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Assessment of Stability and Thermophysical Properties of Jojoba Nanofluid as a Metal-Cutting Fluid: Experimental and Modelling Investigation

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Abstract: Nanofluids based on vegetable oil have emerged as ecological alternatives to conventional cutting fluids. Jojoba-seed oil has recently been identified as adequate for use in metal cutting. Aiming to assess the stability and thermophysical properties of jojoba nanofluids, this article reports an experiment- and modelling-based investigation. The stability, viscosity and thermal conductivity of jojoba MoS_2 nanofluid were studied across a broad range of temperatures and concentrations of nanoparticles. The functional relationship of the viscosity and thermal conductivity to the temperature and concentration was determined by regression analysis. In addition to confirming known phenomena, vis-à-vis the effect of the concentration and temperature on the viscosity and thermal conductivity, this study shows that the increase in the thermal conductivity in line with the concentration stagnates after an initial sharp rise due to an increase in the attractive forces between the particles. The viscosity displays a second-order interactive relationship with the temperature and concentration of the nanoparticles, whereas thermal conductivity follows a complex third-order interaction model. In addition to being economical, jojoba nanofluid matches or surpasses the nanofluid prepared using commercially available mineral-oil-based cutting fluid (LRT 30)—which is specially designed for the minimum-quantity lubrication method of metal cutting. Conclusively, this investigation paves the way for the shop-floor application of jojoba nanofluid in metal-cutting operations.

Keywords: nanofluid; jojoba; stability; viscosity; thermal conductivity; regression model

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1. Introduction

Manufacturers in the machining industry have always relied on cutting fluids to produce machined products that meet their specifications for dimensional precision and good surface quality. Lubrication and cooling are the most important features of these fluids, which help to cool cutting tools while reducing friction. Straight, synthetic, semi-synthetic and soluble oils are used as cutting fluids. Cutting fluids with sufficient thermal conductivity can produce the ideal cooling effect. Normal water is a good coolant, but it is not a good lubricant and is also conducive to the corrosion of ferrous materials. Therefore, although it is generally not recommended to use pure water as a coolant, mixing with an emulsion offsets the low lubrication effect and a corrosive tendency. This product is referred to as water-soluble oil. Straight cutting oils, including mineral oils and fatty oils, are also used as cutting fluids because their lubrication properties are excellent; however, heat absorption is a problem with such oils. The benefits of mineral oils can be improved by adding additives, generally sulfur and chlorinated compounds. Synthetic oils do not contain mineral oil but have several additives to enhance their performance. In addition to being able to emulsify in hard water, synthetic oils do not cause bacterial growth when stored for long periods of time. The limitations of synthetic oils include insufficient lubrication and a tendency to form foam. Some coolants use semisynthetic oils, a blend of mineral oil and synthetic compounds. Synthetic oils have several benefits, but they also have some drawbacks. It is preferable to use semi-synthetic oils with additives.

With the aim of developing an eco-friendly substance with properties equivalent to conventional lubricants, vegetable oils have become the preferred lubricant in many applications. Vegetable oils are biodegradable, have adequate tribological properties and are less expensive than mineral oils. The use of vegetable oils, such as coconut [1], sunflower [2], soybean [3], sesame [4], mahua [5], neem [6], peanut, maize, rapeseed, palm, castor [7] and mustard [8], has been reported in metal-cutting operations. Vegetable oils are suitable for machining applications because they are non-toxic, renewable, biodegradable and highly viscous. They contain triglycerides, which join three long-chain fatty acids to the hydroxyl groups via ester bonds. The oxidising property is a hindrance to the use of vegetable oils. The oil becomes sticky as it oxidises, making the chips adhere to tools, parts and accessories. The performance of vegetable oil is improved by adding a variety of additives, such as nanoparticles, microparticles, anti-wear agents and antioxidants. Adding solid nanoparticle additives, such as molybdenum disulphide (MoS_2) [9], silicon oxide (SiO_2) [10], hexagonal boron nitride (HBN) [11], graphite [12], metal nanoparticles (Cu and Ag [13]), carbon nanotubes [14], etc., can significantly improve vegetable oil's performance.

Heat-transfer applications that use nanofluids have received interest due to their remarkable ability to improve the heat transfer ratio of the base fluid. Nanofluids exhibit better stability when compared to traditional fluids containing solid particles with sizes ranging from microns to millimeters because of the particle size effect and Brownian motion in liquids [15]. Nanoparticles in nanofluids increase thermal conductivity and enhance heat-transfer performance. The improvement in thermal conductivity compensates for the increase in viscosity caused by the addition of nanoparticles [16]. The dispersion of nanoparticles in a base oil at a concentration of less than 5% by volume greatly enhances the thermal conductivity of the base fluid [17]. When used as a cutting fluid, the increased thermal conductivity of the nanofluid promotes heat extraction in the machining zone and produces positive machining results. The improvement in the thermal conductivity of nanofluids depends on the particle type, shape, morphology, surfactant and temperature. Improving the thermal conductivity of nanofluids improves the lifespan and surface quality of machined surfaces by lowering the machining force and temperature. Nanofluids are more effective than traditional cutting fluids in terms of thermal conductivity, overall heat transfer coefficient and viscosity [18]. Su et al. (2016) [19] evaluated the stability, thermal conductivity and surface tension of two nanofluids prepared by different mass concentrations of nanoparticles. They found that the nanofluids with a higher mass concentration of nanoparticles were more stable than those with lower mass concentrations. In addition, increased mass concentration also leads to increased thermal conductivity and surface tension. The heat transfer rate of Newtonian nanofluids containing Fe2O3 and CuO nanoparticles increases with concentration and temperature, while the viscosity decreases as the temperature increases [20].

