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CFD Analysis of Six-Flow Microchannel Heat Sink Using the Different Nanofluid

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Abstract

In this study, we compare the heat-conveying capabilities of ordinary water with those of cooling fluids such as Ag-Water, TiO_2-water, and Al_2O_3-water nanofluid at a volume percentage of 0.50%, and we also examine the six flow micro-channels of the fin-equipped heat sink. Hardware like microprocessors and integrated circuits are not used in the comparison. To evaluate the effectiveness of different cooling fluids, a number of thermal metrics are used, such as temperature distribution, convective coefficient of heat transfer, Nusselt number, and heat sink thermal resistance. In this experiment, the ANSYS software tool Fluent (v16.0) is used. For the purpose of solving the partial differential equations controlling the cooling fluid flow and heat transfer, the Finite Volume Method is employed. The numerical results show that cooling all kinds of nanofluids is better than cooling the regular fluid, due to the very high values of the Nusselt number and the convective heat transfer coefficient. Finally, it has been determined that Ag-water nanofluid is a viable option for improving heat transmission in general.

Keywords: Micro-Channel Heat Sink, Microprocessor Chip, CFD, Heat Transfer, Nanofluids.

INTRODUCTION

To maintain the operating temperature of an electronic microprocessor chip within the safe range, modern cooling technology is the need of the hour to dissipate away the high built up of thermal energy from the system into the fluid. The current cooling technologies in use are heat pipe [1–3] two-phase fluid flow in heat sink flow micro-channels [4, 5] and pool boiling [6]. These existing cooling methods are not efficient enough to satisfy the ever-increasing demand for cooling. For efficiently and rapidly transfer of thermal energy from the system with a narrow range of temperature differential, an effort is made to add nano-scaled particles in standard fluid water. Nanofluid, engineered colloidal dispersions of nano-scaled particles in a standard fluid such as engine oil, H_2O, glycerin and ethylene glycol have novel characteristics that make them capable to be used in heat transfer applications [7]. S.U.S. Choi [8] first proposed the term nanofluid, who noticed that the addition of nano-scaled particles increases the thermal conductivity of cooling fluid, hence increasing the thermal performance. Current electronic devices generate an excessive amount of thermal flux. Hence, the main requirement for cooling recent electronic technologies such as microprocessors and integrated circuits is a high rate of heat dissipation. Heat sink is a device that conducts away the heat produced by a microprocessor chip because of the temperature difference, where it is dissipated away to the cooling fluid flowing the

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flow channels of heat sink [9].

Ijam et al. [10, 11] analyzed heat removal competence of microchannels heat sink when nanofluids are circulated along the flow micro-channels. The authors noticed that when nanofluids like TiO_2-H_2O, Al_2O_3-H_2O and SiC-H_2O is used as a cooling fluid in the flow micro-channels of heat sink enhances the cooling by 1.88-16.53%, 2.95-17.32% and 7.25-12.43%. The impact of the CuO-H_2O nanofluid as a cooling fluid in the rectangular and circular cross-section flow micro-channels of the heat sink on the rate of heat dissipation was numerically examined by Ghasemi et al. [12]. Chamkha et al. [13] reviewed the application of nanofluids in micro-channel and found that dispersing a small amount of nano-scaled particles in standard fluid water can enhance the flow and thermal attributes of cooling fluid in microchannel. Bhattacharya et al. [14] investigated coupled thermal energy transfer in a rectangularly made flow micro-channels of heat sink employing Al_2O_3-H_2O nanofluid. CFD FLUENT is used for this numerical investigation and the algorithm used for pressure-velocity coupling is SIMPLE. The authors found that the use of the nanofluid as a cooling fluid in the flow micro-channels of heat sink at low concentration leads to enhancement in heat dissipation.

