoparticles. The resulting ZnO-Ag hybrid nanoparticles hold promise for various applications due to their unique structure and properties [9].

ZnO-Ag hybrid nanoparticles are notably dense due to the higher density of Ag ions, posing a challenge for their stability in the fluid.This issue was solved by sonicating the nanofluids for about 1 hour. The ultrasonic vibration procedure is commonly used to eliminate the agglomeration of nanoparticles. In this procedure, the ultrasonic vibration produces high-frequency ultrasonic wave in the nanofluid kept inside the ultrasonic bath and excites the nanoparticles, breaks up the agglomerates of the nanoparticles and form a suspension of isolated nanoparticles. In this study, cutting fluids were prepared using a two-step technique with sunflower oil and Jatropha oil as the base fluid, and different volume concentrations, Figure 1 shows the procedure for nanofluid preparation.

Characterization of Hybrid Nanoparticles-based Vegetable Oil

Initially the stability of the both Hybrid nanoparticles-based vegetable oils was measured and compared through the assessment of its zeta potential value. Zeta potential serves as a critical parameter for evaluating the stability of nanofluids. Nanofluids, which are suspensions of nanoparticles in a base fluid, play a pivotal role in numerous practical applications across various fields, including thermal management, lubrication, and energy storage. Determining the zeta potential of nanofluids involves employing methods such as electrophoresis or laser doppler velocimetry. A high absolute value of zeta potential signifies a high degree of nanofluid stability, as it reflects robust electrostatic repulsion between particles, preventing their aggregation and settling. Conversely, a low absolute value of zeta potential indicates reduced stability, raising the likelihood of particle aggregation and settling phenomena.

Thermal conductivity assessments of both the vegetable oil base fluid were carried out in accordance with ASTM and IEEE standards using a KD2 pro thermal conductivity analyser [11, 12]. This transient line source meter employs a 60-mm needle sensor comprising a thin heating wire and a temperature sensor. The sensor was fully immersed in the sample tube, which was placed within a water bath with temperatures ranging from 25°C to 60°C. The water bath heater was set to the desired measurement temperature and allowed to stabilize, with aluminum foils employed to regulate evaporation and maintain sample temperature during thermal conductivity measurements. Experiments were only initiated when the temperature sensor had achieved stability. A constant current source was used to detect heat to the sample, and the resulting temperature increase was recorded over a specific timeframe. Each measurement was conducted twice, and the average reading was used for subsequent data analysis.

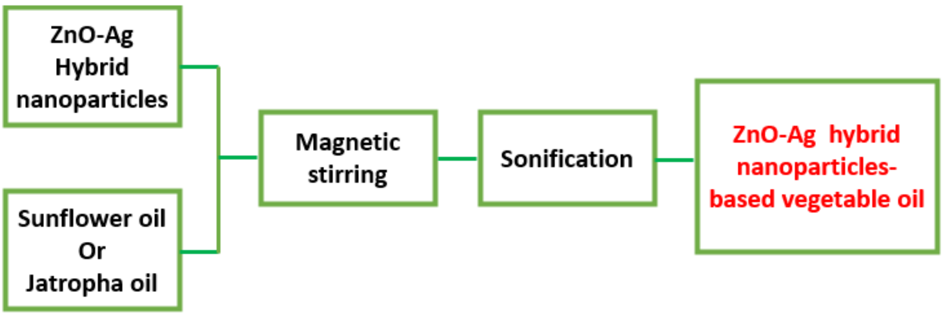

Figure 1. Synthesis of hybrid nanoparticles-based vegetable oil.

Table 1. Zeta potential values of different volume concentrations of Hybrid nanoparticles-based vegetable oil

Volume concentration	Zeta potential value (+/-mV)	
	For sunflower oil	***For jatropha oil***
0.05%	45	44
0.10%	42	41
0.15%	40.5	39
0.20%	38	36.2

RESULTS AND DISCUSSION

In this research, the ZnO-Ag hybrid nanofluid based vegetable oils were prepared and characterized for stability and thermal conductivity analysis. Based on the measured value, the mathematical model based on the comparative analysis was described in the following paragraphs.

