

Numerical Investigation of Thermal Analysis of Coconut Oil-Based Al_2O_3 Nano Cutting Fluid for Sustainable Machining

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Abstract: With the growing demands of sustainable manufacturing, the present research examines the development of eco-friendly fluids for machining. Sustainable machining formulated an alternative to conventional coolant by dispersing nanoparticles into an organic base oil. The investigation of this study for the heat transfer characteristic of a composite of Al_2O_3 /Coconut oil-based nanofluid. A Maxwell mathematical model was developed with the relation of effective thermal conductivity and maximum heat dissipation from the tool/workpiece. During the analysis, we have used the nanoparticle volume fraction of (0 to 5%). The analysis findings observed that increasing the concentration by 0.05 significantly enhanced the thermal conductivity and increased the nanofluid temperature, improving heat transfer performance. In addition, the coconut oil greatly improves the dynamic viscosity of the base fluid. The study highlights the Al_2O_3 /Coconut oil-based nanofluid as an effective and sustainable cooling medium for thermal applications in machining and other mechanical equipment.

Keywords: Sustainable Manufacturing, Nano cutting Fluid, Maxwell Mathematical model.

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1. Introduction

In recent years, due to the increasing demand for sustainable manufacturing play an important role in using the organic and vegetable oil used with the correct fraction of nanoparticles. Heat transfer and nanofluid transport over the surface of the workpiece and tool have been extensively studied, demonstrating the increasing integration of Multiphysics interaction, model realism, and practical application. The thermal performance of the base and the nanoparticles can be greatly underrated by ignoring property variations, as demonstrated by early studies that emphasized the significance of better performance. Similarly, Kadrigamar K et al. identified that the nano-coolant used for the enhancement of heat transfer, and reduced the surface friction for better and durable machining between the workpiece and tool [1]. Recent studies of Wang X et al. on the interconnectedness of industry and ecology, and environmental impact as a main principle of industry [2]. Pambudi, NA et al investigated that the coolant used during the machining operation has a serious ecological concern due to hydrofluorocarbons and other chemical direct effect the ozone depletion and human health risk [3]. Hwang, Y studied that the suspension of nanoparticles (1 to 100nm) with water, oil,

and ethylene glycol has increased the thermophysical properties, maximum transfer of heat due to the convection phenomenon [4]. Choi was the first to study in the 20th century the nanoparticle increase the transfer of maximum heat due to the contact surface between any solid object, the contact surface of the body with the fluid, stick due to the surface friction, the velocity of fluid decreases, and transfer of heat will be maximum[5]. The number of applied investigations shows that the thermal analysis/management system for nanofluid is used in heat exchangers, machining operations, and solar collectors [6, 7]. Nano lubricants and coolants are used for better precision of machining operations like turning, milling, drilling, and grinding [8,9]. Several studies predict that the NPs increase the intrinsic thermal conductivity of the nano fluid used for the machining operation [10]. Wang et al investigated that nanoparticles of copper greatly increased the thermal conductivity of the fluid [11]. According to Yoo et al., reported that the TiO₂ has lower intrinsic thermal conductivity as compared to the Al₂O₃ [12]. The layer formation of the base fluids when they flow at the surface of the workpiece and tool increases the thermal conduction because the contact surface directly affects the heat transfer rate [13, 14, 15]. Agarwal et al investigated that the Al₂O₃ mix with the distilled water and ethyl glycol resulted in a greater thermal conductivity improvement by 40% [16]. Vegetable oil has very good properties for use in different operations, but one thing to keep in mind the flash point of vegetable oil has a maximum [17,18]. During the machining operations have mechanical and thermal needs, so they require effective cooling for tool life and surface integrity [19]. Grinding operation is an abrasive with a specific energy requirement and maximum transfer of heat [20]. However, the Cutting fluid is required for better tool life, continuous chip formation, and better surface finish [21]. The NFs have a variety of machining processes in Fig.01 that increase the cooling, surface finish, and lubrication [22].

