Periodica Polytechnica Chemical Engineering, 69(1), pp. 85–91, 2025

Palm Oil as a Heat Transfer Medium

A Numerical Study with Nanoparticle Enhancements

Suhaila Hussain[1*], Noor Shahida Abdullah[1], Syamsul Syahrun Hashim[1], Suhaimi Illias[1], Kartini Alir[1]

[1] Department of Manufacturing, Faculty of Mechanical Engineering and Technology, University Malaysia Perlis, 02600 Arau, Perlis, Malaysia
[*] Corresponding author, e-mail: suhaila@unimap.edu.my

Received: 09 October 2024, Accepted: 14 January 2025, Published online: 06 February 2025

Abstract

Palm oil plants are abundantly available in Malaysia and are harvested commercially to either be exported in their crude form or used as a base for products such as soap and cooking oil. However, palm oil has also invoked interest in being used as a coolant. As opposed to conventional coolants, vegetable-based coolants such as palm oil offer several advantages, such as being more environmentally friendly upon disposal and safer for users as they are less chemically reactive. It is an accepted hypothesis that the inclusion of nanoparticles would generally increase the heat transfer rate of most fluids as these nanoparticles contribute to a rise in the heat transfer area. This paper presents a numerical study on using palm oil as a medium for heat transfer in machining operations, with and without the use of nanoparticles. It presents heat transfer comparisons between palm oil, conventional water and mineral oil coolants. It was found that the inclusion of nanoparticles increases the heat transfer capability of mineral oil and palm oil with palm oil being more positively affected. However, there is no apparent trend or correlation that can be made between concentration and heat transfer as the percentage increase of the surface heat flux and heat transfer coefficient are inconsistent with the 2% concentration showing a higher percentage increase compared to the 1% and 3% concentrations. Considering the results of this preliminary study, it can be concluded that palm oil together with nanoparticles does present a promising prospect as a coolant.

Keywords

nanocoolant, palm oil, aluminum oxide, heat transfer, simulation

1 Introduction

According to the Malaysian Palm Oil Council website, as of 2020, Malaysia accounted for 25.8% and 34.3% of the total palm oil production and export, making Malaysia the second largest exporter of palm oil produced globally [1]. Malaysia also exported and produced 9.1% and 19.7% of the world's oil and fats in 2020. The most common type of palm oil planted in Malaysia is the tenera variety. Compared to soybean, sunflower and rapeseed, palm oil is more efficient in producing oil, requiring only 0.26 hectares of land to produce 1 ton of oil, with soybean, sunflower and rapeseed requiring 2.22, 2 and 1.52 hectares, respectively, to produce the same amount.

Coolants in machining are generally used to alleviate the effect of heat generated during the cutting process to the manufactured workpiece. The ability of the coolants to perform this task generally depends on their thermal properties, such as thermal conductivity and viscosity. Nanofluids, meanwhile, is defined as engineered colloidal suspensions of nanoparticles (10–100 nm) in base fluids [2]. It is a solid-liquid combination consisting of nanoparticles and a base fluid. They are used for their ability to elevate heat transfer and have emerged as a promising solution to cooling problems in machining. The existing conventional cooling fluids such as ethylene glycol, water and oil have either weak heat transfer characteristics or environmental safety, sustainability and health issues. However, by adding a certain percentage of nanoparticles, nanofluids not only alleviate friction and improve anti-wear properties but also significantly reduce pollution, offering clear environmental benefits [3–9].

There have been numerous documented works on nanoparticles and their influence on the convective heat transfer coefficient which determines how heat is transferred via the convection medium such as that in the cooling

Cite this article as: Hussain, S., Abdullah, N. S., Hashim, S. S., Illias, S., Alir, K. "Palm Oil as a Heat Transfer Medium: A Numerical Study with Nanoparticle Enhancements", Periodica Polytechnica Chemical Engineering, 69(1), pp. 85–91, 2025. https://doi.org/10.3311/PPch.39491

process during machining [10–17]. As mentioned before, existing conventional coolants have heat transfer, health as well as sustainability issues. Therefore, to counter these negative aspects, vegetable-based coolant has been suggested as an alternative [18–21]. Nanoparticles are added to improve their heat transfer capability. There have been a number of previous works regarding the use of palm oil and also palm oil-based nanofluid as coolants in machining [5, 22]. Tong et al. [23] studied the heat transfer and lubrication performance of palm oil-Al_2O_3 nanofluid by comparing them with a mineral oil-based conventional cutting fluid. Experiments were performed on a CNC machine, and they found that palm oil-Al_2O_3 nanofluid performed better as a cutting fluid and, therefore, is a better option since it is safer for humans to use and more environmentally friendly. Meanwhile, Aminnudin et al. [24] used palm oil in a mist-cooling system for milling. They found that increasing the pressure on the cooling mist system may reduce surface roughness on the workpiece.

