Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 8 (2022) 764–775
www.elsevier.com/locate/egyr
TMREES22-Fr, EURACA, 09 to 11 May 2022, Metz-Grand Est, France

Numerical simulation on the effectiveness of hybrid nanofluid in jet impingement cooling application

Nur Syahirah M. Hanafi*, Wan Aizon W. Ghopa, Rozli Zulkifli, Shahrir Abdullah, Zambri Harun, Mohd Radzi Abu Mansor

Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Selangor 43600, Malaysia

Received 21 June 2022; accepted 19 July 2022
Available online 2 August 2022

Abstract

This paper investigates the heat transfer performance of different nanofluid coolants with the employment of a single nozzle, axisymmetric, and confined jet impingement method. A numerical analysis using Ansys FLUENT software is carried out. A mixture of hybrid nanoparticles in a fluid further increases the heat transfer performance. The type of coolants used in this study is pure water as the base fluid, Al_2O_3-Cu/water hybrid nanofluid, and two types of single-particle nanofluids which are alumina, and copper nanofluids. Although the study of hybrid nanofluid as a coolant has become more prominent among researchers, a specific trend of the efficiency and performance of different coolants used in the jet impingement method is still not widely available. The results from this study showed that in comparison with water as the base fluid, there is an increase in the average heat transfer coefficient of the target surface of about 8.73% for hybrid nanofluid, 1.89% for Al_2O_3 nanofluid, and 0.17% Cu nanofluid. Hybrid nanofluid shows the highest heat transfer performance and reduces the greatest amount of heat from the surface to the fluid.

Peer-review under responsibility of the scientific committee of the TMREES22-Fr, EURACA, 2022.

Keywords: Nanofluid; Hybrid nanofluid; Jet impingement; Heat transfer; Cooling technology

1. Introduction

Heat transfer is an important mechanism for cooling or heating an object. For a machine or system to work in an optimum condition, the excessive heat produced needs to be either raised or released. Liquid coolants have been traditionally used to reduce heat on devices such as processors and in various industries such as automotive and electronics [1]. However, conventional liquid coolants exhibit a low thermal conductivity [2]. This encourages innovation and advancement in cooling technology to be made. One of the ways that has been discovered to increase heat transfer performance of liquid coolants is the usage of fluid that contains metal nanoparticles in it which is called

* Corresponding author.
E-mail address: p103705@siswa.ukm.edu.my (N.S.M. Hanafi).

https://doi.org/10.1016/j.egyr.2022.07.096

Peer-review under responsibility of the scientific committee of the TMREES22-Fr, EURACA, 2022.

nanofluid [3]. This is because metal is a type of material that has high thermal conductivity, metal nanoparticles are infused in heat transfer fluid such as water, ethylene glycol and oil to promote the heat transfer performance of liquid coolants [4].

As the research on nanofluid and nanoparticles expands, an advanced method of combining two or three types of metal nanoparticles in the base fluid to increase heat transfer efficiency has been found. This combination of multiple types of metal nanoparticles in base fluid is called hybrid nanofluid. A lot of researchers have found that the usage of hybrid nanofluid in the cooling or heating process of devices portrays a better heat transfer performance [5]. The study of nanoparticles mixture in a base fluid has also been done by many researchers in their effort to find a liquid coolant that exhibits a highest thermal conductivity performance. Heat transfer performance and the thermal conductivity of hybrid nanofluid is affected by several factors such as particle size and volume fraction, working temperature of the fluid, and hybrid nanofluid viscosity [6]. Apart from being a good performance coolant, nanofluid also enhance the energy absorption of material. In a study made by Mubasyir et al. [7], a magnesium alloy that is quenched in distilled water that contain carbon-nanotube particles shows that, the energy absorption increase by 106.68% compared to the controlled sample of distilled water by itself.

Among the metals used in research of nanofluids, alumina is mostly used in the study of hybrid nanofluid as it is chemically stable and has an enhanced mechanical strength [6]. While copper on the other hand is the metal that has the highest thermal conductivity among the metal families, copper is chosen to be mixed with alumina in base fluid to be used as coolant in this study. Base fluid is used as the base fluid because of its high thermal conductivity compared to other heat transfer fluids available [8].

To discover a coolant that has the best performance in dissipating heat from a surface, a study is done to compare the heat transfer performances of different types of coolant. This study also observes the efficiency of hybrid nanofluid in cooling a heated object compared to nanofluid and base fluid. In conjunction with the type of fluid, a method called jet impingement has also been incorporated in the study of cooling systems. Jet impingement method produces a high localized and average heat transfer coefficient on the area impinged with any fluids. Thus, increasing the rate of heat transfer from a hot surface [9]. In an experiment done by Abdullah et al. [10], the technique of infrared thermal imaging that they used helps to visualize the temperature distribution patterns on a flat plate that is cooled by using jet impingement method. In addition, compared to a distilled base-fluid, a cooling system employing a nanofluid jet impingement method may remove heat faster [11], thus making the system more energy efficient.

Although the study of hybrid nanofluid as a coolant has become more prominent among the researchers, a specific trend of the efficiency and performance of different coolants used in jet impingement method is still not widely available. Thus, in present study, the heat transfer performance of hybrid nanofluid in single jet impingement application is investigated by conducting a numerical analysis in comparison with single particle nanofluids and base fluid. The result is also validated by measurement done by previous researcher in order to see the capability of numerical simulation in predicting the heat transfer performance of mixing nanoparticles.