Ghasemi et al. [15] examined the performance of the heat sink of triangular cross-section flow mini-channels employing the alumina- H_2O as a cooling fluid at different volume fraction. The authors reported that flow micro-channels heat sink thermal resistance significantly dropped by increasing the volume fraction of nano-scaled particles in standard fluid water. The findings indicate that utilizing water dispersed nanoparticles of diamond at 1% volume fraction as cooling medium advances the cooling capacity of a MCHS by 10% relative to elementary liquid cooled MCHS. Ghasemi et al. [16] analyzed the impact of the different hydraulic diameter of flow micro-channel on the heat sink performance. The authors conveyed that the augmentation in the convective coefficient of heat transfer is significant at lower values of hydraulic diameter. P.C. Mukesh et al. [17] carried out an analysis on the thermal energy transfer performance of heat sink with extended surfaces using Al_2O_3-H_2O as a cooling fluid in a flow micro-channels for electronic chip cooling. Finally, the authors reported that with the use of nanofluid the surface temperature and the power consumption is reduced. The authors also reported a 70% improvement in reliability of electronic chip using nanofluid as a cooling fluid relative to standard fluid water. Heat sink thermal resistance and temperature profile of micro-channel heat sink making use of diamond-water and Cu-water nanofluid as a cooling medium was computationally examined by Jang and Choi et al. [18].

Kadja et al. [19] performed a computational analysis of a micro-channel heat sink utilizing Al_2O_3-H_2O nanofluid. The authors also recorded a significant gain in the coefficient of heat transfer when making the use of nanofluid as a cooling medium in contrast to water. Ghasemi and Ranjbar et al. [20, 21] examined the impact of Cu nanoscale particles dispersed in elementary liquid water when used as cooling medium in the square enclosure on the free convection coefficient. It was believed that the improvement in the free convection coefficient was substantial due to an escalation in thermal conductivity. H.A. Mohammad et al. and P. Gunasegaran et al. [22] examined the end-results of utilizing different kinds of nanofluids like Ag, CuO, Diamond, Al_2O_3, TiO_2, SiO_2 on the triangularly structured micro-channel heat sink at a volume fraction of 2%. The authors concluded that minimum surface temperature with soaring value of convective co-efficient of heat transfer was attained when diamond-water nanofluid was used as a cooling medium in contrast to other nanofluid and elementary liquid. Al-Rashed et al. [23] studied the consequence of using nanofluid on the cooling potential of the heat sink for CPU heat load of 115 W and 130 W experimentally and numerically by CFD. A reasonable gain of 7.7% in thermal conductance was achieved in scenario of nanofluid as opposed to elementary liquid water. Maganti et al. [24] analyzed the side by side aligned micro-channel of heat sink system for an active cooling of microelectromechanical system (MEMS) making use of different kinds of nanofluids: Al_2O_3, CuO, CNT, SiO_2 and graphene nanoparticles scattered in elementary fluid water.

From the above scientific study, the author concluded that no scientific study has yet been done on the comparison of cooling capability of different cooling fluid. In this study, numerical analysis of the laminar flow of cooling fluid through the six circular-shaped flow micro-channels of the heat sink with the extended surface using TiO_2-water, Al_2O_3-water and Ag-Water at 0.5% volume fraction and standard fluid water as a cooling fluid. The thermal flux was set at ($q_{tb} = 100$ W/cm^2). The result was evaluated based on the following parameters like base temperature variation, convective heat transfer coefficient, the thermal resistance of heat sink and Nusselt number.

NUMERICAL ANALYSIS

Methodology

The micro-channel heat sink geometric model was used in this analysis is demonstrated in Figure 1. It incorporates the six-flow circular micro-channels of 5 mm hydraulic radius, five extended surfaces and microprocessor chip. Three different categories of nanofluid and standard fluid water are used as a cooling fluid in the six-flow micro-channels of heat sink separately. The dimensions of heat sink micro-channel are 55 mm in length, 55 mm in breadth, 50 mm in thickness and microprocessor chip is 30 mm in length, 30 mm in breadth and 2 mm in thickness. All the flow micro-channels of the heat sink are alike in terms of cross-section and length as shown in Figure 2. In this study several iterations for varied flow velocity ranging from 0.02 m/s–0.1 m/s were conducted to compare the cooling capability of heat sink under different cooling fluid circulating through the flow micro-channels of the heat sink and the thermal flux is set at ($q_{tb} = 100$ W/cm^2) on the bottom of the microprocessor chip.

