Simulation of Nanofluid Flow in a Micro-Heat Sink With Corrugated Walls Considering the Effect of Nanoparticle Diameter on Heat Sink Efficiency

Yacine Khetib1,2*, Hala M. Abo-Dief3, Abdullah K. Alanazi5, Goshtasp Cheraghian4, S. Mohammad Sajadi5,6 and Mohsen Sharifpur7,8*

1Mechanical Engineering Department, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia, 2Center Excellence of Renewable Energy and Power, King Abdulaziz University, Jeddah, Saudi Arabia, 3Department of Chemistry, College of Science, Taif University, Taif, Saudi Arabia, 4Independent Researcher, Braunschweig, Germany, 5Department of Nutrition, Cihan University-Erbil, Erbil, Iraq, 6Department of Phytochemistry, SRC, Soran University, Soran, Iraq, 7Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria, South Africa, 8Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan

In this numerical work, the cooling performance of water–Al2O3 nanofluid (NF) in a novel microchannel heat sink with wavy walls (WMH-S) is investigated. The focus of this article is on the effect of NP diameter on the cooling efficiency of the heat sink. The heat sink has four inlets and four outlets, and it receives a constant heat flux from the bottom. CATIA and CAMSOL software were used to design the model and simulate the NF flow and heat transfer, respectively. The effects of the Reynolds number (Re) and volume percentage of nanoparticles (Fi) on the outcomes are investigated. One of the most significant results of this work was the reduction in the maximum and average temperatures of the H-S by increasing both the Re and Fi. In addition, the lowest Tmax and pumping power belong to the state of low NP diameter and higher Fi. The addition of nanoparticles reduces the heat sink maximum temperature by 3.8 and 2.5% at the Reynolds numbers of 300 and 1800, respectively. Furthermore, the highest figure of merit (FOM) was approximately 1.25, which occurred at Re = 1800 and Fi = 5%. Eventually, it was revealed that the best performance of the WMH-S was observed in the case of Re = 807.87, volume percentage of 0.0437%, and NP diameter of 20 nm.

Keywords: heat sink, electronic component, nanoparticles diameter, alumina–water nanofluid, numerical simulation

INTRODUCTION

Advances in technology and electronic devices have posed a formidable challenge for related industries. Increasing the power of electronic devices in many cases causes them to heat up; in some cases it reduces the performance of the devices and, in certain circumstances, causes the electronic devices to fail. Hence, it is of absolute necessity to cool this equipment properly. The application of electronic equipment in devices such as cellphones and tablets in a small space has caused heat transfer to occur in a tiny space. CPUs are one of these electronic devices and cooling them is required in all of the abovementioned devices. As their computing power enhances, the generated...
heat increases, and as a result, they need to be cooled down by heat sinks (H-Ss) to prevent the reduction in their performance (Ghani et al., 2017; Sohel Murshed and Nieto de Castro, 2017; Bahiraei and Heshmatian, 2018a; Ahmed et al., 2018; Pordanjani et al., 2021). Owing to the tiny size of the CPUs, it is necessary to employ micro-heat sinks (MH-Ss) in this regard. In MH-Ss, the fluid flows in the microchannels and cools the H-S and consequently the electronic equipment. The growing needs of industries for MH-Ss with increased cooling capacities has led to an increment in studies in recent decades (Tullius et al., 2011; Shalchi–Tabrizi and Seyf, 2012; Mohammed Adham et al., 2013; Sohel et al., 2015; Kumar et al., 2018). So far, particularly in recent years, several researchers have conducted various studies on the analysis of cooling devices (Bagherzadeh et al., 2019; Ahmadi et al., 2020a; Peng et al., 2020; Shadloo et al., 2020; Safdari Shadloo, 2021). In one of these studies, Kumar and Singh (2019) numerically inspected the influence of inlet and outlet on the thermal performance of an H-S. They studied an H-S comprising some parallel microchannels and utilized $H_2O$ to cool it. Their simulation results demonstrated that augmenting the $Re$
Nanoparticles (NPs) can be made in different dimensions in nanoscale. Many NPs have different dimensions. Alumina NPs, one of the most widely used NPs, are produced in various dimensions. The dimensions of the NPs can affect the thermal conductivity and viscosity of the NF. However, few researchers have considered the effect of the NP diameter on heat transfer, especially in heat sinks. Owing to the importance of cooling electronic devices, particularly CPUs in various functional devices, this article numerically studied a new H-S. This H-S had four similar sections where the fluid entered through 4 inlets and exited out of 4 outlets. In order to improve heat transfer, NPs were employed for cooling, and microchannels with wavy walls (WW) were also considered. The model used for single-phase viscosity and thermal conductivity also depended on the diameter of the nanoparticles (NPs), and its influence on the thermal performance of the WW in H-S has also been investigated. An innovation of this study is to use wavy channel walls in the heat sink and to assess the effect of the nanoparticle diameter on the thermal efficiency of a heat sink.