2. Research methodology

This paper investigates the local and average heat transfer coefficient for single nozzle, axisymmetric and confined impinging fluids. The type of coolants used in this study are pure water as the base fluid, Al_2O_3-Cu/water hybrid nanofluid, and two types of single particle nanofluids which are alumina, and copper nanofluids. The simulation model is as shown in Fig. 1a which represents a fluid impinged through a cylindrical channel towards a target surface. The inlet nozzle diameter is 5 mm while the vertical distance from the impinging jet to the target surface is 20 mm. The mesh structure used in the study is also shown in Fig. 1b.

This study demonstrated a simple three-dimensional geometry simulation. The type of fluids used in the simulation is assumed to be of a single-phase coolant. Other forms of fluids were taken as negligible as the focus of observation is the thermal efficiency of different types of coolants. In addition, a steady-state fluid flow simulation with a k-epsilon viscous turbulent model is adapted in the computational fluid dynamic pre-processing step. The governing equations employed for these assumptions are as follows (Modeling & Simulations 2016):

Continuity Equation

$$\frac{\partial \rho_{nf}}{\partial t} + \frac{\partial (\rho_{nf} u_i)}{\partial x_i} = 0 \quad (1)$$

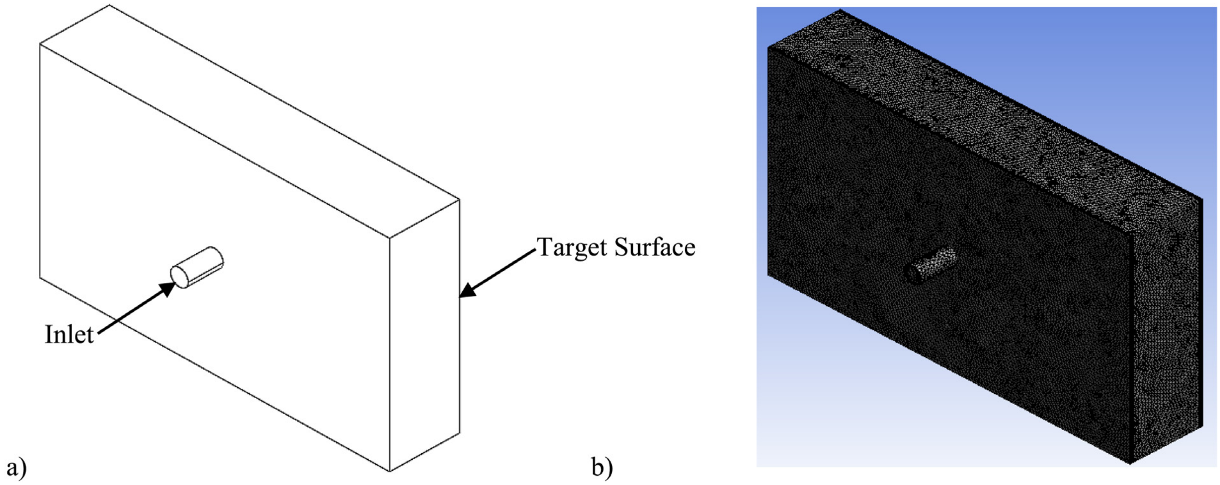

Fig. 1. (a) The figure of single cylindrical nozzle jet impingement model. (b) Mesh structure of the simulation.

Momentum Equation

$$\frac{\partial}{\partial t}\left(\rho_{nf}u_i\right)+\frac{\partial}{\partial x}\left(\rho_{nf}u_iu_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{nf}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right] \tag{2}$$

Energy Equation

$$\frac{\partial}{\partial t}\left(\rho_{nf}h\right)+\frac{\partial}{\partial x_i}\left[\left(\rho c_p\right)_{nf}u_iT\right]=\frac{\partial}{\partial x_i}\left(k_{nf}\frac{\partial T}{\partial x_i}\right)+\mu_{nf}\Phi \tag{3}$$

$$\Phi=\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{4}$$

The Reynolds number used as the input parameter is 10 000. The pressure treatment adopted First Order Upwind scheme for the Turbulence Numeric and the Adventive Scheme. While for the viscous model, a standard k-epsilon model is selected. The simulation is defined as converged at an RMS value of lower than 1.0E−6. The results of the simulation are calculated throughout the computational domain during the simulation process.

2.1. Boundary conditions

For inlet boundary, the velocity is determined based on Reynolds number and nanoparticle volume fraction. The inlet and the target surface temperature are set at 298.15 K and 423.15 K respectively. The temperature is set according to the working temperature of a microchip cooling system which utilizes fluid jet impingement cooling method [12]. The nanoparticle volume percentage in the coolant is set to 0.5%. The type and properties of coolants used in the simulation is as shown in Table 1. The final target surface temperature, wall heat flux and heat transfer coefficient were determined in the post-processing stage.

Table 1. The thermo-physical properties and preprocessing data for base fluid, Al_2O_3-Cu HN, Al_2O_3 and Cu nanofluid.

Types of coolant	Dynamic viscosity (Pa s)	Density (kg/m^3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m K)	Inlet velocity (Re = 10 000) (m/s)	Molar mass (kg/kmol)
Base fluid [13]	0.0008903	996.999	4180.230	0.6096	1.786	18.015
Al_2O_3-Cu hybrid nanofluid	0.0011885	1024.271	4064.389	0.6241	2.321	18.339
Al_2O_3 nanofluid	0.0009338	1011.864	4113.233	0.6184	1.846	18.435
Cu nanofluid	0.0009338	1036.679	4016.714	0.6188	1.801	18.243

2.2. Grid independence

To determine the ideal number of grids used and the impact of the number of elements on heat transfer and final temperature of the target surface, a mesh analysis is carried out. A tetrahedron mesh with a total of 629 055 number of elements and 0.008 mm cell size was employed in this study. Fig. 2 shows the result of the grid independence test. Additionally, patch conforming method and inflation method is applied on the geometry to ensure the flow of fluid near the target surface is well defined.