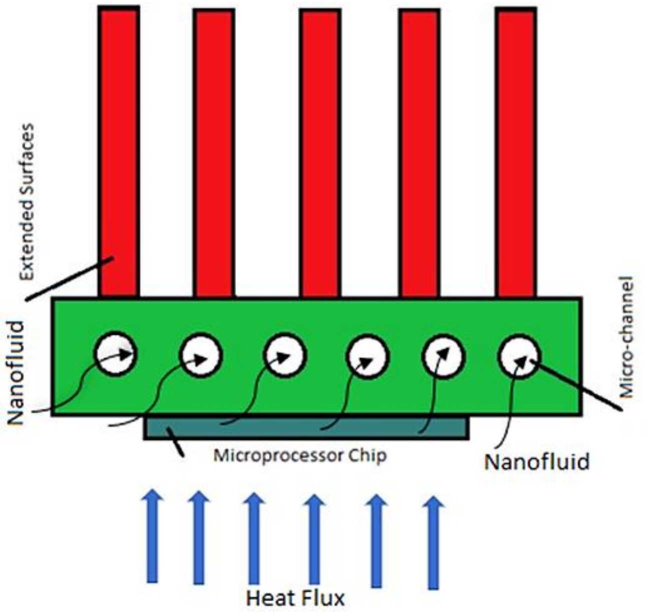


Figure 1. Schematic of six flow micro-channels heat sink.

Governing Equations

To analyze the cooling capability of different cooling fluid in the flow micro-channels of heat sink, the partial governing differential equations of mass balance, momentum and energy is written with appropriate assumptions:

1. 3-Dimensional, incompressible and laminar flow
2. Thermo-physical characteristics of silicon and cooling fluid are independent of temperature
3. Fluid flow is steady and in single-phase state
4. All heat sink surfaces are heat-proof except the bottom one which is in contact of the microprocessor chip, the thermal flux is applied at the bottom of microprocessor to imitate the thermal energy generation from microprocessors.

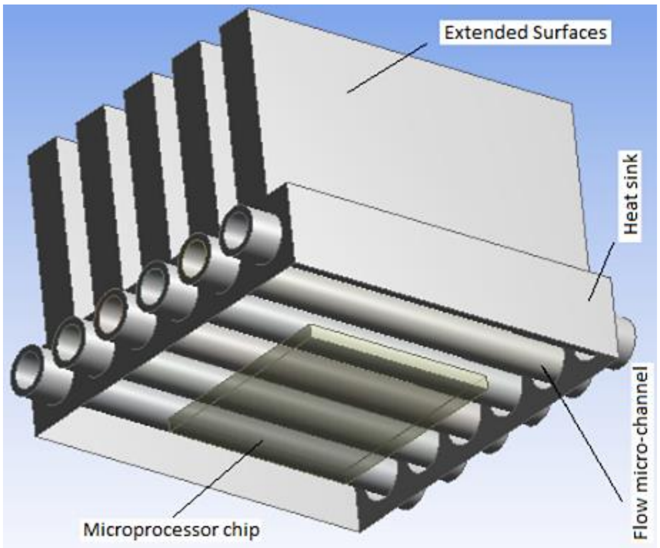


Figure 2. Schematic of flow micro-channel heat sink with five extended surfaces.

The equation of mass balance, momentum and energy is written down from Eq. 1 to Eq. 6 [16] ;

Equation of continuity:

$$\frac{\delta \mathrm{B_u}}{\delta \mathrm{u}} + \frac{\delta \mathrm{B_v}}{\delta \mathrm{v}} + \frac{\delta \mathrm{B_w}}{\delta \mathrm{w}} = 0 \qquad (1)$$

Equation of momentum in u, v, w directions:

$$\rho_{sf}\left(B_u\frac{\delta B_u}{\delta u} + B_v\frac{\delta B_u}{\delta v} + B_w\frac{\delta B_u}{\delta w}\right) = -\frac{\delta p}{\delta u} + \mu_{sf}\left(\frac{\delta^2 B_u}{\delta u^2} + \frac{\delta^2 B_u}{\delta v^2} + \frac{\delta^2 B_u}{\delta w^2}\right) \qquad (2)$$