Stability Measurement

The assessment of stability for both hybrid nanoparticles-based vegetable oil is conducted using a zeta potential analyzer (Nano-ZS; Malvern Instrument). Zeta potential is a concept rooted in electrophoresis theory, representing the repulsive force between particles within the same fluid, crucial for maintaining the stability of colloidal suspensions. When this repulsive force outweighs Van der Waal's forces, it enhances the stability of the nanoparticle suspension. Colloidal stability tends to decrease when the zeta potential falls below 30 mV. Table 1 illustrates the experimental zeta potential values for varying concentrations (Φ = 0.05% to 0.20%) of ZnO-Ag-based sunflower oil and jatropha oil. Notably, the absolute zeta potential values range from +/- 30 to +/- 60, indicative of excellent dispersion of ZnO-Ag nanoparticles within the base fluid, thereby ensuring the fluid's stability.

Thermophysical Property Analysis

As previously mentioned, hybrid nanoparticles were dissolved in a vegetables oil as a base fluid at different fractions of 0.05%, 0.10%, 0.15%, and 0.2% by volume. The thermo-physical characteristics of these nanofluids were then determined using a KD2 Pro thermal analyzer. The accuracy was checked by EG and DI water in the range of +/- 2% accuracy. The effect of temperature (25°C–55°C) and volume concentration on its thermal conductivity was examined. An increased thermal conductivity was seen for increasing the values of the concentration of nanoparticles and temperature. It is found that for 0.20% volume concentration of nanoparticle, the maximum 16.8% enhancement in thermal conductivity compared with base fluid at 25^0 C was recorded for jatropha oil. Due to the improved Brownian motion of the nanoparticles, the lattice vibration between molecules increases that causes the enhancement in the thermal conductivity.

The changes in relative thermal conductivity with temperature for various nanoparticles volume fractions Figure 2. As can be noticed, the relative thermal conductivity increases slightly as the temperature rises for all investigated volume fractions. An increase in the relative thermal conductivity is more pronounced at high temperatures than at low ones. It is clear from that the volume fraction has a greater impact on the thermal conductivity of nanofluids concerning temperature. The presented graph shows thermal conductivity improvement as a percentage of different temperatures and concentrations in a nanofluid. Higher temperatures and concentrations have a notable effect on the nanofluid's heat transfer capability. The most significant enhancement of 16.8% is observed at the highest temperature and concentration, highlighting the advantageous outcomes of incorporating nanoparticles into the base fluid regarding thermal conductivity.

The thermal conductivity of sunflower oil-based ZnO-Ag hybrid nanoparticles was determined using a thermal analyzer. In Figure 3, the graph illustrates the variation in thermal conductivity for ZnO-Ag hybrid nanoparticles-based vegetable oil at 25°C (Figure 3). Notably, the thermal conductivity of this hybrid nanofluid surpasses that of pure sunflower oil across all concentrations. The most substantial enhancement in thermal conductivity, at 21.01%, is observed at 25°C compared to pure sunflower oil. This improvement can be attributed to the wet chemical synthesis method employed in creating hybrid nanoparticles, ensuring a uniform coating of Ag nanoparticles on ZnO micelles and subsequently enhancing nanoparticle stability. The heightened conductivity of Ag-coated ZnO nanoparticles contributes to an overall elevation in the thermal conductivity of ZnO-Ag-based sunflower oil.

The thermal conductivity comparison of the ZnO-Ag hybrid nanoparticles dispersed in Sunflower vegetable oil and Jatropha oil at various concentrations is shown in Figure 4. It was witnessed that the thermal conductivity of the ZnO-Ag hybrid nanoparticle-based both the nanofluid increases with rise in temperature. Hybrid nanoparticles move more freely under the influence of Brownian motion as the temperature rises, increasing their thermal conductivity.

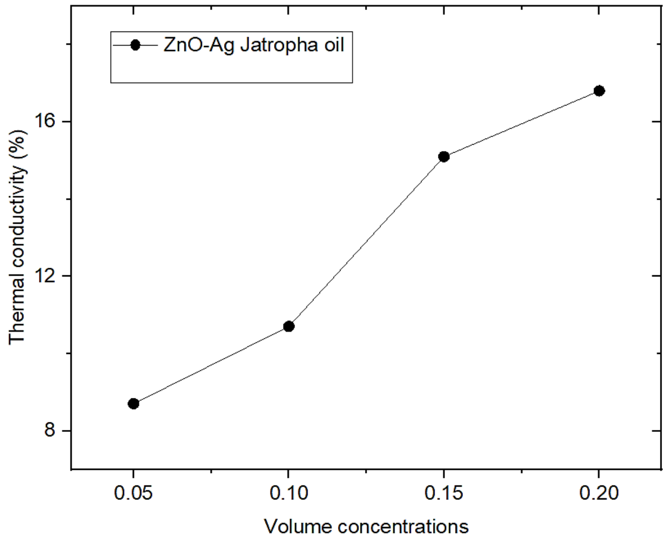

Figure 2. Thermal conductivity of the hybrid nanoparticles dispersed in Jatropha vegetable oil at various concentrations.