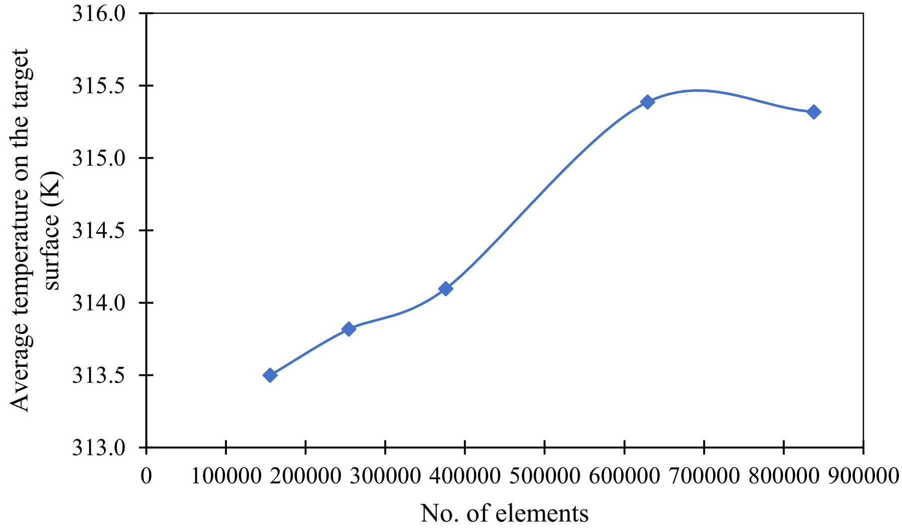

Fig. 2. Grid independence test.

2.3. Thermo-physical properties

Adding nanoparticles in a base fluid is known to improve the thermophysical properties of the fluid and also enhance the heat transfer coefficient [14]. The thermo-physical properties of coolants used is manually set during the FLUENT Pre-processing using the equations of:

Density of nanofluid [15]

$$\rho_{nf} = (1-\varphi)\,\rho_{bf} + \varphi\rho_{np} \tag{5}$$

$$Where, \varphi = \varphi_{\mathrm{Cu}} + \varphi_{\mathrm{Al_2O_3}} \tag{6}$$

Density of hybrid nanofluid

$$\rho_{hnf} = (1-\varphi)\,\rho_{bf} + \varphi_{\mathrm{Cu}}\rho_{\mathrm{Cu}} + \varphi_{\mathrm{Al_2O_3}}\rho_{\mathrm{Al_2O_3}} \tag{7}$$

Specific heat capacity of nanofluid

$$(\rho C_p)_{nf} = (1-\varphi)\,(\rho C_p)_{bf} + \varphi(\rho C_p)_{np} \tag{8}$$

Specific heat capacity of hybrid nanofluid

$$(\rho C_p)_{hnf} = (1-\varphi)\,(\rho C_p)_{bf} + \varphi_{\mathrm{Cu}}(\rho C_p)_{\mathrm{Cu}} + \varphi_{\mathrm{Al_2O_3}}(\rho C_p)_{\mathrm{Al_2O_3}} \tag{9}$$

Thermal conductivity of nanofluid [16]

$$k_{nf} = \frac{k_{np} + 2k_{bf} - 2\varphi(k_{bf} - k_{np})}{\dfrac{k_{np}}{k_{bf}} + 2 + \varphi\left(\dfrac{k_{bf} - k_{np}}{k_{bf}}\right)} \tag{10}$$

Thermal conductivity of hybrid nanofluid [17]

$$\frac{k_{hnf}}{k_f} = -151.5\varphi^2 + 8.916\varphi + 1.004 \tag{11}$$

Effective dynamic viscosity of nanofluid [18]

$$\frac{\mu_{nf}}{\mu_{bf}} = 0.983e^{12.959\varphi} \tag{12}$$

Effective dynamic viscosity of hybrid nanofluid [17]

$$\frac{\mu_{hnf}}{\mu_{bf}} = -1283\varphi^2 + 84.31\varphi + 0.9454 \tag{13}$$

Inlet velocity, derived from Reynolds number formula,

$$\nu = \frac{Re\mu}{\rho D_h} \tag{14}$$

where nf is nanofluid, hnf is hybrid nanofluid, np is nanoparticle, k is thermal conductivity, φ is hybrid nanofluid volume fraction, ρ is the hybrid nanofluid density, C_p is specific heat capacity, μ is dynamic viscosity, bf is base fluid, Re is Reynolds number, ν is inlet velocity, and D_h is hydraulic diameter.

3. Results and data processing

In the present study, fluid jet impingement cooling of a flat isothermal wall was numerically investigated. Effects of different types of coolant used on the heat transfer, fluid flow variation, and thermal characteristics for the cylindrical channel fluid jet and flat isothermal plate were numerically examined. The heat transfer performance was defined using the fundamental parameters of heat transfer coefficient (h) as given in the following equation [19].

Heat transfer coefficient

$$h_{nf} = \frac{Q}{(T_w - T_b)_{avg}} \tag{15}$$

Bulk temperature

$$T_b = \frac{T_{in} + T_{out}}{2} \tag{16}$$

where $(T_w - T_b)_{avg}$ is the average temperature difference between the wall of target surface and bulk temperature at the inlet and the outlet sections of the duct, h is the convective heat transfer, D_h is hydraulic diameter, k is the fluid thermal conductivity, Q is the wall heat flux respectively.