$$\rho_{sf}\left(B_u\frac{\delta B_v}{\delta u} + B_v\frac{\delta B_v}{\delta v} + B_w\frac{\delta B_v}{\delta w}\right) = -\frac{\delta p}{\delta v} + \mu_{sf}\left(\frac{\delta^2 B_v}{\delta u^2} + \frac{\delta^2 B_v}{\delta v^2} + \frac{\delta^2 B_v}{\delta w^2}\right) \qquad (3)$$

$$\rho_{sf}\left(B_u\frac{\delta B_w}{\delta u} + B_v\frac{\delta B_w}{\delta v} + B_w\frac{\delta B_w}{\delta w}\right) = -\frac{\delta p}{\delta w} + \mu_{sf}\left(\frac{\delta^2 B_w}{\delta u^2} + \frac{\delta^2 B_w}{\delta v^2} + \frac{\delta^2 B_w}{\delta w^2}\right) \qquad (4)$$

Energy equation of cooling medium:

$$\rho_{sf}C_{p,sf}\left(B_u\frac{\delta T_{sf}}{\delta u} + B_v\frac{\delta T_{sf}}{\delta v} + B_w\frac{\delta T_{sf}}{\delta w}\right) = k_{sf}\left(\frac{\delta^2 T_{sf}}{\delta u^2} + \frac{\delta^2 T_{sf}}{\delta v^2} + \frac{\delta^2 T_{sf}}{\delta w^2}\right) \qquad (5)$$

Energy equation of solid region:

$$k\left(\frac{\delta^2 T_s}{\delta u^2} + \frac{\delta^2 T_s}{\delta v^2} + \frac{\delta^2 T_s}{\delta w^2}\right) = 0 \qquad (6)$$

Thermo-physical characteristics of Cooling fluid

In this analysis, the cooling fluid such as three different categories of nanofluids TiO_2-H_2O, Al_2O_3-H_2O, Ag-H_2O and standard fluid water was circulated through the six flow micro-channels of the heat sink. Cooling fluid thermo-physical characteristics were calculated from the given Eq. (7) to Eq. (10) like mass density, thermal conductivity, absolute viscosity and heat capacity as proposed by [18]. All the properties of standard fluid containing scattered nano-scaled particles of Ag, TiO_2 and Al_2O_3 at a volume fraction of 0.5% are mentioned in Table 1. Addition of nanoscaled particles in the standard fluid has significantly increased the thermal conductivity, density and viscosity, whereas specific heat capacity has been reduced relative to the standard fluid.

Density of cooling fluid:

$$\rho_{cf} = (1-\emptyset_n)\rho_{sf} + \emptyset_n \rho_p \tag{7}$$

Specific heat capacity of cooling fluid:

Table 1. Thermo-physical attributes of nanofluid at 293 K and 0.50% volume fraction.

Elements	**Nanoparticle (Al_2O_3)**	**Standard fluid (H_2O)**	**Nanofluid (Al_2O_3-H_2O)**
ρ	3970	998.2	1013.059
$C_{p,cf}$	765	4182	4115.046
$\kappa_{p,cf}$	40	0.613	0.624826
μ_{cf}	-	0.001003	0.001015648
Elements	***Nanoparticle (TiO_2)***	***Standard fluid (H_2O)***	***Nanofluid (TiO_2-H_2O)***
ρ	4250	998.2	1014.459
$C_{p,cf}$	686.2	4182	4108.7
$\kappa_{p,cf}$	8.9358	0.613	0.623128
μ_{cf}	-	0.001003	0.001015648
Elements	***Nanoparticle (Ag)***	***Standard fluid (H_2O)***	***Nanofluid (Ag-H_2O)***
ρ	10500	998.2	1045.709
$C_{p,cf}$	235	4182	3983.84
$\kappa_{p,cf}$	429	0.613	0.98514
μ_{cf}	-	0.001003	0.00101565

$$C_{p,cf} = \frac{(1-\emptyset_n)\left(\rho C_{p,sf}\right)_{sf} + \emptyset_n (\rho C_p)_p}{\rho_{cf}} \tag{8}$$

Viscosity of cooling fluid:

$$\mu_{cf} = \frac{\mu_{sf}}{(1-\phi_n)^{2.5}} \tag{9}$$

Thermal conductivity of cooling fluid:

$$k_{cf} = \frac{k_p + (e-1)k_{sf} - (e-1)\phi_n(k_{sf}-k_p)}{k_p + (e-1)k_{sf} + \phi_n(k_{sf}-k_p)} k_{sf} \tag{10}$$