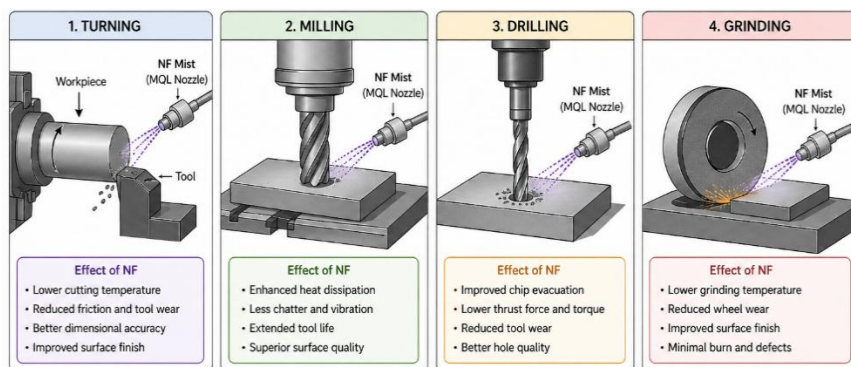


Fig. 01. Schematic diagram during machining operations

In this research investigation, we have developed the coconut oil- based Al₂O₃ cutting fluid for finding the heat transfer behavior with a mathematical model to simulate temperature variation using MATLAB.

2. Materials and Methodology

The coconut oil (Virgin and cold pressed) and Al₂O₃ nanoparticle with percentage concentration (0% to 4%) were used. A colloidal Suspension is produced by suspending the nanoparticle in coconut base fluid [23].

Table 01 Description of Al₂O₃ nanoparticles [24]

Property	Value
Purity	99.9%
Average particle size	60.5 ± 2 nm
Color	White
Morphology	Nearly spherical
Specific surface area	110 m ² /g
Bulk density	0.5 g/cm ³

Table.02 Physical Properties of coconut oil [25]

Specification	Range
Saturated fatty acids	90–94%
Unsaturated fatty acids	6–10%
Viscosity index (VI)	142
Viscosity in cSt at 40 °C	28.56
Viscosity in cSt at 100 °C	6.76
Refractive index at 25 °C	1.448–1.450
Specific gravity at 25/25 °C	0.915
Flash point (°C)	278
Smoke point (°C)	232
Cloud point (°C)	27
Melting point (°C)	21
Pour point (°C)	20

3. Mathematical Modeling for the Analysis of Heat Transfer through Nanofluid

The developed Mathematical model for nano-based fluids was solved using MATLAB by incorporating the parameters adopted from [25] under similar operating conditions to ensure the accuracy for better results.

Convection Heat Transfer Relation $Q = h.A. (T_s - T_f)$	(1)
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Effective Thermal Conductivity (Maxwell Model)	
$k_{nf} = k_f \left(\frac{k_p + 2k_f + 2\phi(k_p - k_f)}{k_p + 2k_f - \phi(k_p - k_f)} \right)$	(2)

ϕ = Volume Fraction of Nanoparticle

k_f = Thermal Conductivity Of Base Fluid

k_p = Thermal Conductivity Of Nano – Particle

Volume fraction Mathematical Expression $\phi = V_p / V_p + V_f$	(3)
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V_p = Volume Fraction of NPs

V_f = Base Fluid volume

Temperature Estimation Equation	
$T = T_s - \frac{Q}{hA}$	(4)

h = convective heat transfer coefficient

Specific Heat of Nanofluid	
$(C_p)_{nf} = (1 - \phi)(C_p)_f + \phi(C_p)_p$	(5)

C_p = Specific heat capacity of particles

The developed Mathematical model utilizes Eqs. (1)-(5) to compute the simulation outcomes.