The jet flow is axisymmetric about x-axis with a stagnation point in the middle of the target surface. According to Bernoulli's equation along the stagnation streamline, the stagnation point is where the highest pressure and the lowest velocity is found on the target surface's surface. Fig. 3 shows that single jet impingement flows with pure water as the base fluid produces a stagnation point on the center of the target surface. The stagnation point centralizes at point (0,0.5) in the middle of the plate where the contour is colored in red, with the value of 1237.6 Pa.

Figs. 4 and 5 shows the pressure contour comparison between all the cases and the distribution of fluid flow pressure along the middle line of the target surface. The figures show that hybrid nanofluid produces the highest fluid flow pressure with the value of 2285.66 Pa compared to the other coolant. This is because hybrid nanofluid has been found to have the highest value of inlet velocity compared to all other coolants. Which leads to a high velocity impact of the fluid when it strikes the solid target surface. The fluid that initially behaves in a compressible manner, resulting in an increase in pressure. This follows the equation of

$$P = \rho C V \tag{17}$$

where P is the pressure, ρ is the fluid density, C is the velocity of the fluid's compressional wave, and V is the impact velocity [20], which in this case is taken as the inlet velocity.

Around the stagnation point, a stagnation region is found. As shown in Fig. 6, the stagnation region is where the fluid flow decelerates to a lowest magnitude as it reaches the wall. Upon reaching the wall, the jet turns parallel to the wall as it loses its axial velocity. Because of conservation of momentum, the jet flow then accelerates as the wall boundary layer develops. Furthermore, Zuckerman and Lior [21] stated that, as the jet flows further in a radial outward direction, the jet experiences deceleration until it reaches the edge of the target surface. This is the

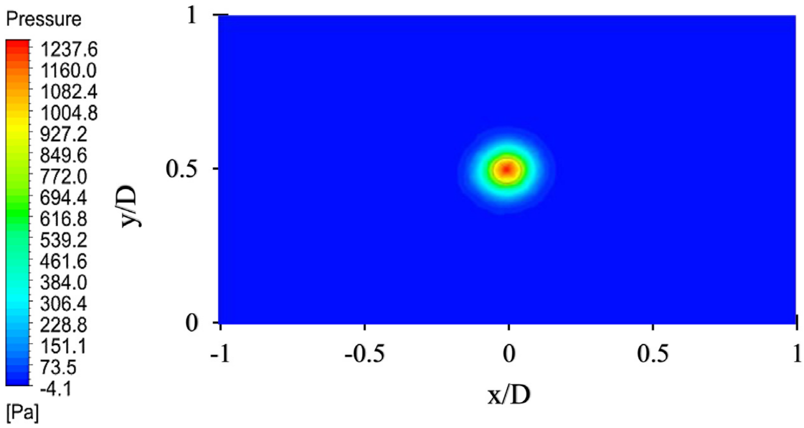

Fig. 3. Pressure contour of base fluid on the target surface. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

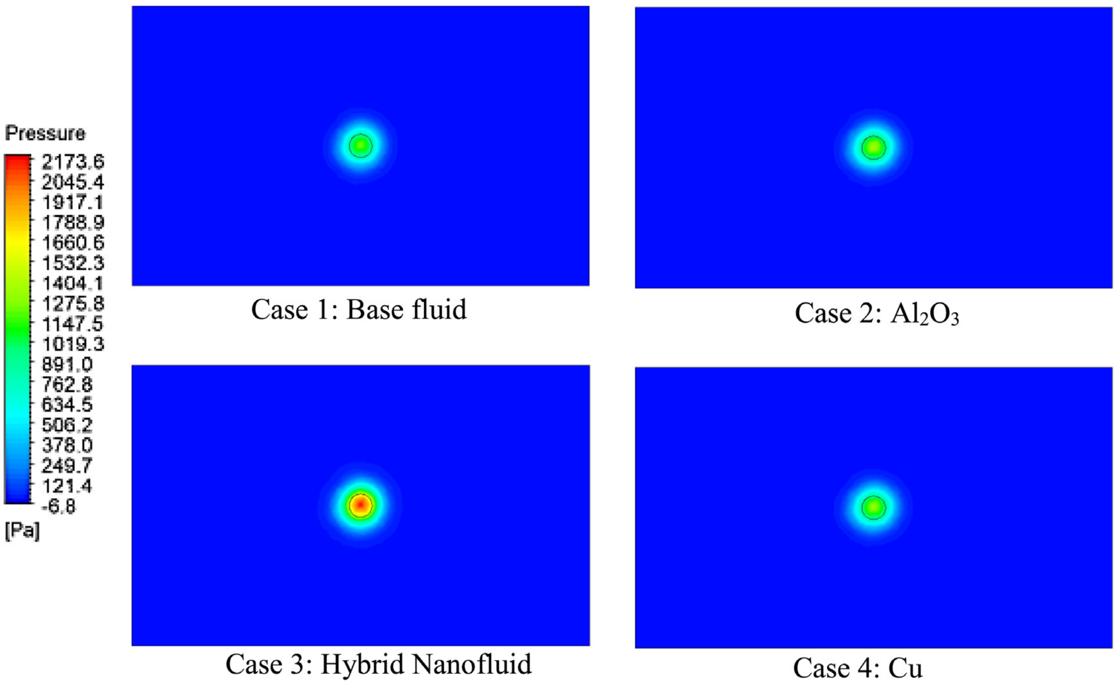

Fig. 4. Pressure contour.

result of mass conservation. The fluid flow acceleration that happened resulted in the reduction of boundary layer thickness, thus increasing the rate of heat transfer from the target surface [22].