The improvement in viscosity due to the addition of nanoparticles is quantified in terms of nanoparticle concentrations and nanofluid temperature. The classical model of the viscosity of fluids with suspensions [21] relates viscosity enhancement (i.e., the ratio of the viscosity of the nanofluid μ_{nf} and the base fluid μ_{bf}) with nanoparticle concentration ($\varnothing$) is as follows:

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + A\varnothing \tag{1}$$

Recent literature reports viscosity enhancement as a nonlinear function of temperature (T) and nanoparticle concentration ($\varnothing$). For example [22]:

$$\frac{\mu_{nf}}{\mu_{bf}} = 1.123 + 0.3252\varnothing - 0.08994T + 0.002552T^2 - 0.00002386T^3 + 0.9695\left(\frac{T}{\varnothing}\right)^{0.01719} \tag{2}$$

The mathematical expression of the viscosity enhancement model is not standardised. More than 25 expressions are listed in one of the recent reviews on nanofluids [23], which is obvious, as the interaction between different nanoparticle types and corresponding base fluids differs significantly. As a consequence, each new combination of basic fluid and nanoparticles has to be modelled individually.

As with the viscosity, the enhancement of the thermal conductivity of the nanofluids (i.e., ratio of thermal conductivity of the nanofluid k_{nf} and base fluid k_{bf}) is modelled as a function of the nanoparticle concentration (∅); for example, the thermal conductive enhancement relation for equal proportion Cu: Zn + Groundnut nanofluid [24] is given as follows:

$$\begin{aligned}\frac{k_{nf}}{k_{bf}} &= 0.7054 + 0.871\varnothing - 0.009896T - 6.479 \times 10^{-5}T^2 - 0.09749T\varnothing \\ &\quad -4.741\varnothing^2 - 0.0002781T^2\varnothing - 0.1174T\varnothing^2 + 0.1174\varnothing^3\end{aligned} \tag{3}$$

Due to nanofluids' improved performance and the environmental friendliness of vegetable oils, vegetable-oil-based nanofluids are reported for different machining processes, such as turning, grinding and milling [25]. Lubrication in these processes is provided through the flooding or minimum-quantity lubrication (MQL) method. The MQL method minimises oil consumption because the oil (in a very low proportion) is mixed with air or carrier gas as a coolant and lubricant. The technique has been used successfully for machining difficult materials, such as Ti alloys [26]. The air-and-oil mixture is lean enough to enter the cutting tool and chip interface, altering the friction coefficient [27]. Metalworking is the method that benefits most from the use of nanofluids; however, the application of nanofluids is very diverse and includes recent applications, such as solar thermal collectors [28], biomedicine [29], insulation cooling in transformers [30], high-voltage equipment [31] and energy-efficiency enhancement [32].

Recently, jojoba oil has been reported to improve the overall performance and environmental performance of cutting operations [33]. Jojoba oil (pronounced 'hohoba'), an excellent metalworking fluid for several other manufacturing processes, such as forming, can be used with other lubrication applications in mechanical operations. Jojoba is a unique perennial shrub in the plant kingdom that grows naturally in the desert; it is becoming increasingly popular as an industrial crop. Currently, the jojoba crop is grown in southern Arizona, southern California, northwestern Mexico and some parts of many other countries. Jojoba is unique because of its greater oil % by weight in seed sources and high molecular weight of long-straight-chain (C_{20} and C_{22}) monoesters of fatty acids and fatty alcohols. Compared to other oils, jojoba oil does not contain glycerides, making it more self-stable. Jojoba oil has excellent properties, such as metal wetting, anti-wear, great stability, oiliness at high temperatures and high load-carrying capacity under extreme pressure conditions. The properties of jojoba oil make it useful for several industrial applications, such as cooling, lubrication, rust prevention and flushing away chips from metalworking machines. The use of jojoba oil is reported to reduce the cost of cutting operations by 27% compared with mineral-based cutting fluid [33]. Jojoba oil's high viscosity index and limited availability prevent it from being used as a flood coolant. However, these limitations could be overcome by the innovative use of jojoba oil as a fluid medium in MQL.

Furthermore, the high viscosity index of jojoba oil is envisaged to prevent the agglomeration of nanoparticles and thereby improve cutting performance. The thermophysical properties of jojoba oil-based nanofluid are not reported. This investigation is motivated by the requirement to examine and document the properties of a prospective environmentally friendly oil (i.e., jojoba), with the broader objective of increasing its application in an industrial scenario. In conjunction, this paper is also driven by the possibility of developing nanoparticle additives to improve the properties of jojoba oil. Specifically, this study aims to qualitatively and quantitatively assess the properties of stability, viscosity and thermal conductivity required for the use of jojoba oil as a metalworking fluid. The research aims of this investigation are threefold: (a) to investigate the properties of jojoba nanofluid (jojoba oil + $nMoS_2$ 0.1, 0.5, and 0.9% by volume) for its stability (sedimentation and Zeta potential) and thermophysical properties (viscosity and thermal conductivity) at different temperatures, (b) explore the possibility of developing predictive models of the thermal conductivity and viscosity of nanofluids as a function of temperature and nanoparticle concentration and (c) benchmark jojoba nanofluid against commercially available cutting oil (LRT 30), which is specially formulated for the MQL method. Section 2 of the article presents the materials and methods used in this investigation. Section 3, presents the results and a discussion of the stability and thermophysical properties of jojoba nanofluid, the development of the predictive model and a comparison between the jojoba nanofluid and the LRT 30 nanofluid.

2. Materials and Methods

2.1. Nanofluid Preparation

Molybdenum disulfide nanopowder ($nMoS_2$) used in this investigation was 80–100 nm in diameter. The specifications of $nMoS_2$ are listed in Table 1. Figure 1 shows the SEM image of $nMoS_2$.

Table 1. Specifications of nanopowder ($nMoS_2$).