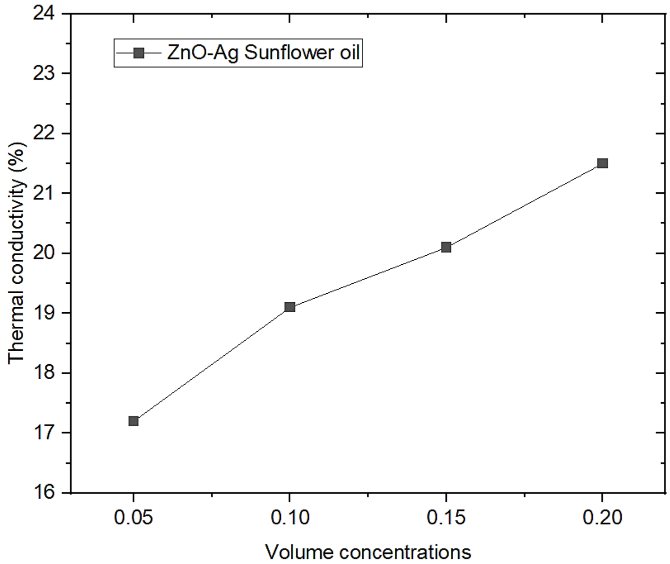

Figure 3. Thermal conductivity of hybrid nanoparticles dispersed in sunflower vegetable oil at various concentrations.

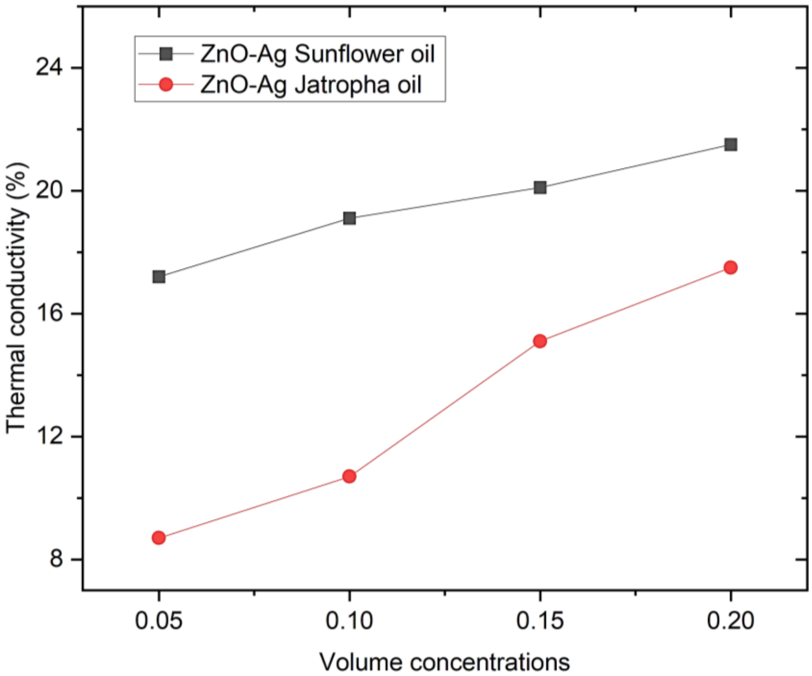

Figure 4. Thermal conductivity comparison of the ZnO-Ag hybrid nanoparticles dispersed in Sunflower vegetable oil and Jatropha oil at various concentrations.

Table 2. Specific heat values of different volume concentrations of hybrid nanoparticles-based vegetable oil

Concentrations	**0.05%**	**0.10%**	**0.15%**	**0.20%**
ZnO-Ag Sunflower oil	2.16	2.08	2.00	1.992
ZnO-Ag Jatropha oil	2.26	2.181	2.09	2.0134

The specific heat of a nanofluid (C_{nf}) refers to the amount of heat energy required to raise the temperature of a unit mass of the nanofluid by a certain amount. It is important to note that the specific heat of nanofluids can depend on various factors such as the type and concentration of nanoparticles, the base fluid, and the temperature. For both the nanofluid the specific heat measurement is calculated by of the synthesized nanofluid calculated by Eq.1 where C_{np} and C_{bf} are specific heat nanoparticle and base fluid respectively its values illustrated in Table 2.