**PROBLEM DEFINITION**

The studied WMH-S, presented in Figure 1, had four inlets and four outlets. This aluminum WMH-S comprised of four similar sections. The height of the WMH-S was 0.5 mm and its overall dimension was 18 × 6.2 mm. The dimensions of the heat sink inlet are 1.8 mm, and the height of microchannels is 0.4 mm. A 0.2-mm-thick aluminum door is placed on the heat sink. Within the WMH-S, nanomaterials, \( Al_2 O_3 /H_2 O \) NF with volume percentages ranging from 0 to 5% flowed in a \( Re \) of 300, 800, 1,300, and 1,800. A constant heat flux, from the operation of an electronic device, was applied on the bottom of the WMH-S. The aluminum used in the heat sink has a thermal conductivity of 179.96 W/m.K, a density of 2,712.6 kg/m³, and a heat capacity of 0.96 kJ/kg K (Kant et al., 2017).

**GOVERNING EQUATIONS**

The general equations governing the fluid flow within the H-S in the single-phase form are as follows. These equations include the conservation of mass, momentum, and energy. The fluid flow is laminar and steady, and the fluid is an incompressible Newtonian (Akbari et al., 2011).

\[
\nabla \cdot (\rho \vec{v}) = 0, \tag{1}
\]

\[
\rho \vec{v} \cdot \nabla \vec{v} = -\nabla P + \nabla \left( \mu \nabla \vec{v} \right). \tag{2}
\]
∇ \left( \rho \vec{v} T \right) = \nabla \cdot (k \nabla T), \quad (3)

0 = \nabla \cdot (k_{\text{aluminum}} \nabla T), \quad (4)

where $\vec{v}$, $T$, and $P$ are velocity, temperature, and pressure, respectively. In the above equations, $\rho$ represents density, $k$ thermal conductivity, $c_p$ specific heat, and $\mu$ viscosity of NF. These properties are related to the NF and the following equations are employed to calculate them:

\begin{align}
\rho &= F_i \rho_p + (1 - F_i) \rho_f, \quad (5)
\rho c_p &= (1 - F_i)(\rho c_p)_f + F_i(\rho c_p)_p. \quad (6)
\end{align}

In the above-mentioned equations, the indices $p$ and $f$ refer to the NPs and the base fluid, respectively. The NF viscosity was calculated using the following equation, which is specific to the $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ NF (Khanafar and Vafai, 2011).

\begin{align}
\mu &= -0.4491 + \frac{28.837}{T} + 0.574 F_i - 0.1634 F_i^2 + 23.053 \frac{F_i^2}{T^3}
+ 0.0132 F_i^3 - 2354.735 \frac{F_i}{T^3} + 23.498 \frac{F_i^2}{d^2} - 3.0185 \frac{F_i^3}{d^2}, \quad (7)
\end{align}

where $d$ is the diameter of the NPs in nanometers $F_i$ is the volumetric percentage of the NPs. The relationship of thermal conductivity, which depends on the diameter of the NPs, was as follows (Teng et al., 2010).

\begin{align}
\frac{k}{k_f} &= 0.991 + 0.253 (100\omega) - 0.001 T - 0.002 d - 0.189 (100\omega)^2 + 6.190 \times 10^{-7} T^2
+ 1.317 \times 10^{-5} d^2 + 0.049 (100\omega)^3 - 7.66 \times 10^{-5} T^3, \quad (8)
\end{align}

where $\omega$ is the mass percentage of NPs, and $T$ is the temperature in degree Celsius. The other properties of the fluid and $\text{Al}_2\text{O}_3$ NPs are provided in Figure 2.

**BOUNDARY CONDITIONS**

Figure 3 shows the boundary condition of the problem. The temperature values and boundary conditions at the inlet and outlet of the heat sink are displayed in Figure 2. The properties of water and NPs are also present in this figure. A constant flux of 100 W/cm$^2$ is applied to the bottom of the heat sink as shown. According to Figure 2, the upper, front, and left walls of the heat sink are at constant temperature.
sink are insulated, and the symmetry boundary condition is applied to the back and right walls.