Specification	Value
APS	80–100 nm
Purity	99.9%
Colour	Black
Density	4.8 g/cm^3
Molecular Weight	160.07 g/mol
Melting Point	1185 °C
Morphology	Flaky Plates

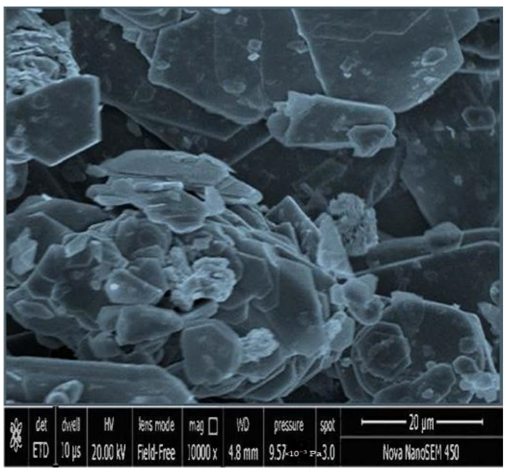


Figure 1. SEM of Molybdenum disulfide nanoparticles.

Jojoba (vegetable-based) oil was used as the base fluid. The performance of vegetable nanofluid was also benchmarked against commercial MQL cutting oil LRT 30 (mineral-based)—specially manufactured for hard machining and supplied by Dropsa (Milano, Italy). Table 2 shows the properties of base fluids.

Table 2. Properties of base fluids.

Properties	Jojoba Oil	LRT 30 Oil
Viscosity cP at 40 °C	24.9	24
Viscosity cP at 90 °C	8.0	7.6
Density (kg/m^3)	867	953
Flammability point °C	295	220
Solubility	Not soluble in water	Not soluble in water
Specific gravity at 25 °C	0.86	0.9
Appearance	Clear golden yellow	Clear golden yellow

The nanofluid was prepared by dispersion of $nMoS_2$ in different concentrations (0.1%, 0.5% and 0.9%). The dispersion of the nanoparticles in the base fluids was accomplished by an ultrasonic stirrer and an ultrasonic bath. An ultrasonic microprocessor-based vibrator (Sonics and Materials, Inc., Newtown, CT, USA), generating pulses of 40 kHz at 100 W, was used with 25% amplitude, pulse on at 25 s and pulse off at 5 s for nanofluid preparation. The nanofluid formulation was sonicated for 45 min to achieve a homogeneous and stable suspension of nanoparticles. Lauryl sodium sulfate of 0.1% weight of the nanoparticle was used as a surfactant. The law of mixture estimates the number of nanoparticles required to prepare nanofluids. The estimate of nanoparticle concentration (volume/volume) is given as:

$$\%\ \text{Concentration} = \frac{100 \times W_p/\rho_p}{W_p/\rho_p + W_{bf}/\rho_{bf}} \tag{4}$$

where W and ρ (subscript p and bf for nanoparticles and base fluid, respectively) are the weight and density. Table 3 shows the density of the nanofluids.

Table 3. Properties of nanofluids.

Nanofluid	$nMoS_2$ Concentration (% vol.)	Density (kg/m^3)
$nMoS_2$ + jojoba oil	0.1	870
	0.5	896
	0.9	912
$nMoS_2$ + LRT 30	0.1	968
	0.5	979
	0.9	987

2.2. Stability and Thermophysical Properties Measurement

2.2.1. Stability Assessment

Due to the settling of nanoparticles over time, nanofluids gradually lose their heat-transfer capacity. Thus, it is crucial to consider the stability of nanofluids as they may affect the thermophysical properties required for application. The nanofluid's stability was determined using a sedimentation test and Zeta-potential measurements. The sedimentation test was conducted by monitoring the formation of sediments in a transparent glass vial. This was performed by capturing photographs of the vial using a camera and comparing them to each other. Pictures of the nanofluids were taken at various time intervals. Zeta potential was evaluated using a Zetasizer Nano ZSP (ZEN 5600) (Malvern Panalytical Ltd., Malvern, UK) following ASTM D4185-82. It measures the Zeta potential of particles of sizes up to 0.3 nm dispersed in any liquid solution. A sample of 5 mL of nanofluid was used to measure the cuvette/cell to measure the Zeta potential. The experiment was performed with an electrode voltage of 140 V, a temperature of 25 °C and a measuring time of 180 s. The average value was calculated by repeating each experiment three times, i.e., number of independent repeats n = 3. Zeta potential of 0–30 mV meant that the solution was unstable and coagulated quickly. Zeta potential of 30 to 40 mV meant that the solution was relatively stable, while 40 to 60 mV showed good stability. There was remarkable stability when the values were more than ±60 mV [34].

2.2.2. Viscosity Measurement

Viscosity is a property of a fluid that indicates its ability to lubricate. The viscosity of a fluid is determined by comparing the viscous drag of the fluid to the spindle rotation. Using a variety of spindle geometry and speeds, a wide range of viscosity measurements can be taken. The fluid's viscosity in this investigation was determined using a rheometer (RheolabQc, Anton-Paar, Graz, Austria) following ASTMD440. A thermostat bath was employed to keep all measurements at the same temperature. A range of temperatures from 40 to 90 °C was used to determine the viscosity.

2.2.3. Thermal Conductivity

Hot-disc thermal conductivity analyser and KD2 pro-thermal conductivity meter (Decagon Devices, Inc., Pullman, WA, USA) were used to test the thermal conductivity of base oil and nanofluids at three temperatures: 30, 40 and 50 °C. The transient hot-wire method was used to determine thermal conductivity within the ranges of 0.02 to 2.00 W/m (KD2 pro) and 0.03 to 100 W/mK (hot disk). After reaching steady-state temperature, the thermal-conductivity-measurement procedure was initiated. All data were collected three times (n = 3), and the average values were examined to determine the outcome.

3. Results and Discussion

3.1. Stability Assessment

The stability of a nanofluid, a colloidal system, refers to its ability to retain thermophysical properties for a sufficient duration before the nanoparticles start coagulating and phase separation occurs. The stability of a colloidal system depends on van der Waals's attractive and electrical double-layer repulsive forces. The double-layer is the sheath of opposite charges near the particle surface. The net charge at the particle surface attracts ions of opposite polarity, which create an electric double layer around the particle. The potential difference between the double layer and the bulk liquid away from the double layer is known as the Zeta potential. When the attractive force is larger than the repulsive force, the particles collide and aggregate and eventually settle under the influence of gravity. The basic tendency of nanofluid to aggregate is assessed by the Zeta potential, while time-induced segregation is assessed through a sedimentation test. The Zeta potential, therefore, indicates the nanofluid stability inflow and stationary conditions after the preparation of the nanofluid, while the sedimentation test indicates the stability of the fluid when it remains stationary for a long duration after preparation.