In this paper, palm oil was mixed with 1%, 2% and 3% of aluminum oxide (Al_2O_3) nanoparticles to gauge its ability to be used as coolant.

2 Simulation setup and procedure

In order to determine the heat transfer capabilities of these fluids, computational fluid dynamics simulations were performed to predict the heat transfer process. These simulations were modeled and validated based on the works by Karimi et al. [25]. In their research, they performed simulations on three different working nanofluids of magnesium oxide (MgO), cupric oxide (CuO) and aluminum oxide (Al_2O_3) nanoparticles combined with water as the base fluid. They validated their simulation results with experimental values using the case of MgO water-based nanofluid. The nanoparticle concentration was 0.09%. The physical properties of MgO nanoparticles and water used are given in Table 1.

Table 1 Physical properties of MgO nanoparticles, water, the MgO water-based nanofluid and steel [25]

	Thermal conductivity (W/m K)	Heat capacity (J/kg K)	Density (kg/m³)	Viscosity (kg/m s)
MgO	48	877	3580	–
Water	0.6	4182	998.2	0.001003
MgO-water	0.7709	4164.7934	979.962	0.0010269
Steel	16.27	502.48	8030	–

Karimi et al. [25] used a two-phase formulation for their nanofluids. However, for this particular paper, the validation simulation used a single-phase formulation using the following property models [26]:

$$\text{Density: } \rho_{nf} = (1-\phi)\rho_f + \phi\rho_s, \quad (1)$$

Specific heat capacity:

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_f + \phi(\rho c_p)_s, \quad (2)$$

Thermal conductivity:

$$\frac{k_{nf}}{k_f} = \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + 2k_f + \phi(k_f - k_s)}, \quad (3)$$

where ρ is density, ϕ is volume concentration, k is thermal conductivity, c_p is the specific heat. The subscripts f and s refer to fluid and solid components of the mixture, respectively, and nf refers to the nanofluid mixture.

Meanwhile, the viscosity model for the MgO-water combination was based on the following model [27]:

$$\text{Viscosity: } \mu_{nf} = \frac{\mu_f}{(1-\phi)^{0.25}}, \quad (4)$$

where μ is the viscosity.

Figs. 1 and 2 show the pipe configuration used in the paper, which has been reconstructed for this study using CATIA (for geometrical modeling) [28], and Ansys Fluent

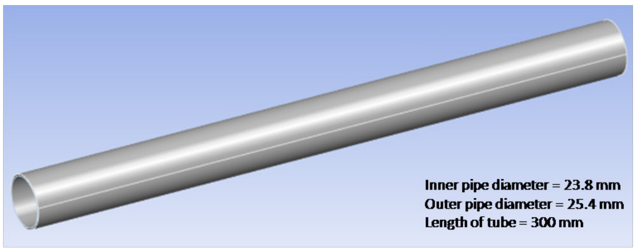

Fig. 1 Pipe dimensions

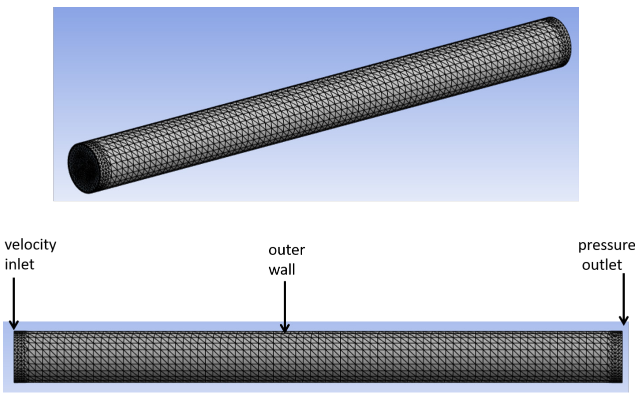

Fig. 2 Mesh representing the computational domain and boundary conditions

Student version 2021 (for fluid simulation) [29]. It consisted of two zones: the outer solid zone, using steel as the material, and the inner fluid zone, where the test fluid flows. The test fluid flows into the tube via a velocity inlet boundary, set at a constant temperature of 26.85 °C. The velocity was set to 1.44 m/s. The walls were made to have a constant heat flux of 41.186 W/m^2 as prescribed in Karimi et al. [25].