**NUMERICAL METHOD AND VALIDATION**

For simulating the problem model, its geometry was first drawn in CATIA software. In the next step, the mentioned geometry was transferred to CAMSOL software. Next, an all-hexagonal mesh was applied to the geometry. Then, by entering the properties of NFs and other boundary conditions in this software, the equations were solved and the necessary simulations were performed using the finite element method. The convergence criterion for Eqs 7–10 is considered. To achieve a proper grid for geometry, many changes were made to the number of elements. Finally it was found that these yield the best results in terms of the solution time as well as the accuracy of the results for the number of 1,550,000 elements. The average temperature changes of the heat sink for the number of different elements are given in **Table 1** in the Re = 300 for 5% nanofluid. The trend of the changes in the heat sink average temperature shows the accuracy of selecting this number of elements.

In order to validate the numerical solution, the results of the present study were compared with some articles, one of which is provided below. Thus, the average Nusselt number obtained from the present work is compared with the experimental work of Ho and Chen (2013) for different channel lengths (Table 2). It can be observed that the amount of error between the present results and those reported by Ho and Chen (2013) is less than 4%, indicating that the present simulations are acceptable.

**DATA REDUCTION**

To assess the thermal performance of the H-S, it was of necessity to investigate parameters such as the heat transfer coefficient (HTC) and the pumping power PP. The convective HTC for the H-S was defined as follows (Bahiraei and Heshmatian, 2017).

\[ h = \frac{q''}{T_{\text{Ave}} - T_{\text{mid}}} \]  

(9)

\( T_{\text{mid}} \) can be obtained using \( T_{\text{in}} + T_{\text{out}} \), where \( T_{\text{in}} \) is the inlet temperature and \( T_{\text{out}} \) is the outlet temperature. \( T_{\text{Ave}} \) is also the average temperature of the H-S bottom and \( q'' \) represents the thermal flux applied to the WMH-S.
In the following relations, two increased ratios of HTC and PP are introduced.

\[ PP = \frac{Q \Delta P}{h_{t}} \]  
\[ h_{\text{eff}} = \frac{(h - h_{t})}{h_{t}} \times 100. \]  

In the PP relation, \( Q \) indicates the volumetric flow rate of the fluid and \( \Delta P \) is the pressure difference on both sides of the H-S. Other parameters can also be utilized to measure the thermal performance of H-Ss. Two important parameters in evaluating the performance of H-Ss are the thermal resistance and temperature uniformity, the relationships of which are listed below. The lower the two parameters, the better the performance of H-Ss.

\[ R = \frac{T_{\text{Max}} - T_{\text{in}}}{q''} \]  
\[ \Theta = \frac{T_{\text{Max}} - T_{\text{Min}}}{q''} \]  

In the above equations, the indices Max and Min represent the maximum and minimum temperatures on the lower surface of the H-S.

A parameter that is considered when using NFs in various devices is the figure of merit (FOM), whose relationship is presented below, indicates the ratio of convective HTC of NF to \( H_{2}O \) to the \( \Delta P \) of NF to \( H_{2}O \) (Bahiraei and Heshmatian, 2017).

\[ \text{FOM} = \frac{h}{h_{t}} \frac{\Delta P_{t}}{\Delta P_{f}} \]  

RESULTS AND DISCUSSION

Figure 3 demonstrated the temperature contour of the WMH-S for \( H_{2}O \) and NF 2% in different \( Re \). At low velocities of the fluid, it can be seen that the fluid heated up at the beginning of WMH-S and had a low heat transfer in the end. As the fluid velocity increased, the fluid with lower temperatures moved inside the WMH-S, and as a result, cooling in the end of the WMH-S increased.

Figure 4 shows the \( T_{\text{Max}} \) at the bottom of the WMH-S for variations of \( Re, d, \) and \( Fi \). As it can be observed, an intensification in the \( Re \) always decreased the \( T_{\text{Max}} \). Faster passage of fluid through the WMH-S improved cooling, thus, the heat transfer increased and the WMH-S temperature got closer to the fluid temperature. Hence, the \( T_{\text{Max}} \) was also decreased. Increasing the \( Fi \) also reduced the \( T_{\text{Max}} \) of the WMH-S. The application of NF resulted in a higher thermal conductivity of the fluid, which increased the heat transfer from the WMH-S to the fluid. Therefore, it lowered the temperature of the

![FIGURE 5](image-url)
WMH-S. In the higher Fi, the $T_{\text{Max}}$ obtained using NF containing small-sized NPs was lower, while in the low volume percentage, NF containing large-sized NPs generated lower $T_{\text{Max}}$. Both the viscosity and the thermal conductivity depend on the temperature, the volumetric percentage of the NPs, and the diameter of the NPs; hence, in different volume percentages and temperatures, the effect of NP diameter on the heat transfer could vary.