The empirical form factor is assumed to be 3 for the spherically grouped nano-scaled particles [17]. The cooling fluid flow and thermal characteristics in flow micro-channels is calculated from the Eq 11 to Eq. 14. [17];

$$Q_{cf} = m_{cf} C_{p,cf} \, (T_{out} - T_{in})_{cf} \tag{11}$$

Heat transfer coefficient:

$$h_{cf} = \frac{Q_{cf}}{A_c(T-T_{cf})} \tag{12}$$

Average Nusselt number:

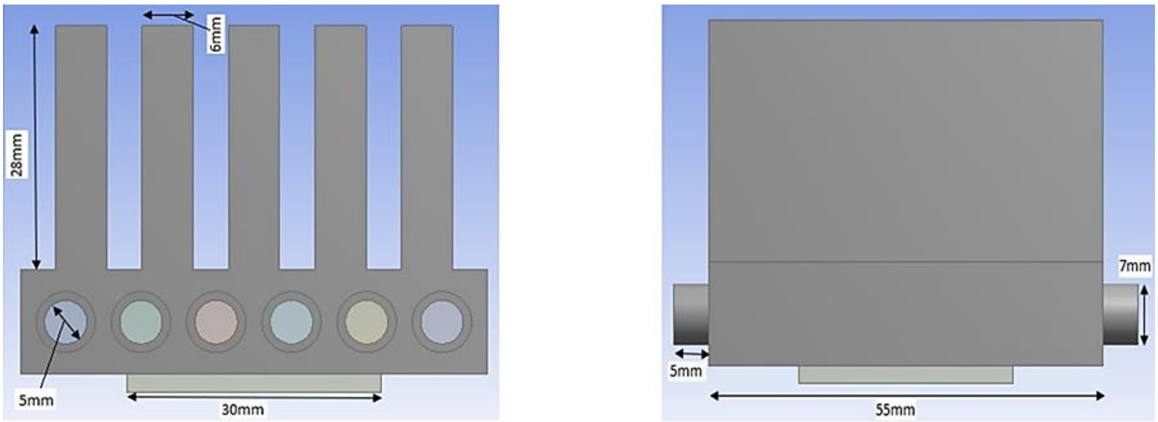
$$Nu = \frac{h_{av} D_{hy}}{k_{cf}} \tag{13}$$

Thermal resistance of heat sink:

$$R_t = \frac{(T_{MAX} - T_{in})}{Q_{in}} \tag{14}$$

Geometry

ANSYS Design modeler is used to develop the geometric model of six flow micro-channel of the heat sink with alike circular cross-section of hydraulic diameter 5 mm, extended surfaces to increase the heat transfer area which results in a surge in the convective rate of heat transfer from the system to the environment as illustrated in Figure 3. The dimensions of flow micro-channel heat sink are mentioned in Table 2.



a b

Figure 3. Schematic view of six flow micro-channels of heat sink with Dimensions (a) Front View of heat sink (b) Side view of heat sink.

Table 2. Dimension of Heat sink with extended surfaces.

Dimension	**Magnitude**
Length of micro-channel, L_c (mm)	65
Hydraulic diameter, D_{hy} (mm)	5
Heat transfer area, A_c (m^2)	0.00086393797
Length of heat sink, L_{HS} (mm)	55
Width of heat sink, W_{HS} (mm)	55
Height of heat sink, H_{HS} (mm)	40
Number of fins, N	5
Length of microprocessor chip, L_{MC} (mm)	30
Width of microprocessor chip, W_{MC} (mm)	30
Thickness of microprocessor chip, T_{MC} (mm)	2

CFD Methodology

Geometry model which was developed using Ansys Design modeler is imported into the Ansys Fluent (v16.0) where discretization is carried out. Meshing of geometry model has resulted in 133556 number of nodes and 469827 number of elements as shown in Figure 4. Finite volume method strategy was employed to solve the governing partial differential equations of mass balance, momentum and energy [19]. In this strategy, the governing partial differential equations are converted into the algebraic equations. Pressure-Velocity is coupled by using a SIMPLE algorithm. Isometric mesh view of a heat sink is demonstrated in Figure 5. A grid independence test was conducted at different no of elements as shown in Figure 6, which resulted in selection of 469827 number of elements for water as coolant.