The number of meshes was 23,175 tetrahedral meshes. The governing equations solved in performing the heat transfer simulation were:

$$\text{Continuity equation: } \nabla \times (\rho \vec{v}) = 0, \tag{5}$$

$$\text{Momentum equation: } \nabla \times (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \times (\bar{\bar{\tau}}), \tag{6}$$

$$\text{Energy equation: } \nabla \times (\vec{v}(\rho E + p)) = \nabla \times (k \nabla T), \tag{7}$$

where $\vec{v}$ is the velocity vector, p is the static pressure, $\bar{\bar{\tau}}$ is the stress tensor, E is energy, and T is the temperature. The surface heat flux and heat transfer coefficient are calculated based on the input boundaries parameters *via* the solution of Fourier's law applied at the walls [30].

Following the referenced paper, the simulation applied the k-epsilon RNG model with enhanced wall treatment function. The pressure at the outlet was set to be atmospheric pressure. A no-slip boundary condition was assumed for the interaction between the liquids and the walls. Table 2 shows the results of the validation simulation compared to the experimental value.

As the percentage difference between the current validation simulation and the experiment was less than 10%, it could be safely assumed that the current validation modeling and setup were acceptable. Therefore, the same models were used to simulate the test fluids. As explained in Section 3, the difference would only be with the viscosity values.

3 Simulation of test fluids

For the simulation of the test fluids, the same simulation model as in Section 2 on validation was used. The property models were the same for density (Eq. (1)), specific heat capacity (Eq. (2)) and thermal conductivity (Eq. (3)). However, the viscosity values used in the test fluids simulations were based on the experimental works of Abdullah [31]. The experimental works performed measured the viscosity values for palm oil, mineral oil, water and the combinations of these fluids with Al_2O_3 nanoparticles. To determine which boundary conditions to be used in the simulation, this study referred to another previously performed conventional dry turning experiment. In these experiments, the turning process was recorded using an infrared thermal camera, FLIR C2. This camera can measure temperatures between −10 °C to 150 °C with a thermal sensitivity of 0.01 °C. It can provide measurements of up to 2% in accuracy. Fig. 3 shows an example recorded from one of the experiments performed. It shows a snapshot of the condition 10 s after the turning process was initiated. It shows that the maximum temperature was about 45 °C and was recorded at the contact point between the workpiece and the cutting tool. Subsequently, in this paper, for simulation of the test fluids using the model in Fig. 1, a temperature of 45 °C was set at the outer wall. Again, from Fig. 3, it can be assumed that the surrounding temperature was around 30 °C. This was set to be included in the pressure outlet boundary condition. In setting the fluid temperature flowing inside the pipe (i.e., velocity inlet boundary condition), the value of 40 °C was chosen which was between the temperatures of wall and the surrounding temperature. This was also to be aligned with the values of the viscosity obtained from Abdullah [31]. The temperature boundary conditions for the outer wall and base fluids are given in Table 3. The velocity of the flow inside the pipe remained the same at 1.44 m/s as this value was within the values of coolant speed mentioned

Table 2 Results of validation simulation with experiment

	Heat transfer coefficient (W/m^2 K)			Difference between current data and Ref. [25] (%)
	From current validation simulation	From simulation in referenced paper [25]	From experiment in referenced paper [25]	
MgO-water 0.09%	10,422.12	9323	9705	7.4%

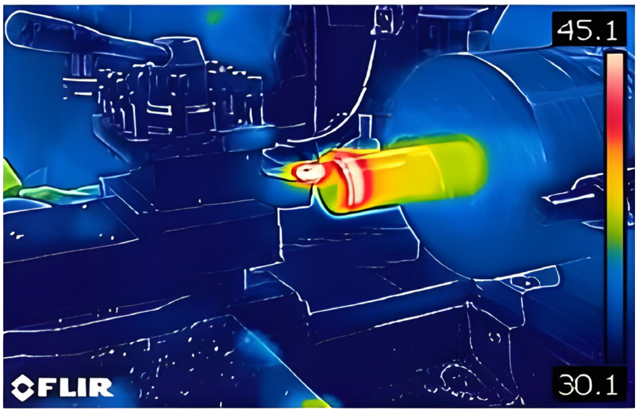

Fig. 3 Temperatures recorded using infra-red camera from a turning process after 10 sec of machining

in [32, 33]. In between the pipe wall and the flowing fluid, a coupled boundary condition was set.