Figure 5 displays the average temperature of the bottom of the H-S for variations of Re, d, and Fi. As it can also be observed, an intensification in the Re diminished the average temperature in the WMH-S and an intensification in the Fi decreased the average temperature. As mentioned above, the increase in these two parameters increased the heat transfer between the WMH-S and the fluid, thus reducing the overall temperature of WMH-S and making its temperature closer to the temperature of the fluid. The changes in the average temperature varied based on the changes in the NP diameter at different volume percentages. Of course, the amount of these changes was far less than the temperature changes with the Fi and Re. The average temperature appeared to be lower in medium-sized NPs, especially at high volumetric percentages.

Figure 6 demonstrated the PP required to flow the fluid for dissimilar values of Re, d, and Fi. The intensification in Re and, consequently, the escalation in fluid velocity greatly increased the PP. An increase in the Fi also increased this parameter, stemming from the increase in $\Delta P$ in the WMH-S. It can be seen that the variations in the PP with the NP diameter were very small; however, in a high-volume percentage, employing smaller NPs resulted in the requirement of less PP. The use of smaller NPs increased the viscosity, and consequently, the shear stress reduced. As a result, the employment of smaller NPs slightly increased PP.

Figure 7 demonstrates the increase percentage in the HTC for different values of Re, d, and Fi. Increasing the Re and the Fi always increased the HTC. It was seen that growing the Fi maintained the upward trend of increasing the HTC and always increased it. However, with the intensification of the Re in the high volume percentages of NPs, the increase in the HTC was initially low, but in higher Re, the increasing trend was steeper and increased significantly; while in the low Fi, the increase in the Re always created an increasing trend in the HTC. It was also noticed that in high and low Re, the effect of adding NPs was more promising than that in medium Re. Furthermore, the increase in the HTC was higher for the average-sized NPs.

Figure 8 demonstrates the temperature uniformity on the bottom of the WMH-S for dissimilar values of Re, d, and Fi. Here, the intensification in the Re and the volumetric percentage of the NPs reduced the Theta, indicating that the temperature at the bottom of the WMH-S was uniform. The decrease in temperature
FIGURE 7 | Increase in percentage in the HTC for different values of Re, d, and Fi.

FIGURE 8 | Temperature uniformity on the bottom of the WMH-S for dissimilar values of Re, d, and Fi.
caused the temperature to be uniform in this part, stemming from better heat transfer between the fluid and the solid walls. In the average diameters of NPs, \( \theta \) was higher, meaning that the larger diameter of NPs had better temperature uniformity.

Figure 9 shows the FOM for dissimilar values of \( Re, d, \) and \( Fi \). The best case for adding NPs in terms of heat transfer to \( \Delta P \) was in high \( Re \) such that the highest FOM was approximately 1.25, which occurred in the \( Re \) of 1800 for 5\% of the \( Fi \). In higher \( Re \), the increase in HTC was greater than the increase in \( \Delta P \); while in lower \( Re \) (300), the decrease in FOM was less than one, meaning the ratio of increase in \( \Delta P \) with the addition of NPs was higher than the increase in HTC. Investigating the NP diameter demonstrated that application of NPs with a larger size resulted in a higher FOM.

CONCLUSION

In this article, a new WMH-S with five microchannels was simulated. The walls of the microchannels were wavy. \( H_2O \) and \( Al_2O_3/H_2O \) NF were employed as the coolant. The model utilized for viscosity and conductivity of the NF was related to the diameter of the NPs. With the changes in the \( Re \), the volumetric percentage of the NPs, and their diameters, the thermal performance of the WMH-S was considered and the main obtained results are as follows:

1) Increasing the \( Re \) and the percentage of NPs reduced the maximum and minimum temperatures at the bottom of the WMH-S.
2) Increasing the diameter of the NPs at a higher \( Fi \) increased the \( T_{Max} \) of the WMH-S, while those at a low volume percentage reduced it. The addition of nanoparticles reduces the heat sink maximum temperature by 3.8 and 2.5\% at the Reynolds numbers of 300 and 1800, respectively.
3) With increasing the \( Re \) and volume percentage, more PP was required. Thus, the cost of PP also increases.
4) In high percentages of NPs, the increase in the size of NPs also raised the PP.
5) The HTC augmented with increasing \( Re \) and \( Fi \).
6) The temperature uniformity increased with the intensification of \( Re \) and the volumetric percentage of NPs, and its thermal resistance decreased.
7) The highest FOM was approximately 1.25, occurring in high \( Re \) and volume percentages of NPs.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.
AUTHOR CONTRIBUTIONS

All authors wrote the manuscript, provided critical feedback, and helped shape the research, analysis, and manuscript. All authors discussed the results and commented on the manuscript.

REFERENCES

Afrand, M., Farahat, S., Nezhad, A. H., Ali Sheikhzadeh, G., and Sarhaddi, F. (2014). 3-D Numerical Investigation of Natural Convection in a Tilted Cylindrical Annulus Containing Molten Potassium and Controlling it Using Various Magnetic Fields. Int. J. Appl. Electromagnetics Mech. 46, 809–821. doi:10.3233/sec-141975
Ahmadi, A., Arabbeiki, M., Ali, H. M., Goodarzi, M., and Safaei, M. R. (2020). Numerical Investigation of the Effect of Base Fluid, Temperature, and Concentration on the Thermal Properties of Hybrid Nanofluids of Alumina–Ferrofluid: Experimental Data, Modeling through Enhanced ANN, ANFIS, and Curve Fitting. Int. J. Therm. Anal. Calorim. 143 (6), 4149–4167. doi:10.1007/s10973-020-00378-w
Ambreen, T., and Kim, M.-H. (2020). Influence of Particle Size on the Effective Thermal Conductivity of Nanofluids: A Critical Review. Appl. Energ. 264, 114684. doi:10.1016/j.apenergy.2020.114684
Arani, A. A. A., Sadripour, S., and Kermani, S. (2017). Nanoparticle Shape Effects on the Performance of a Minichannel Using Water–Alumina Nanofluid by Non-dominated Sorting Genetic Algorithm and Response Surface Method. Nanomaterials (Basel) 10 (5), 901. doi:10.3390/nano10050901
Afrand, M., Mohseni-Gharayehsafa, B., Ghazvini, M., Goodarzi, M., Jilie, R. D., and Kumar, R. (2020). Comparing Various Machine Learning Approaches in Modeling the Dynamic Viscosity of CuO/water Nanofluid. J. Therm. Anal. Calorim. 139 (4), 2585–2599. doi:10.1007/s10973-019-08762-6
Ahmed, H. E., Salman, B. H., Kherbeet, A. S., and Ahmed, M. I. (2018). Development, Challenges, and Applications. J. Energy. 2019, 116626. doi:10.1016/j.energy.2019.116626
Bahiraei, M., and Heshmatian, S. (2017). Application of a Novel Biological Nanofluid in a Liquid Block Heat Sink for Cooling of an Electronic Processor: Thermal Performance and Irreversibility Considerations. Energy Convers. Manage. 149, 155–167. doi:10.1016/j.enconman.2017.07.020
Bahiraei, M., and Heshmatian, S. (2018). Electronics Cooling with Nanofluids: A Critical Review. Energy Convers. Manage. 172, 438–456. doi:10.1016/j.enconman.2018.07.047
Bahiraei, M., and Heshmatian, S. (2018). Thermal Performance and Second Law Characteristics of Two New Microchannel Heat Sinks Operated with Hybrid Nanofluid Containing Graphene-Silver Nanoparticles. Energ. Convers. Manage. 168, 357–370. doi:10.1016/j.enconman.2018.05.020