3.1.1. Zeta Potential Test

The fluid's Zeta potential value (positive and negative) indicates a stronger electrostatic repulsion, which prevents particles from colliding and aggregating. Nanoparticles with Zeta potential values of more than 30 mV are stable, while nanoparticles with less than 15 mV are unstable. The Zeta-potential values of the jojoba and LRT nanofluids are presented in Figure 2. The error bars show the standard error of the measurement. The nanofluids with 0.1% of $nMoS_2$ nanoparticles in jojoba oil showed a Zeta potential of −36.8 mV, which suggests excellent stability.

Higher concentrations of nanoparticles reduce the Zeta potential, particularly at 0.9% concentration. The nanofluid becomes unstable as the Zeta potential approaches the threshold value of 15 mV. The jojoba nanofluid is almost as stable as the nanofluid prepared using the LRT oil. The values of the Zeta potential of the jojoba nanofluid was in the same range as that observed for other vegetable nanofluids; for example, rapeseed oil +50–100 nm MoS_2 exhibited a Zeta potential of 28.5 and 33.5 mV, for 0.5% and 1.0% concentrations of nanoparticles, respectively [35].

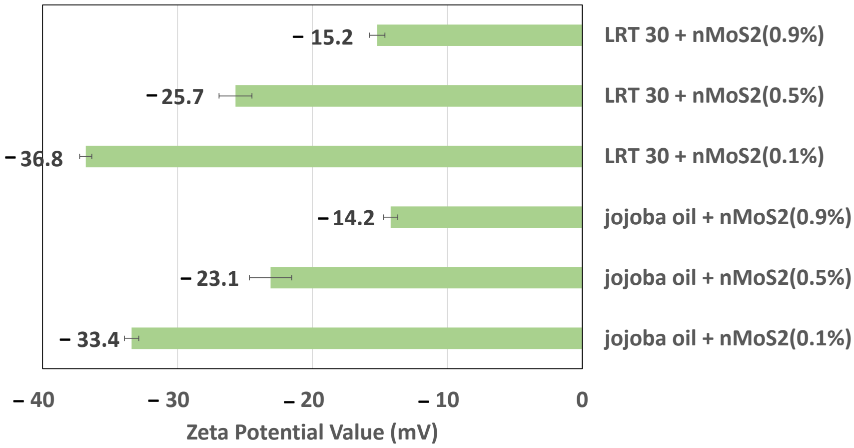


Figure 2. Zeta potential value of nanofluids.

3.1.2. Sedimentation Test

Figure 3 shows the results of the sedimentation test carried out by monitoring the formation of sediment in a transparent glass vial. The photographs of the nanofluids were taken at various time intervals, namely 0, 24, 96 and 168 h. The six nanofluids were stable for the first 24 h, until the deposition of the nanoparticles commenced. Nanoparticle suspension stability is better with higher nanoparticle concentrations. Higher mass concentrations within the nanofluid increase the density and viscosity at ambient temperature (Table 3). As a result, aggregation is prevented at relatively higher concentrations, namely 0.9%. Beyond the limit of the concentrations used in this investigation, further increases, such as2.5%, would have accelerated the sedimentation due to gravity, as observed in other investigations [36]. Although the 0.1% concentration nanofluid sediments earlier than the higher-concentration samples, its Zeta potential is the maximum. This means that it is less likely to coagulate due to attractive forces. As a result, nanofluid at 0.1% concentration nanofluid shows a remarkable improvement in thermal conductivity (despite having lower density), as discussed below.

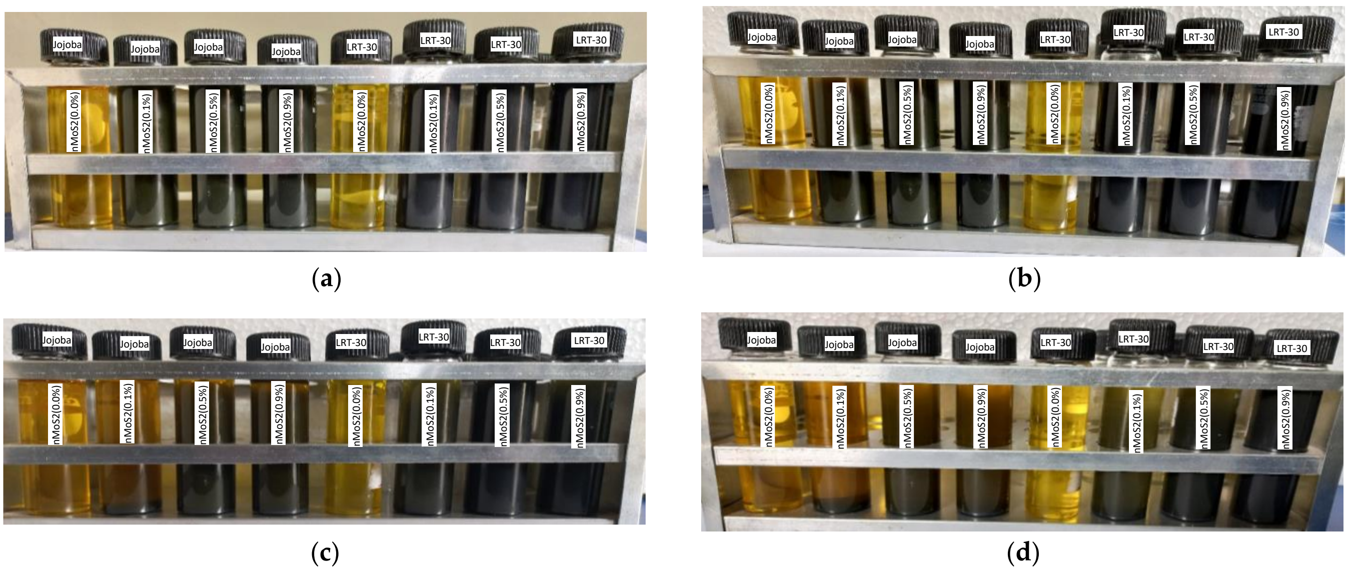


Figure 3. Sedimentation photographs of nanofluid at different concentrations of nanoparticles at different times (**a**) 0, (**b**) 24, (**c**) 96 and (**d**) 168 h.