Boundary Conditions

Boundary conditions are constraints mandatory to find the solution of the Computational Fluid Dynamic problem. The computational domain is simplified with the imposition of these constraints.

Hence, it's a crucial element of a mathematical model. The temperature of cooling fluid at the inlet of flow micro-channels of the heat sink is 293 K and the velocity at inlet is varied from 0.02 m/s–0.1 m/s. Heat conducted by heat sink from a microprocessor chip is carried away by the cooling fluid flowing through the six flow micro-channels of a heat sink. Velocity components of cooling fluid in v and w direction are presumed to be negligible. Pressure at the outlet of the flow micro-channels is set to be atmospheric. All heat sink surfaces are considered to be heat-proof except the lower surface. A thermal flux ($q_{tb} = 100\ W/cm^2$) is set at the base of the microprocessor chip.

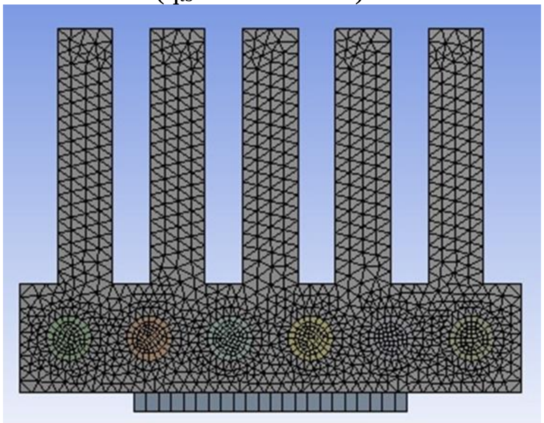


Figure 4. Mesh view of six flow micro-channel heat sink.

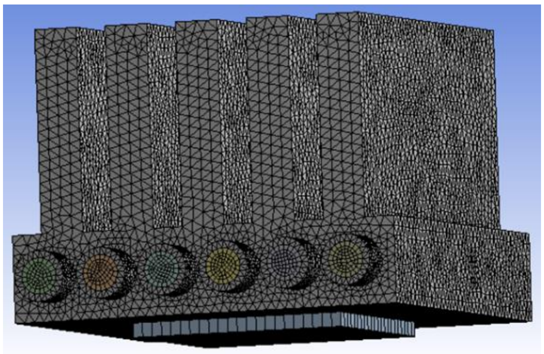


Figure 5. Isometric Mesh view of six flow micro-channels of heat sink.

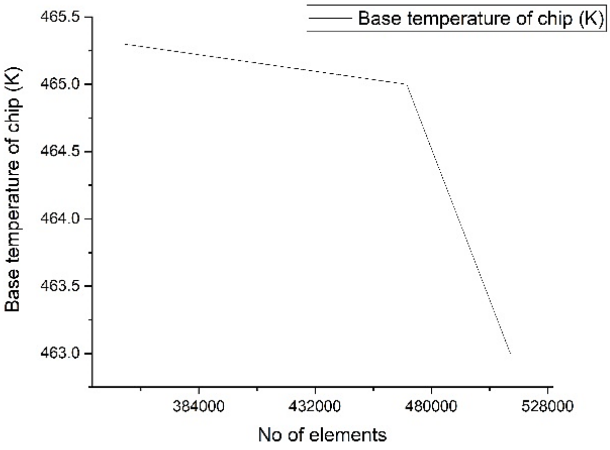


Figure 6. Grid Independence Test.

RESULTS AND DISCUSSIONS

In this numerical study, the comparison of cooling capability of different cooling fluid such as Ag-water, TiO_2-water, and Al_2O_3-water nanofluid at 0.5% volume fraction and standard fluid water when circulated along the six-flow micro-channel of the heat sink. The parameters like temperature variation, convective heat transfer coefficient, Nusselt number and thermal resistance are used to evaluate the micro-channel heat sink and cooling fluid performance.