Fig. 6 also shows that hybrid nanofluid has the highest inlet velocity compared to all other cases. The region with a high velocity jet flows is where the heat is dissipated the most from the target surface as rate of heat transfer increases with the increase in velocity [23]. This is interpreted on Fig. 7, taking the case of hybrid nanofluid as an example, which shows the center of the target surface having the lowest temperature while the edge of the target surface having the highest temperature as the jet velocity decreases from the center to the edge. Fig. 8a shows that jet impingement with hybrid nanofluid as the coolant has the highest velocity along the stagnation point compared to all other type of fluids. While Fig. 8b, on the other hand, shows the temperature variation along the stagnation point. The percentage of temperature difference of hybrid nanofluid before and after the jet impingement process

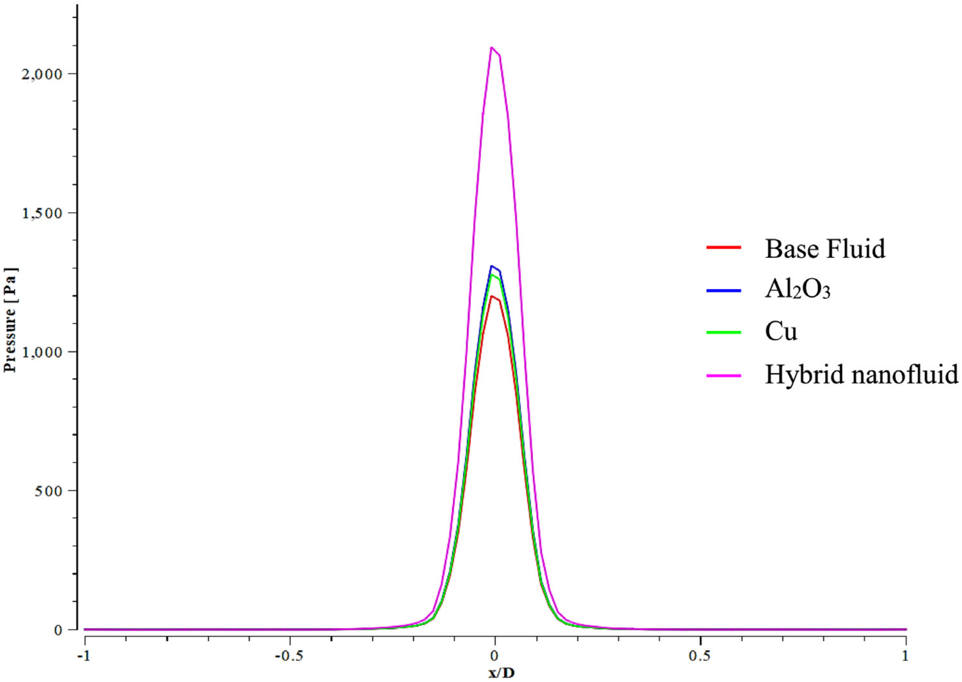

Fig. 5. The graph of fluid flow pressure along the target surface.

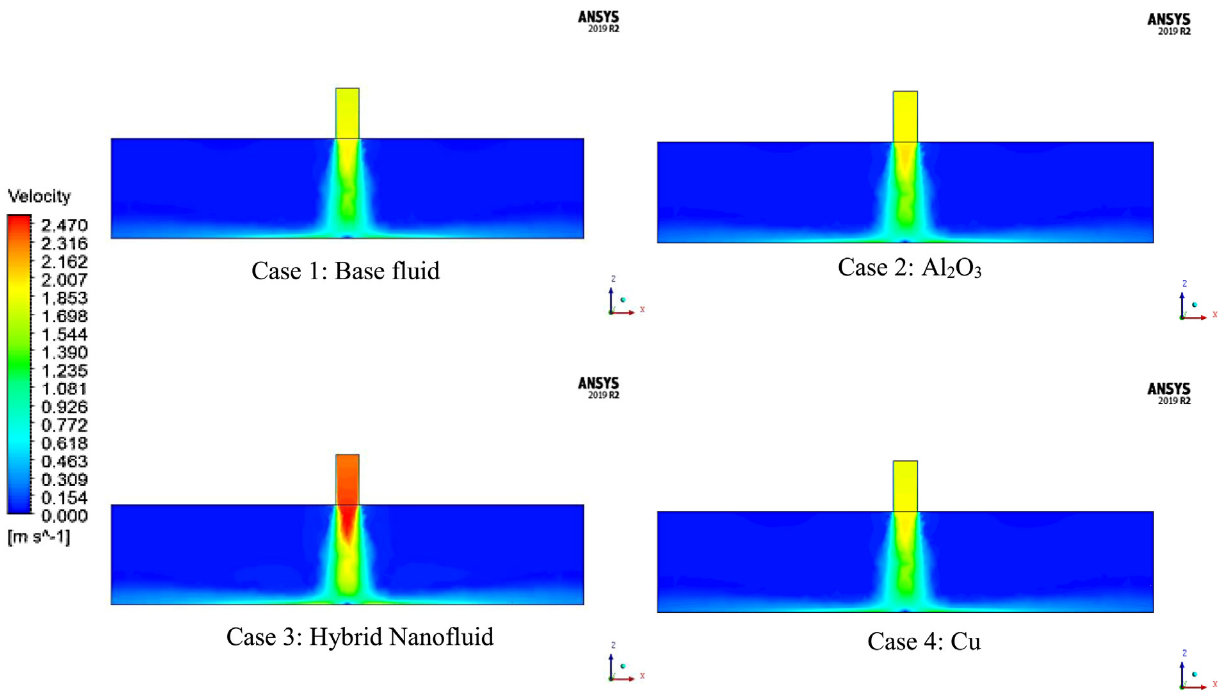

Fig. 6. The velocity contour on the xz plane for all cases.