3.2. Influence of Concentration and Temperatures on Viscosity

The fluid viscosity indicates its internal resistance to flow, which influences the injection capacity and the heat-transfer characteristics. The plots of the viscosity vs. the nanoparticle ($nMoS_2$) concentration (%) and temperature of the jojoba- and LRT-based nanofluids are shown in Figure 4. The nanofluids with higher nanoparticle concentrations showed a significant increase in viscosity compared to those with lower nanoparticle concentrations. The maximum viscosity of the jojoba-based fluid and LRT-base fluid was obtained at a 0.9% concentration of the $nMoS_2$, followed by 0.5%, and the lowest enhancement occurred at a 0.1% concentration of the $nMoS_2$. With an increase in concentration, the density of the nanofluid increases (Table 3), as does the dynamic viscosity, as shown in Figure 4.

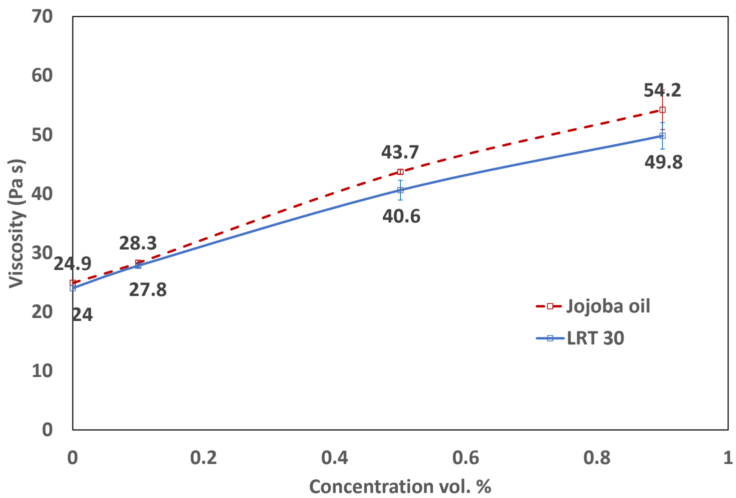


Figure 4. Viscosity of jojoba- and LRT 30-based nanofluid concerning the concentration of $nMoS_2$.

Viscosity is a critical property in high-temperature applications. The viscosity of the jojoba- and LRT-based nanofluids was measured at temperatures of 40, 65 and 90 °C. Figure 5 shows that the viscosity of the jojoba and LRT nanofluids decreases with increasing temperature. The nanofluid viscosity at 40 °C is significantly different from the viscosity at 90 °C. With an increase in temperature, the density of the vegetable oil reduces by approximately 5% for the range of temperature applied in this investigation [37]. However, the corresponding change in the viscosity is more than 60% (Figure 5). This is likely due to the weakening of the solid–liquid interaction and the reduction in the liquid shear stress, leading to a weaker thickening and entanglement mechanism [38]. At high temperatures, the weaker intermolecular force of attraction between the particles reduces the viscosity. However, molecular forces tend to be strong as the concentration of nanoparticles increases, which aids viscosity enhancement.

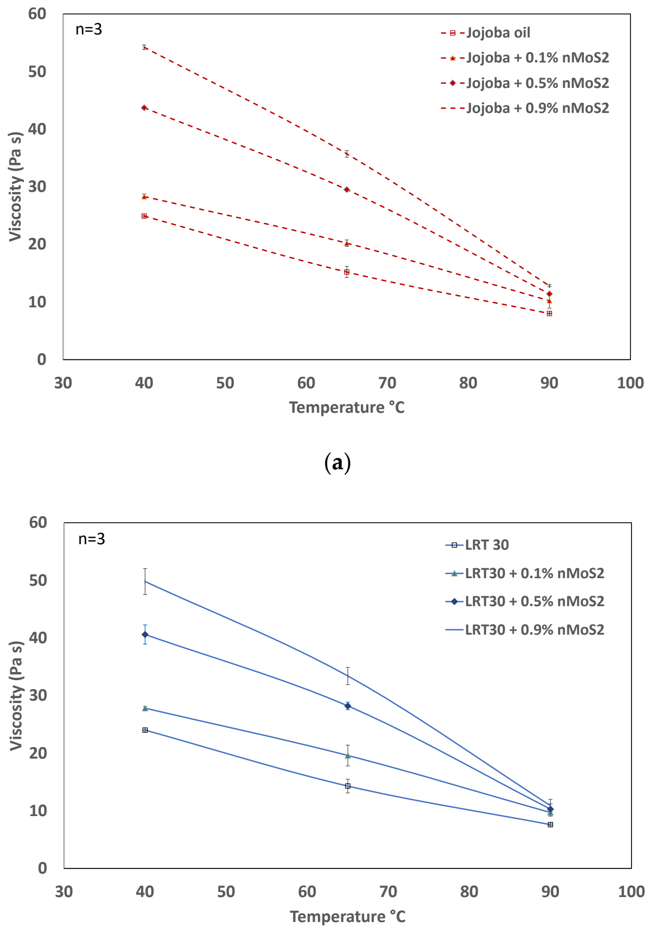


Figure 5. Viscosity of (**a**) jojoba- and (**b**) LRT 30-based nanofluid concerning temperature variations.