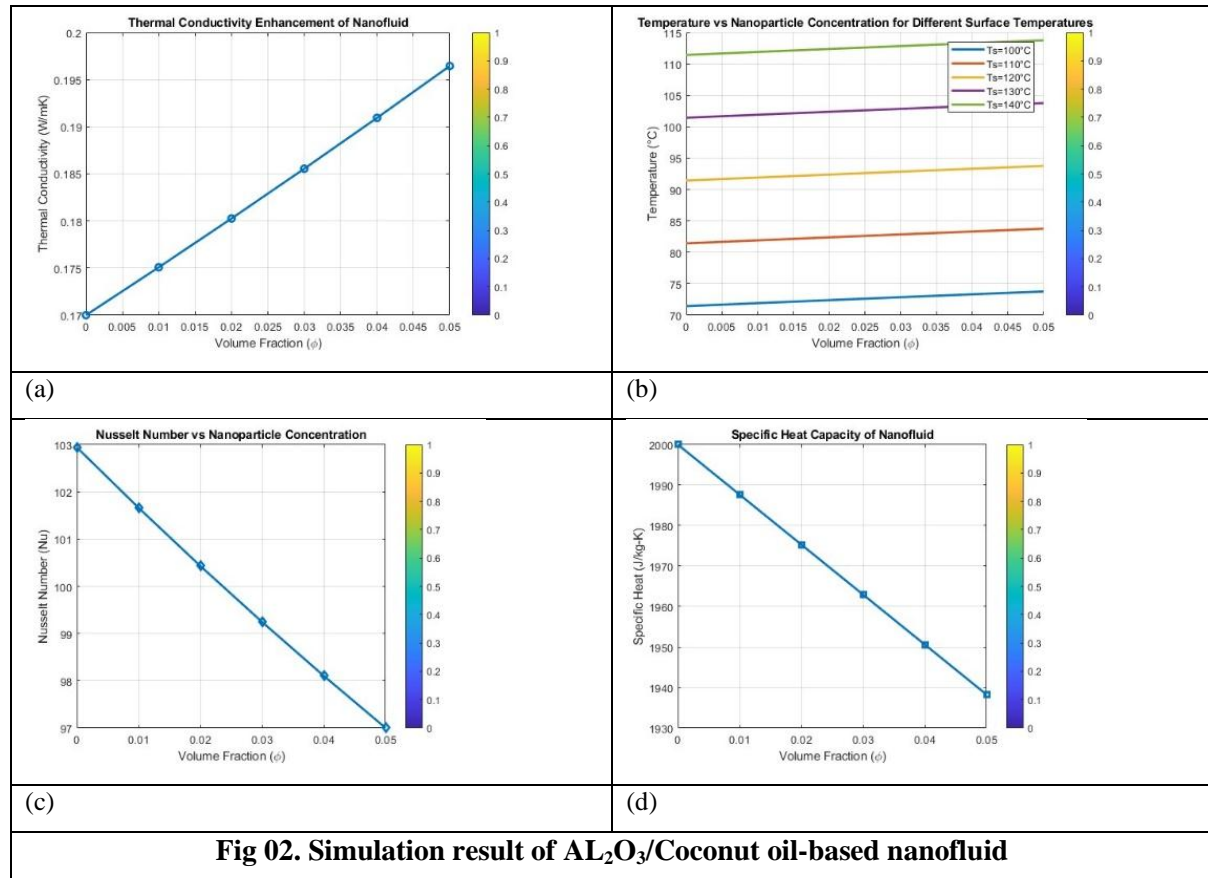
4. Result and Discussion

The Developed mathematical model for analysis of heat transfers the following parameters are mentioned below on Table.03. The selected parameters ensure realistic simulation conditions and allow with experimentally work.

Table 3: Input Parameters for Mathematical Modeling

Parameter	Values
Thermal Conductivity of Coconut Oil	0.17 W/mK
Thermal Conductivity of Al ₂ O ₃	36 W/mK
Heat Input	50 W
Area	0.01 m ²
Surface Temperature	100°C to 140°C
Nano particle Volume Fraction	0 to 5%

The simulation result of the mathematical model displays a significant enhancement for using the variable fraction of nanoparticles; these findings show the strong validation of previous experimental work.