$$C_{nf} = C_{np} * \emptyset + C_{bf}(1 - \emptyset) \quad (1)$$

The increase in viscosity observed in sunflower and jatropha vegetable oil with the dispersion of ZnO-Ag nanoparticles is remarkably similar. This viscosity augmentation in both oils is directly linked to the concentration of the suspended nanoparticles. The presence and concentration of ZnO-Ag nanoparticles play a pivotal role in influencing the rheological properties of the vegetable oils, highlighting the importance of nanoparticle dispersion in understanding and controlling the viscosity of these bio-based fluids.

Researchers are increasingly emphasizing the substantial integration of thermophysical properties to augment the heat transfer efficiency of working fluids. This heightened focus has led to comprehensive investigations, delving into key parameters like temperature and volume concentration, aiming to identify factors that positively influence thermal performance. Among these parameters, thermal conductivity stands out as a pivotal transport property, quantitatively defined as the ratio of heat flux to the local temperature gradient. In-depth analysis reveals that a nuanced understanding of temperature variations and volume concentrations significantly impacts thermal conductivity, showcasing the intricate relationship between these variables. Experimental data has illustrated a direct correlation between elevated temperatures and enhanced thermal conductivity, indicating the sensitivity of the working fluid's heat transfer capabilities to changes in temperature. Moreover, meticulous studies on volume concentration have demonstrated a nonlinear relationship, elucidating how variations in nanoparticle concentration distinctly affect thermal conductivity. This quantitative insight into key parameters contributes substantially to the ongoing discourse on optimizing working fluid compositions for superior heat transfer in diverse applications, from energy systems to advanced thermal management technologies. As researchers delve deeper, these findings not only expand our fundamental understanding of heat transfer mechanisms but also pave the way for the development of more efficient and tailored working fluid formulations.

Numerous prior investigations have undertaken the development of correlations for predicting the thermal conductivity of suspensions. These correlations take into account crucial factors such as the interfacial layer and Brownian movement, offering a comprehensive understanding of the complex behaviors exhibited by nanofluids. The genesis of these models and empirical correlations lies in meticulous experimental studies tailored to specific nanofluid types. These studies meticulously consider the chemical properties of nanofluids, encompassing preparation conditions like sonication time and surfactant addition, as well as the geometric parameters such as particle shape and size. The resulting correlations serve as valuable tools, providing insights into the intricate interplay between these factors and thermal conductivity, thereby facilitating the optimization of nanofluid formulations for diverse applications in heat transfer and thermal management.

The nanoparticles prepared for this study exhibit an approximately spherical shape. A thin interfacial layer is formed over the ZnO nanoparticles, housing Ag ions. This unique configuration contributes to a notable increase in the thermal conductivity of the nanofluids. The synergistic effect of spherical nanoparticle morphology and the interfacial layer enhances the heat transfer capabilities of the nanofluids, making them promising candidates for applications in thermal management and energy systems.

Further this hybrid nanoparticle-based vegetable oil coolant will be best option for the sustainable manufacturing process with support of the minimum quantity lubrication.

CONCLUSIONS

In the present study, ZnO-Ag nanoparticles-based dispersed in sunflower and jatropha vegetable oil and its thermal conductivity was measured experimentally. Based on the experimental data, the comparative analysis of thermal conductivity of jatropha oil and sunflower oil-based ZnO-Ag hybrid nanofluid is reported.

Significant thermal conductivity enhancements observed in all types of hybrid nanoparticles-based vegetable oil. This shows the nanofluids will be the promising next generation heat transfer fluids used for machining operations as a coolant.

The thermal conductivity of all nanofluids exhibited a rise in conjunction with higher particle volume concentrations within the base fluids and increasing temperatures. In essence, the thermal conductivity of these nanofluids is depended upon both particle volume concentrations and temperature variations.

The enhancement of thermal conductivity for ZnO-Ag/sunflower oil and ZnO-Ag/jatropha oil were about 21.5% and 16.8% compared with base fluids respectively with 0.2 vol% at 25°C. Among both of nanofluids for ZnO-Ag/sunflower hybrid nanofluids showed the higher thermal conductivity enhancement over ZnO-Ag/jatropha oil. For both the hybrid nanofluids thermal conductivity is increased linearly with increase of temperature.

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