3.3. Influence of Concentration and Temperatures on Thermal Conductivity

The thermal conductivity of the jojoba and LRT nanofluids was measured with varying nanoparticle concentrations (0.1%, 0.5% and 0.9%) at different temperatures (30 to 50 °C). The thermal conductivity vs. nanoparticle concentrations (%) and thermal conductivity vs. temperature graphs for jojoba + $nMoS_2$ and LRT + $nMoS_2$ nanofluids are shown in Figures 6 and 7, respectively. The thermal conductivity of the nanofluids rises with increasing nanoparticle concentrations. The rises in concentration (%) cause a greater aggregation of nanoparticles, which increases the heat-transfer rate. However, the enhancement of thermal conductivity observed with an increase in the concentration of nanoparticles from 0 to 0.1% did not show a significant change in the range of 0.1 to 0.9%. This may be attributed to the decrease in the Zeta potential at higher concentrations, as noted above (Figure 2). Coagulation at higher concentrations breaks molecular chains; thus, the ability to transfer thermal vibrations decreases. Therefore, the benefit of increased concentration is offset by increased coagulation. The increase in thermal conductivity in line with the increase in temperature (Figure 7) is attributable to the collisions of nanoparticles and the growing Brownian motion of nanoparticles with temperature. Furthermore, the increase in temperature reduces the viscosity of nanofluids and decreases the friction between the oil/$nMoS_2$ films, thus increasing the thermal conductivity of nanofluids [38].

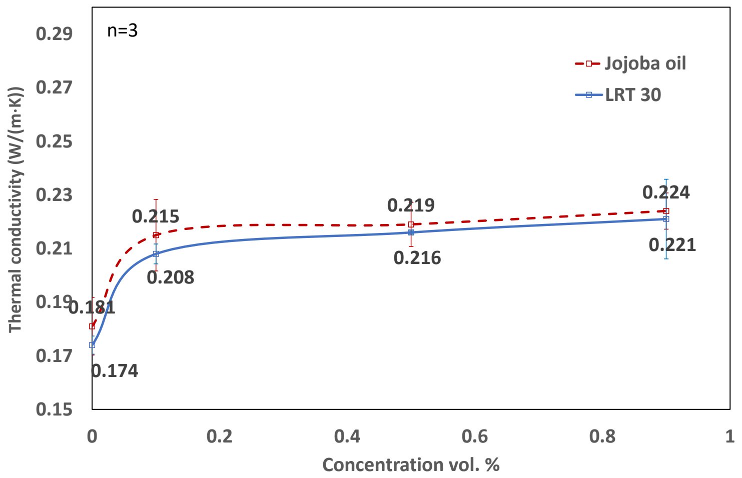
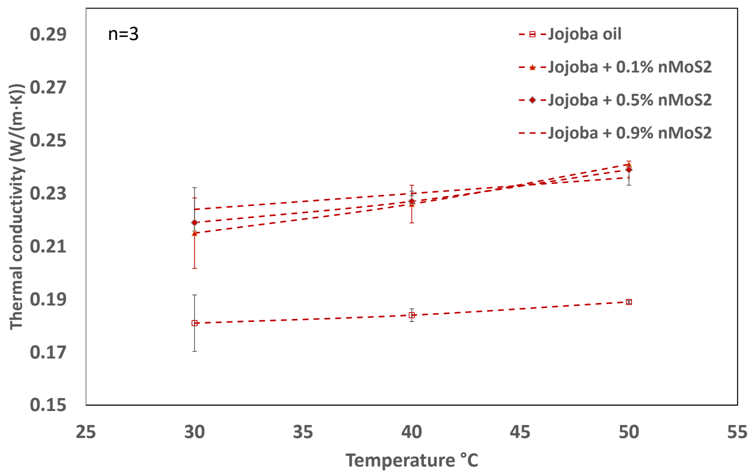
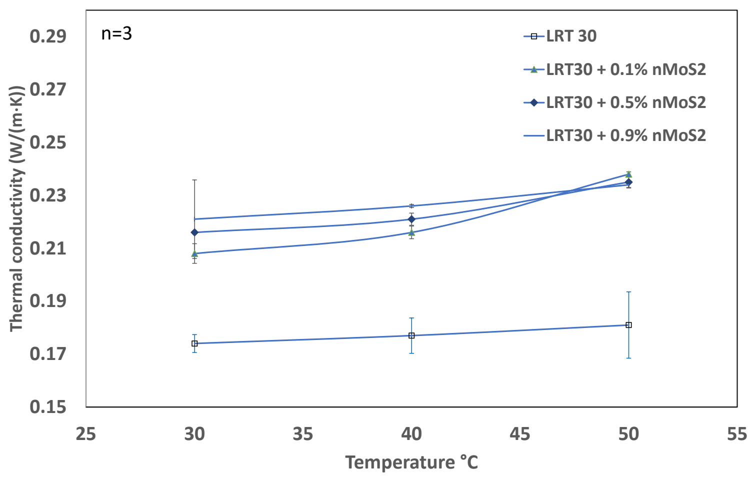


Figure 6. Thermal conductivity of jojoba- and LRT 30-based nanofluid concerning the concentration of $nMoS_2$.



(**a**)



(**b**)

Figure 7. Thermal conductivity of nanofluid concerning temperature variations. (**a**): jojoba; (**b**): LRT 30.