Bahrani, M., Akbari, M., Bahgerzadeh, S. A., Karimipour, A., Afrand, M., and Goodarzi, M. (2019). Develop 24 Dissimilar ANNs by Suitable Architectures & Training Algorithms via Sensitivity Analysis to Better Statistical Presentation: Measure MSEs between Targets & ANN for Fe-CuO/Eg/Water Nanofluid. Physica A: Stat. Mech. its Appl. 519, 159–168. doi:10.1016/j.physa.2018.12.031
Esfe, M. H., Esfandeh, S., Afrand, M., Rejvani, M., and Rostamian, S. H. (2018). Experimental Evaluation, New Correlation Proposing and ANN Modeling of thermal Properties of EG Based Hybrid Nanofluid Containing ZnO-DWCNT Nanoparticles for Internal Combustion Engines Applications. Appl. Therm. Eng. 133, 452–463. doi:10.1016/applthermaleng.2017.11.131
Ghanbari, M., Maleki, A., Haghhi, A., Safdari Shadloo, M., Alhuyi Nazari, M., and Tili, I. (2020). Applications of Nanofluids Containing Carbon Nanotubes in Solar Energy Systems: A Review. J. Mol. Liquids 313, 113476. doi:10.1016/j.molliq.2020.113476
Ghomi, I. A., Siddik, N. A. C., and Kamaruzaman, N. (2017). Hydrothermal Performance of Microchannel Heat Sink: The Effect of Channel Design. Int. J. Heat Mass Transfer 107, 21–44. doi:10.1016/j.ijheatmasstransfer.2016.11.031
Ghodsinizad, H., Sharifpur, M., and Meyer, J. P. (2016). Experimental Investigation on Cavity Flow Natural Convection of Al 2 O 3 -water Nanofluids. Int. Commun. Heat Mass Transfer 76, 316–324. doi:10.1016/j.ijheatmasstransfer.2016.06.005
Giwa, S. O., Sharifpur, M., Goodarzi, M., Alslami, H., and Meyer, J. P. (2021). Influence of Base Fluid, Temperature, and Concentration on the Thermophysical Properties of Hybrid Nanofluids of Alumina–Ferrofluid: Experimental Data, Modeling through Enhanced ANN, ANFIS, and Curve Fitting. J. Therm. Anal. Calorim. 143 (6), 4149–4167. doi:10.1007/s10973-020-03972-w
Guo, H., Huang, S., Ding, J., Tian, F., Xu, Q., and Zhao, J. (2020). Chemical Environment and Magnetic Moment Effects on point Defect Formations in CuCrNi-Based Concentrated Solid-Solution Alloys. Acta Materialia 187, 122–134. doi:10.1016/j.actamat.2020.01.044
Hajizadeh Pordanjani, A., Aghakhani, S., Afrand, M., Mahmoudi, B., Mahian, O., and Wongwises, S. (2019). An Updated Review on Application of Nanofluids in Heat Exchangers for Saving Energy. Energ. Convers. Manage. 198, 111866. doi:10.1016/j.enconman.2019.111866
Handschuh-Wang, S., Wang, T., and Tang, Y. (2021). Ultrathin Diamond Nanofilms—Development, Challenges, and Applications. Small 17 (30), 2007529. doi:10.1002/smll.202007529
Hemmat Esfe, M., Rostamian, H., Esfandeh, S., and Afrand, M. (2018). Modeling and Prediction of Rheological Behavior of Al2O3-Mwcnt/5W50 Hybrid Nano-Lubricant by Artificial Neural Network Using Experimental Data. Physica A: Stat. Mech. its Appl. 510, 625–634. doi:10.1016/j.physa.2018.06.041
Ho, C.-J., and Chen, W.-C. (2013). An Experimental Study on thermal Performance of Al2O3/water Nanofluid in a Minichannel Heat Sink. Appl. Therm. Eng. 50 (1), 516–522. doi:10.1016/j.applthermaleng.2012.07.037
Hu, P., Cao, L., Su, J., Li, Q., and Li, Y. (2020). Distribution Characteristics of Salt-Out Particles in Steam Turbine Stage. Energy 192, 116626. doi:10.1016/j.energy.2019.116626
Hu, Y., Qing, J. x., Liu, Z. H., Conrad, Z. J., Cao, J. N., and Zhang, X. P. (2021). Hovering Efficiency Optimization of the Ducted Propeller with Weight Penalty Taken into Account. Aerospace Sci. Technol. 117, 106937. doi:10.1016/j.ast.2021.106937
Irandoust Shahrkani, M., Maleki, A., Safdari Shadloo, M., and Tili, I. (2020). Numerical Investigation of Forced Convective Heat Transfer and Performance Evaluation Criterion of Al2O3/Water Nanofluid Flow inside an. Axisymmetric Microchannel 12 (1), 120. doi:10.3390/sym12010120
FUNDING

This work was supported by the Taif University Researchers Supporting grant number (TURSP-2020/266) of Taif University, Taif, Saudi Arabia.