In this paper, the simulation model assumed the coolant to be flowing through a heated pipe whereas in the experiment, the coolant is being splashed or sprayed onto a hot workpiece. As the purpose was to consider only the heat transfer that occurs between the coolant and the workpiece/pipe wall, such a semblance was deemed to be acceptable. The thermophysical properties; i.e., density, thermal conductivity, specific heat capacity and viscosity, of the base fluids are given in Table 4 [34–36] while Table 5 [37] shows the Al_2O_3 nanoparticle properties for density, thermal conductivity and specific heat capacity.

Table 6 presents the calculated physical properties of water + 1% Al_2O_3 nanofluid, mineral oil + 1% Al_2O_3, palm oil + 1% Al_2O_3, palm oil + 2% Al_2O_3 and palm oil + 3% Al_2O_3 nanofluid calculated based on Eq. (1) to Eq. (3). Again, the values for the viscosities for the nanocoolant mixtures were from the experimental works of Abdullah [31] since these values would be more accurate compared to using a model.

Table 3 Boundary conditions

No	Parameter	Temperature
1	Outer wall	45 °C
2	Base fluid	40 °C

4 Results and discussion

The results presented in Table 7 are the heat transfer coefficients and the surface heat fluxes obtained from the simulations performed. Heat transfer that occurred was between the wall of the pipe and the fluids entering and leaving the pipe.

Figs. 4 and 5 illustrate varying trends in base fluid behavior after adding nanoparticles. While the heat transfer coefficient and surface heat flux of the water-Al_2O_3 mixture decreased, mineral oil and palm oil slightly increased in these values. Notably, the palm oil-Al_2O_3 mixture demonstrated better heat transfer characteristics than mineral oil, indicating that palm oil could be a suitable base fluid for nanocoolants, as it reacted positively to the inclusion of nanoparticles.

Figs. 6 and 7 depict the concentration effects on the heat transfer coefficient and surface heat flux for the palm oil-Al_2O_3 mixture. All three nanoparticle concentrations show increased heat flux and heat transfer coefficient. However,

Table 4 Physical properties of base fluids at 40 °C

Base fluid	Density (kg/m³)	Thermal conductivity (W/m K)	Specific heat capacity, c_p (J/kg/K)	Viscosity (kg/m s)
Palm oil [34]	880	0.1708	1902	0.03541
Mineral oil [35]	876.2	0.14205	1962	0.26175
Water [36]	992.2	0.631	4179	0.000653

Table 5 Al_2O_3 Nanoparticles properties [37]

Nanoparticles	Density (kg/m³)	Thermal conductivity (W/m K)	Specific heat capacity, c_p (J/kg/K)
Al_2O_3	3880	36	773

Table 6 Nanofluid properties at 40 °C

Fluid	Thermal conductivity (W/m K)	Density (kg/m³)	Specific heat capacity, c_p (J/kg/K)	Viscosity at 40 °C (kg/m s)
Water - 1% Al_2O_3	0.6491	1021.078	4052.461	0.00084
Mineral oil - 1% Al_2O_3	0.1463	887.23	1921.478	0.0712
Palm oil - 1% Al_2O_3	0.1759	910	1853.862	0.03541
Palm oil - 2% Al_2O_3	0.1811	940	1808.797	0.0685
Palm oil - 3% Al_2O_3	0.1864	970	1766.52	0.0995

Table 7 Heat transfer results estimated for the test fluids from the simulations

Fluid	Water	Water + 1% Al_2O_3	Mineral oil	Mineral oil + 1% Al_2O_3	Palm oil	Palm oil + 1% Al_2O_3	Palm oil + 2% Al_2O_3	Palm oil + 3% Al_2O_3
Heat transfer coefficient (W/m² K)	16,057	14,677	965	971	1,029	1,058	1,211	1,267
Surface heat flux (W/m²)	50,813	48,202	4,621	4,649	4,913	5,046	5,737	5,986