3.4. Predictive Models

3.4.1. Viscosity Model

The trends in Figure 5 indicate that the dynamic viscosity of the LRT 30 and jojoba nanofluids can be expressed in relation to the concentration and temperature. A simple quadratic equation with the terms of interaction corresponds well to the experimental data for both base oils. The viscosity enhancement expressions obtained through stepwise regression analysis are as follows:

Jojoba nanofluid:

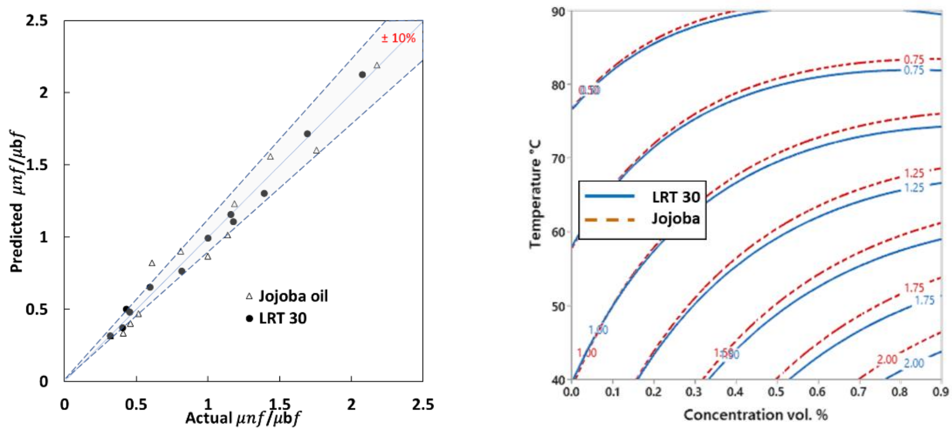
$$\frac{\mu_{nf}}{\mu_{bf}} = 1.51 - 1.32 \times 10^{-2}T + 2.67\varnothing - 2.28 \times 10^{-2}T\varnothing - 4.25 \times 10^{-1}\varnothing^2 \quad (5)$$

LRT 30 nanofluid:

$$\frac{\mu_{nf}}{\mu_{bf}} = 1.53 - 1.36 \times 10^{-2}T + 2.53\varnothing - 2.14 \times 10^{-2}T\varnothing - 4.66 \times 10^{-1}\varnothing^2 \quad (6)$$

where T is the temperature in °C and $\varnothing$ is the vol.% of the nanoparticle. μ_{bf} is the dynamic viscosity of the base fluid at 40 °C.

The viscosity enhancement relations have R^2 values of 0.9954 and 0.9919 for Equations (5) and (6), respectively. The agreement between the actual and predicted values of the viscosity enhancement is shown in Figure 8a. The predicted viscosity enhancement differed from the actual enhancement within the range of ±10% for all the samples, bar one. The effect of the temperature and concentration is evident from Figure 8b. The addition of nanoparticles at lower temperatures, of 40 °C, enhances the viscosity, which can reach twice the value of the base fluid at higher concentrations (e.g., 0.9). As the temperature increases, the increase in the viscosity begins to reduce; for example, at 80 °C, even at higher concentrations, nanofluid shows a decline in viscosity rather than an enhancement. Therefore, when supplied as a coolant under MQL conditions, the low viscosity of the high-temperature fluid helps it to enter between sliding surfaces. It can be seen that the viscosity results of both the jojoba base oil and the nanofluid were very near to those of the LRT 30, which is a commercial oil for use on hard-to-machine materials in MQL conditions. This means that jojoba meets the required viscosity requirements of cutting fluids used on the shop floor.



(**a**) (**b**)

Figure 8. (**a**) Accuracy of prediction of the regression model and (**b**) interactive effects on viscosity enhancement.

3.4.2. Thermal Conductivity Model

The relationship between the concentration and the thermal conductivity is not as simple as the viscosity; consequently, the second-order model does not correspond to the thermal-conductivity-enhancement model. Thermal conductivity enhancement is a third-order feature similar to the previous Cu:Zn Groundnut nanofluid [24]. However, in the current investigation, the stepwise regression method removed the unnecessary model terms that hamper the robustness of the model [39]. The regression equations obtained for the thermal conductivity enhancement are as follows:

Jojoba nanofluid:

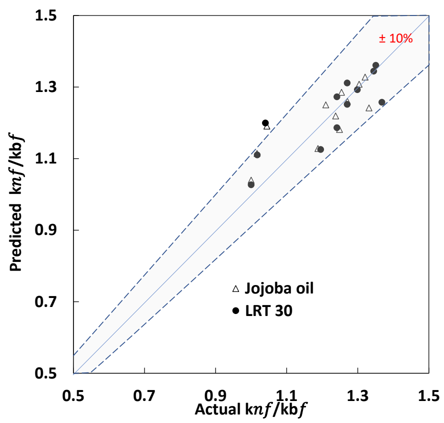
$$\frac{k_{nf}}{k_{bf}} = 8.38 \times 10^{-1} + 4.55 \times 10^{-3} T + 3.08\varnothing - 7.8191\varnothing^2 + 5.22\varnothing^3 \quad (7)$$

LRT 30 nanofluid:

$$\frac{k_{nf}}{k_{bf}} = 8.20 \times 10^{-1} + 4.96 \times 10^{-3} T + 3.25\varnothing - 8.138\varnothing^2 + 5.42\varnothing^3 \quad (8)$$

where T is the temperature in °C and $\varnothing$ is the vol.% of the nanoparticle. k_{bf} is the thermal conductivity of the base fluid at 30 °C. The thermal-conductivity-enhancement relations have R^2 values of 0.9793 and 0.9664 for Equations (7) and (8), respectively.

The agreement between the actual and predicted values of the viscosity enhancement is shown in Figure 9a. The predicted viscosity enhancement differed from the actual enhancement within the range of ±10% for all the samples, bar one. At a relatively lower concentration (up to 0.3%), the enhancement in the jojoba-based nanofluid's thermal conductivity remains the same as that of the LRT-30-based nanofluid (Figure 9b). At higher concentrations, jojoba nanofluid requires relatively higher temperatures to attain the same enhancement in thermal conductivity as that attained by LRT 30. The thermal conductivity of jojoba base oil is more than that of LRT 30 base oil (Figures 7 and 8); thus, for the same change in the thermal conductivity due to the addition of nanoparticles, jojoba nanofluid shows less enhancement.



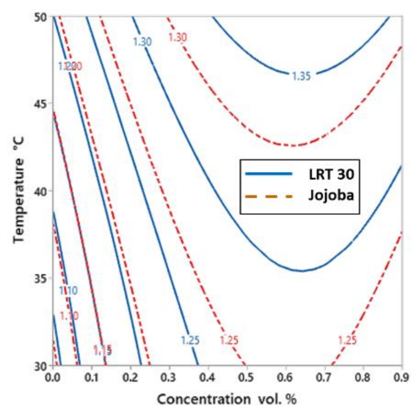


Figure 9. (**a**) Accuracy of prediction in the regression model and (**b**) interactive effects in thermal conductivity.