is 34.12% compared to base fluid which is 34.02%. In comparison, hybrid nanofluid is 0.29% more effective in reducing the target plate temperature. It is apparent that hybrid nanofluid produces the lowest temperature of target

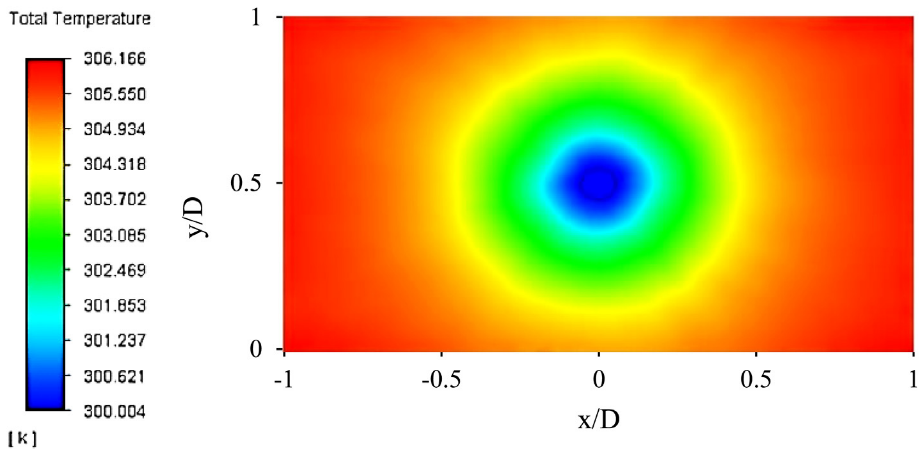

Fig. 7. Hybrid nanofluid temperature contour on the target surface.

surface during the jet impingement process. This means that the rate of heat transfer from the target surface is the highest when using hybrid nanofluid as the coolant.

3.1. Effect of different coolant on heat transfer coefficient

Fig. 9 shows the distribution of heat transfer coefficient along the stagnation point on target surface. The heat transfer coefficient shows the minimum value on the left and right edge of the plate and reaches maximum at stagnation point. A research done by Faris et al. [24] also agrees with this result, where the twin jet impingement that they study enhances the heat transfer coefficient on the area where the fluid jet touches the plate surface. Based on the graph, it is clearly seen that hybrid nanofluid has the highest value of heat transfer coefficient followed by Al_2O_3/water, Cu/Water and base fluid. This is due to the addition of Cu nanoparticles which has a higher thermal conductivity into the nanofluid. This means that, hybrid nanofluid releases heat better than other coolants. In a numerical investigation of heat transfer characteristics of single particle and hybrid nanofluids in uniformly heated tube, Garud and Lee [25] have also verified this fact in their research. Comparing with the base fluid, the average increase of heat transfer coefficient of hybrid nanofluid is about 8.73% for hybrid nanofluid, 1.89% for Al_2O_3 nanofluid, and 0.17% Cu nanofluid. Fig. 9 on the other hand shows the contour of heat transfer coefficient on the target surface for all types of fluid used in the study. The color of the contour with high value of heat transfer coefficient covered a large area of the target surface when hybrid nanofluid is used during the jet impingement. While the area that is very least covered with high heat transfer coefficient is when the fluid used is base fluid. The contour tallied with the graph on Fig. 10.

Moghadassi et al. did a research of the effect of water based Al_2O_3 Nanofluid and Al_2O_3-Cu hybrid nanofluid on laminar forced convective heat transfer. With Reynolds number of less than 2300, and 0.1% nanoparticle volume concentration, they found out that Al_2O_3-Cu hybrid nanofluid shows a higher convective heat transfer coefficient compared to Al_2O_3 nanofluid and base fluid. The simulation result of the paper indicates a good agreement with experimental result done by Suresh et al. [26] and Shah's equation. While Fig. 11 on the other hand, shows the heat transfer coefficient distribution on the middle line of the target surface done by Glynn and Murray [9] in comparison with the heat transfer coefficient of base fluid of the present research. Glynn and Murray did a lab experiment on the jet impingement cooling of a circular flat plate using water as the coolant. The study looks at the effect of different Reynolds number value and jet-to-target surface spacing (H/d) on heat transfer coefficient. A similar value and trend can be seen where the heat transfer coefficient reaches maximum at the stagnation point and decreases as it reaches the edge of the plate. However some different between the value of heat transfer coefficient might be caused by the different value of jet diameter to jet-to-target spacing ratio, thickness and also the material of the target surface used in both research.