The Mathematical model was used to investigate the thermophysical and heat dissipation characteristics of the Al_2O_3 /coconut oil nanofluid as a function of nanoparticle volume fraction ($\phi = 0-0.05$) and surface temperature of the tool/workpiece surface interface ($T_s = 100 -140^\circ\text{C}$). The results are demonstrated in Figs. a-d.

(A) Thermal Conductivity Enhancement of Nanofluids

The graphical representation of the disparity of effective thermal conductivity with nanoparticle concentration. The parameters enhance the value of thermal conductivity, which is observed as ϕ (0 to 0.005). For the present properties ($k_f = 0.17 \text{ W/m}\cdot\text{K}$, $k_p = 36 \text{ W/m}\cdot\text{K}$), the effective conductivity rises by approximately 15.5–24.6% at $\phi = 0.05$ compared to the base fluid. This increment is credited to the higher thermal conductivity of Al_2O_3 particles, and contact with the solid surface heat conduction improved within the suspension. The trend of nonlinear designates the enhancement most observable at high concentrations of the solid-liquid interface during the machining operations.

(b) Temperature vs. nanoparticle concentration at different surface temperatures

It is observed that the trend profile of the temperature ($T_s=100-140^\circ\text{C}$), the fluid temperature increases by 2 to 4C increase with all concentration ranges. The graphical representation of the stable thermal behavior. However, the surface temperature variation during the machining operation provides a driving force that directly affects the limited concentration range ($\leq 5\%$).

(c) Nusselt Number Variation Vs Volume Fraction of Nanoparticles

Figure C illustrates the Nusselt number as a function of Nano particle volume fraction(ϕ). A significantly progressive increasing behavior is observed, the Nusstle number increasing values by approximately 10 to 20% at the maximum volume fraction at $\phi = 0.05$. During the machining operation, the coolant strikes the surface of both the tool tip/workpiece, increasing the convective heat transfer coefficient(h) due to increased thermal conductivity and energy transport during machining.

(d) Specific Heat Capacity of Nanofluid Vs Volume Fraction of Nanoparticles

The graphical representation in Figure d clearly showed the linear decrease in the specific heat capacity with increasing the volume fraction of nanoparticle (ϕ). The reduction is approximately 2.8 to 6% at the maximum concentration of nanofluid, which is expected to decrease the specific heat capacity compared to coconut oil. So, the thermal diffusivity clearly defines that the thermal conductivity is inversely proportional, which affects the decrease in storage capacity during machining operations.

4.1 Thermal conductivity Enhancement vs Volume fraction of Nano Particle AL_2O_3

Figure A highlights that the relationship is linear & Positive increase in thermal conductivity of the base fluid as the volume fraction of the nanoparticle increases. The thermal conductivity is 0.170 to 0.197 W/m. k by increasing the volume fraction represents the 15.9% enhancement.

$$\frac{0.197 - 0.17}{0.17} \times 100 = 15.9\%$$

5. Conclusion

This study investigates the performance of Heat transfer enhancement of AL_2O_3 /Coconut oil-based nanofluid, which improved the wettability, dynamic viscosity, and thermal conductivity. MATLAB-based analytical model under variation of volume fraction simulation indicates that thermal conductivity is adjusted to control the concentration from 0 to 5% nanoparticle and reduce the machining temperature. The thermal analysis indicates that the base fluid temperature increases with the concentration, confirming the heat dissipation capability. Overall, AL_2O_3 /Coconut oil-based nanofluids are effective green cooling agents in machining and thermal management systems.

6. Future Work:

1. Future research can extend this study in Laboratory experiments, validating with other nanoparticles used for better machining operations.
2. CFD analysis for flow and heat transfer
3. Use the hybrid nanoparticle with vegetable oil

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