The models developed for the thermal conductivity and viscosity capture the basic science of the thermophysical properties of nanofluids. Furthermore, the quality of the prediction was assessed by the uncertainty in the prediction. The 95% confidence interval bands, calculated based on a statistical analysis, are shown in Figure 10. It is clear that the viscosity prediction is quite reliable due to the narrow confidence interval bands. On the other hand, the thermal conductivity is more sensitive to changes in concentration and temperature (third-order equation); therefore, the 95% confidence interval bands are relatively wide.

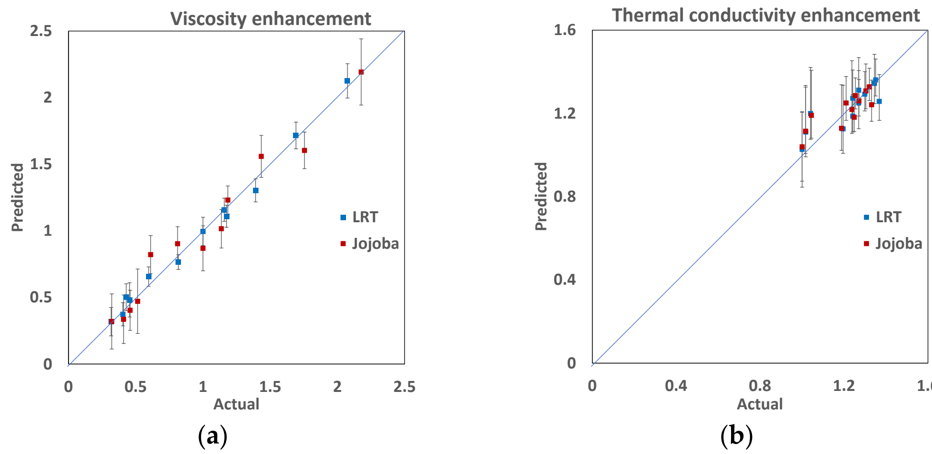


Figure 10. Uncertainty in prediction (i.e., 95% confidence interval) of (**a**) viscosity and (**b**) thermal conductivity.

This investigation established that jojoba nanofluid is very similar in its thermophysical properties to commercial cutting fluid (LRT 30). Jojoba-based oil and nanofluids are more viscous than LRT 30. The jojoba base oil and the jojoba nanofluid exhibited better thermal conductivity than the LRT 30 nanofluid at the same nanoparticle concentration. The superior thermal conductivity of the jojoba nanofluids was maintained for the entire range of temperatures applied in this investigation. However, as the temperature increases, the viscosity of the nanofluid decreases and approaches the viscosity of the base fluid at the same temperature. At the same time, the thermal conductivity increases, along with the temperature. Combining the two makes the nanofluids suitable for MQL application because a fluid that can easily spread (i.e., less viscous) and exhibit higher thermal conductivity is a desirable condition offered by nanofluids at higher temperatures. The metal-cutting operation generates sufficient heat to keep the workpiece sufficiently hot to facilitate the wetting of the surface by a nanofluid, whose heat-dissipation capacity increases with temperature.

4. Conclusions

This article reports a study on the stability, viscosity and thermal conductivity of vegetable oil-based nanofluids (jojoba + MoS_2 nanoparticles) over a wide range of temperatures and nanoparticle concentrations. The properties of the jojoba nanofluid and commercially available mineral oil (LRT 30) nanofluid were compared. Models for the viscosity and thermal conductivity were developed. The following conclusions were drawn from the findings of this study:

1. The nanoparticle concentration affects the stability of the nanofluids jojoba + $nMoS_2$ and LRT 30 + $nMoS_2$. The as-prepared nanofluid shows higher Zeta potential at lower concentrations (e.g., 0.1%) than at higher concentrations (e.g., 0.9%). Increases in concentration lead to a condition in which the attractive force is greater than the repulsive force vis-à-vis the particles colliding and aggregating.
2. The nanofluids remain stable for the first 24 h. Subsequently, the nanofluids with a higher concentration of nanoparticles help to increase the density and viscosity; thus, nanofluids with a concentration of 0.1% sediment before those at 0.5 and 0.9% concentrations.
3. The viscosity of jojoba- and LRT 30-based nanofluids (at a reference temperature of 40 °C) increases linearly with the addition of MoS_2 nanoparticles. With increases in temperature, the viscosity falls. At higher temperatures (e.g., 90 °C), the effects of changes in the nanoparticle concentration are not visible, i.e., the viscosity at 0.1 to 0.9% concentration at 90 °C remains almost the same.
4. The thermal conductivity shows a sharp rise when a small amount of nanoparticle (0.1 vol.%) is added to the base fluids. Subsequently, significant gains are not observed. At higher concentrations, the expected increase in thermal conductivity due to the increase

in density is counter-balanced by the increase in attractive forces, which hampers the mobility of nanoparticles and the corresponding change in thermal conductivity.

5. The viscosity of jojoba nanoliquid is nearly the same as that of LRT 30, especially at higher temperatures. Jojoba nanofluid at higher concentrations reaches a higher thermal conductivity, even at lower temperatures, than LRT 30 nanofluid.
6. Viscosity and thermal conductivity can be accurately predicted with respect to nanoparticle concentrations and temperatures. The viscosity's relation to nanoparticle concentrations and temperatures fits well with a second-order function. The thermal conductivity relationship is more complicated and follows a third-order interaction function.

This investigation demonstrates that jojoba + $nMoS_2$ nanofluid remarkably competes with the commercial-mineral-oil LRT 30 in terms of stability and thermal properties. This demonstrates that jojoba is an environmentally friendly replacement for traditional cutting fluids. In the future, the application of jojoba oil in metal cutting will expand through the use of other nanomaterials to prepare the nanofluid.

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