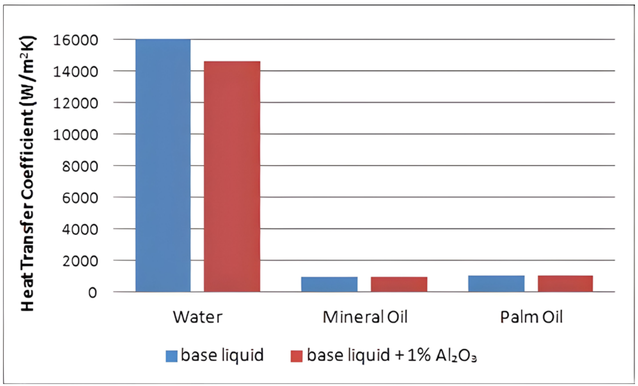

Fig. 4 Comparison of heat transfer coefficients between base liquids and base liquids mixed with Al_2O_3 nanoparticles

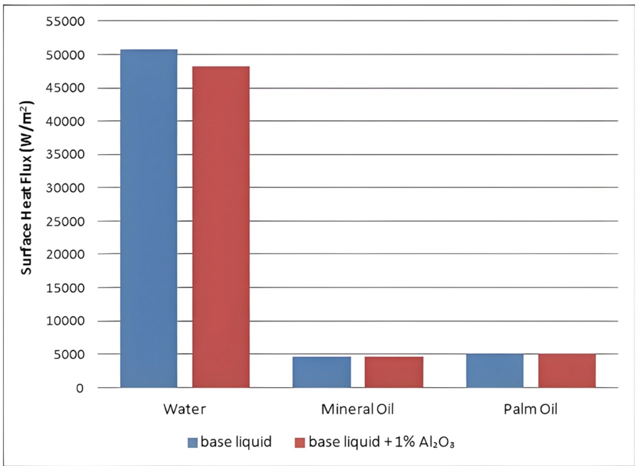

Fig. 5 Comparison of surface heat flux between base liquids and base liquids mixed with Al_2O_3 nanoparticles

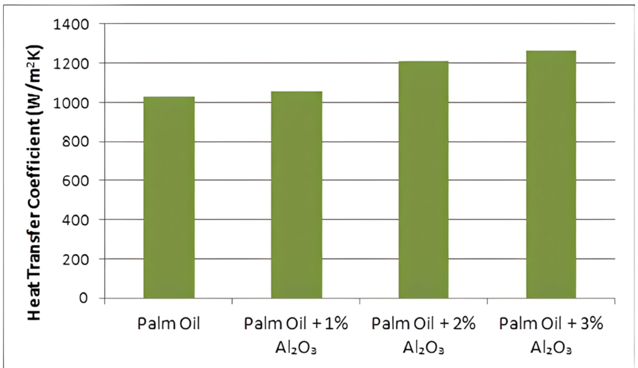

Fig. 6 Effect of different concentrations of Al_2O_3 nanoparticles on heat transfer coefficients

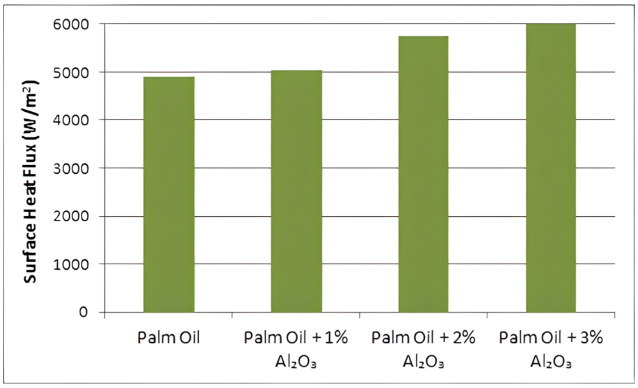

Fig. 7 Effect of different concentrations of Al_2O_3 nanoparticles on surface heat flux

the lack of a clear trend or correlation between concentration and heat transfer, as evidenced by the inconsistent percentage increase of the heat transfer properties at the 2% concentration, suggests that more concentration values must be tested to understand the relationship between concentration and heat transfer fully. This underscores the ongoing nature of our research and the need for further investigation.

5 Conclusion

From the simulations performed, it was found that the addition of nanoparticles had increased the heat transfer capability of mineral oil and palm oil with palm oil being more positively affected by the addition of nanoparticles. Therefore, as the research goal was to assess the possibility of using palm oil combined with nanoparticles to increase the heat transfer properties of manufacturing coolants, it can be concluded that palm oil does indeed can be considered for such a purpose.

Acknowledgement

The author would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2018/TK03/UNIMAP/03/9 from the Ministry of Education Malaysia.

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