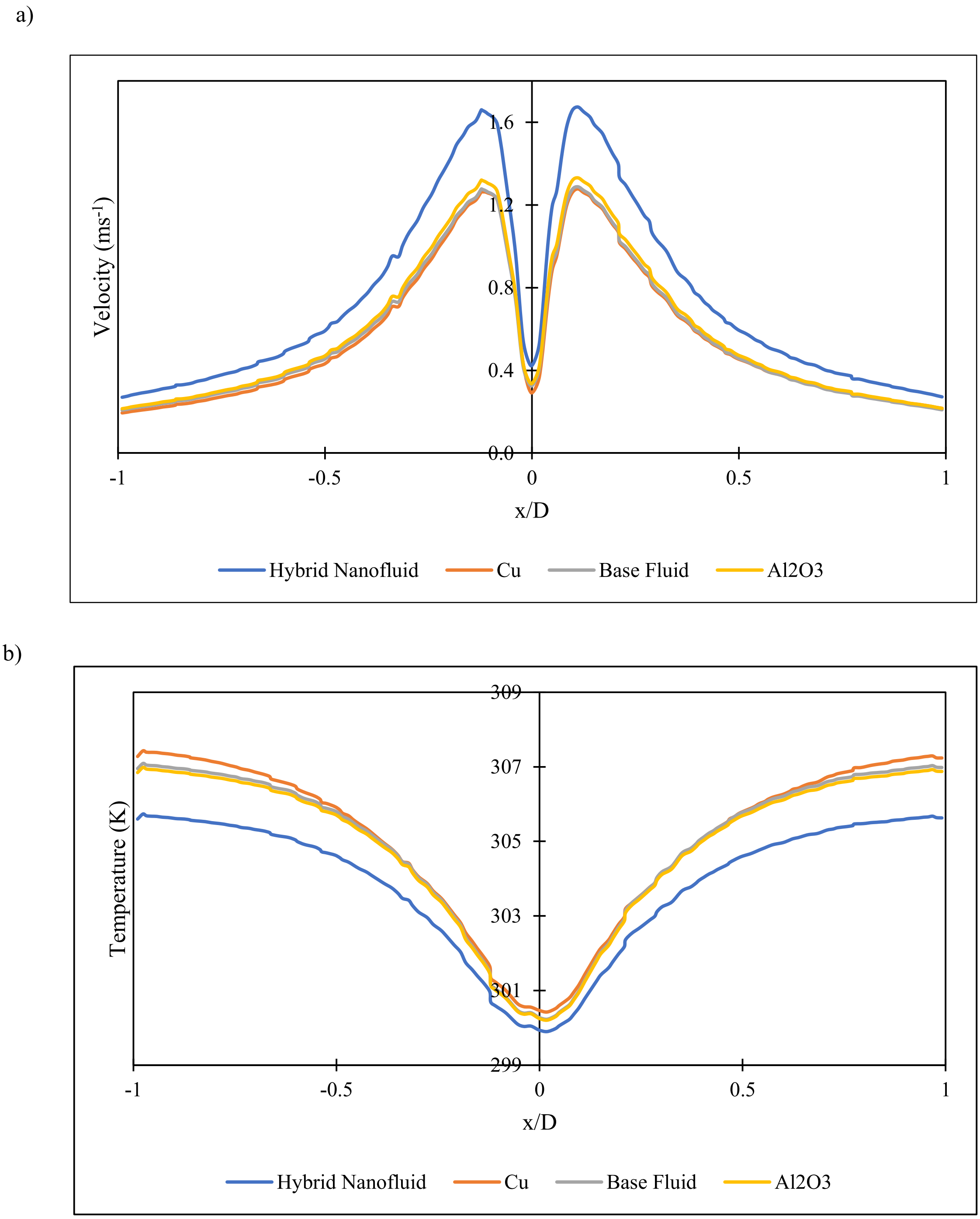

Fig. 8. (a) Graph of velocity and (b) temperature along the stagnation point.

4. Conclusion

In this research, a numerical simulation on a steady state turbulent liquid jet impingement method was done using water as the base fluid, Al_2O_3/water nanofluid, Cu/water nanofluid, and Al_2O_3-Cu/water hybrid nanofluid. For this purpose, a single-phase model was considered and the comparison with past researches were carried out in terms

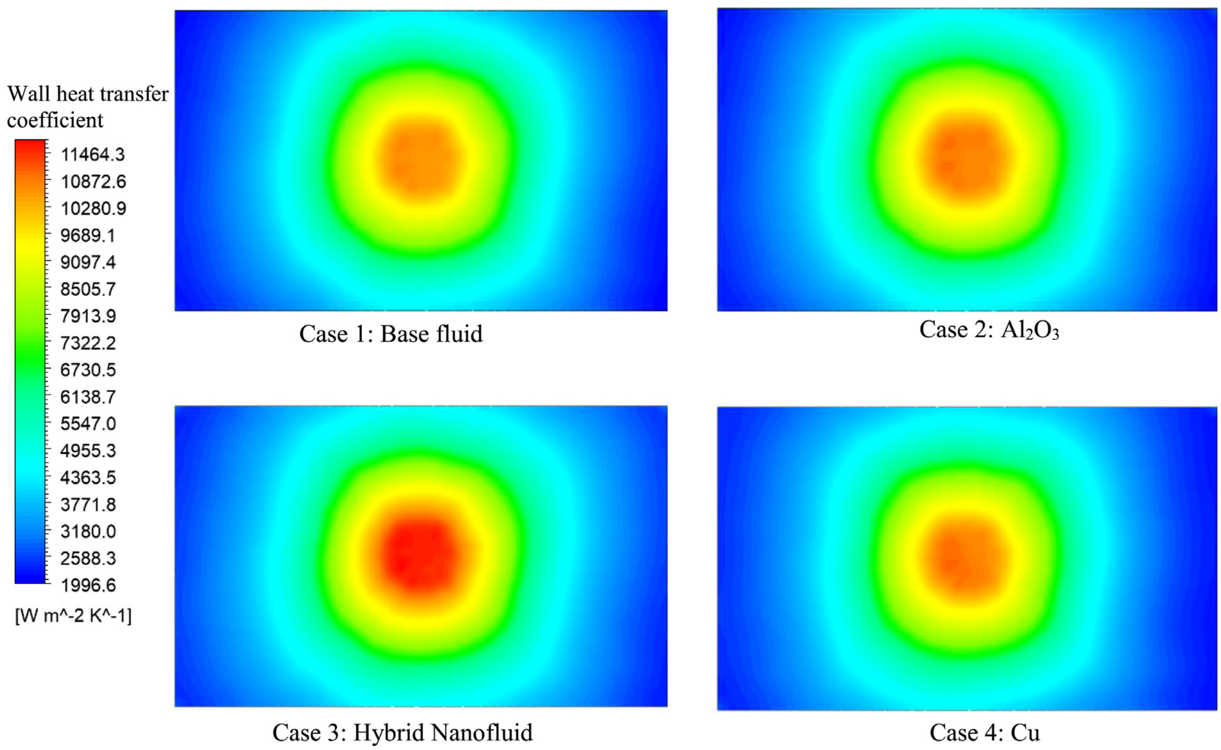

Fig. 9. Contour of the heat transfer coefficient on the target surface. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

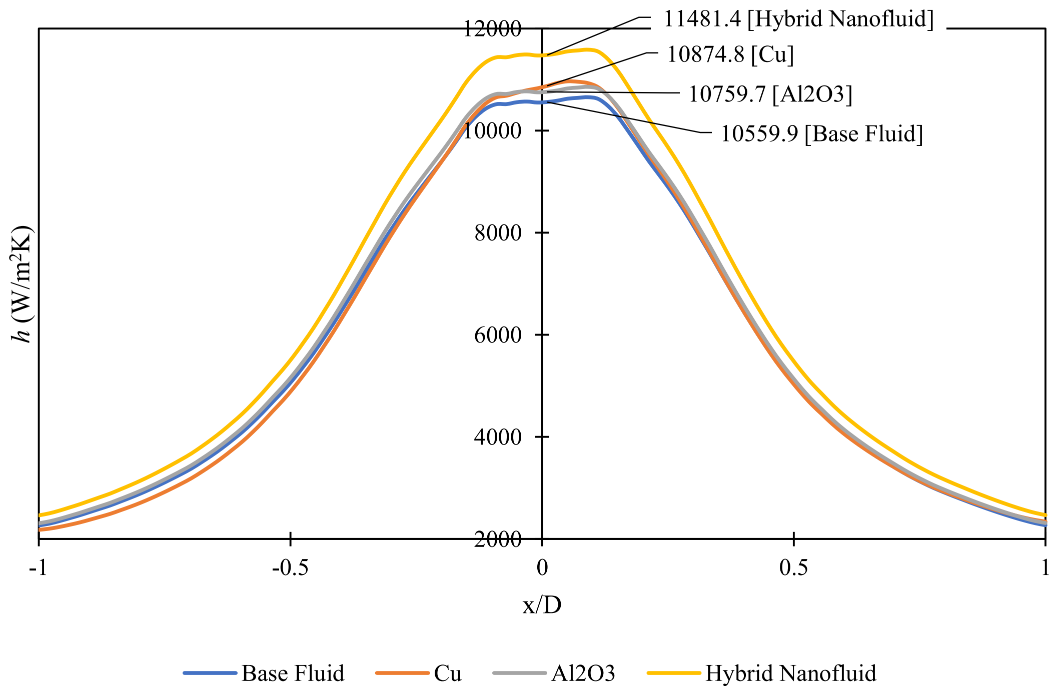

Fig. 10. Graph of wall heat transfer coefficient.

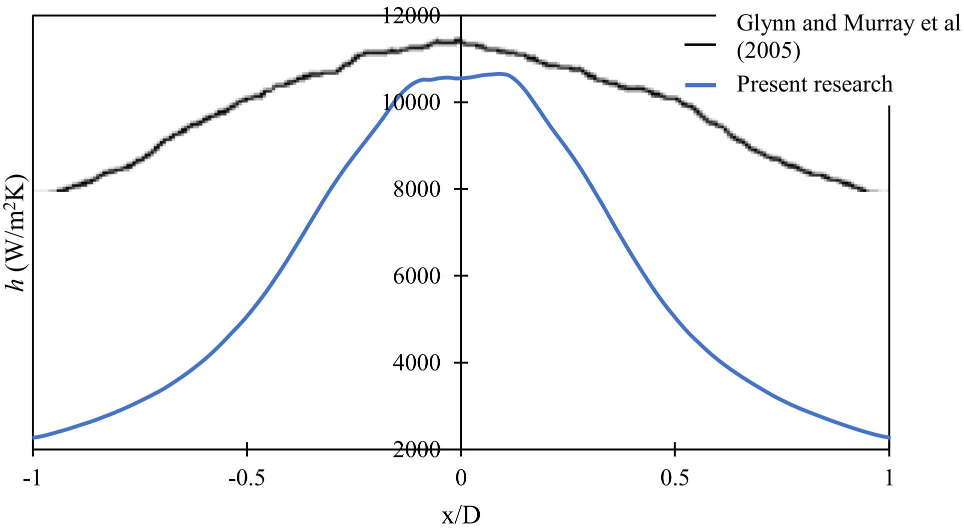

Fig. 11. Comparison of heat transfer coefficient of base fluid with [9].

of the heat transfer coefficient. To investigate the flow and heat transfer characteristics, the heat transfer coefficient was measured on the target surface with a fixed initial temperature. The results shows that there is an increase in the average heat transfer coefficient of the target surface of about 8.73% for hybrid nanofluid, 1.89% for Al_2O_3 nanofluid, and 0.17% Cu nanofluid in comparison with water as the base fluid,. This indicates that the addition of nanoparticles in a fluid increases the heat transfer coefficient. In addition, the mixture of hybrid nanoparticles in a fluid further improves the heat transfer performance. In conclusion, hybrid nanofluid is proven to have the best heat transfer performance and reduces the greatest amount of heat from target surface to the fluid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The research has been funded by the Ministry of Higher Education, Malaysia and Universiti Kebangsaan Malaysia under the Fundamental Research Grant Scheme FRGS/1/2018/TK07/UKM/02/8.

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