Temperature Distributions

The variation of base temperature of microprocessor chip versus flow velocity ranging from 0.02 m/s–0.1 m/s at 0.50% volume fraction of nanofluid is shown in Figure 7. The main aspiration of this study is to reduce the operating temperature of the microprocessor chip by using the modern cooling technique. It is clear from the figure that using nanofluid as a cooling fluid in the six flow micro-channels of heat sink a remarkable drop in the temperature is obtained, thus keeping the microprocessor chip within the safe operating temperature range, this is achieved by dumping the high amount of heat energy generated into the cooling fluid. The maximum drop in temperature obtained is 5.2 K when Ag-water nanofluid is utilized as a cooling fluid at a flow velocity of 0.02 m/s. Also, with increasing flow velocity, the operating temperature reduces, this is because the effect of forced convection increases rapidly which in turn intensify the dissipation of heat into the fluid.

Convective Heat Transfer Coefficient

The variation of coefficient of heat transfer versus flow velocity ranging from 0.02 m/s–0.1 m/s at 0.50% volume fraction of nanofluid is shown in Figure 8. Addition of nano-scaled particles in standard fluid water circulating through the six flow micro-channels of the heat sink has convected away a large amount of thermal energy conducted by heat sink from the microprocessor chip. This increased rate of convection from the heat sink thus increases the heat transfer coefficient of nanofluid relative to standard fluid water when used in flow micro-channels as a cooling fluid. This is particularly because of an increase in nanofluid thermal conductivity in comparison to standard fluid water, as a result, the heat transfer coefficient is amplified. It can be seen from Figure 8 that the coefficient of heat transfer is enhanced with an increment in the velocity of flow. This means a high flow velocity can convect away more heat energy from the heat sink. The coefficient of heat transfer of Al_2O_3-H_2O and TiO_2-water cooling fluid is nearly the same. The heat transfer is more in the case of Ag-water nanofluid.

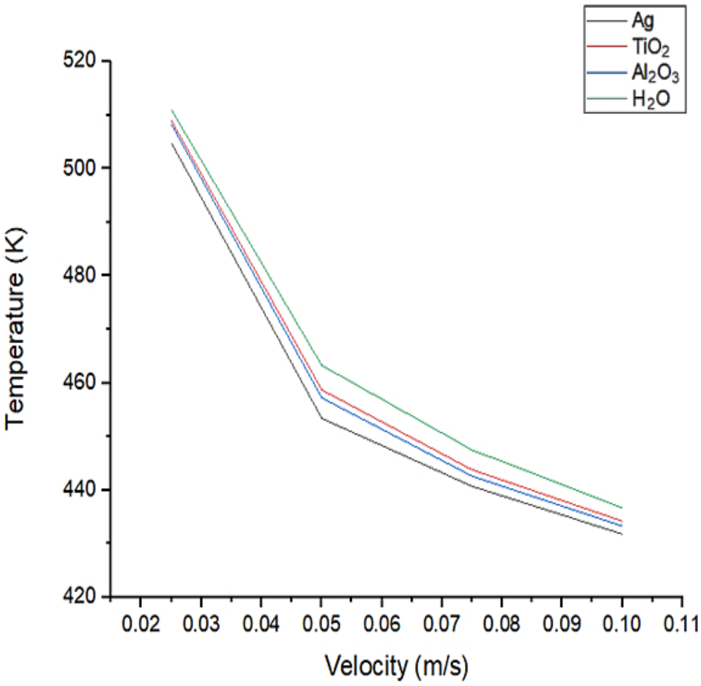


Figure 7. Base temperature of microprocessor chip versus flow velocity.

Nusselt Number

The variation of Nusselt number versus flow velocity ranging from 0.02 m/s–0.1 m/s at 0.50% volume fraction of nanofluid is shown in Figure 9. The Nusselt number of nanofluid is higher than standard fluid water, this is because of the higher value of the coefficient of heat transfer of nanofluid relative to standard fluid water. The Nusselt number is higher for Ag-H_2O nanofluid compares to TiO_2-H_2O and Al_2O_3-H_2O nanofluid. Nusselt number is highest at a flow velocity of 0.1 m/s and minimum at a flow velocity of 0.02 m/s. It can be inferred that Nusselt number intensify with an increase in flow velocity, which means a high flow velocity can enhance the heat conveying the power of cooling fluid.

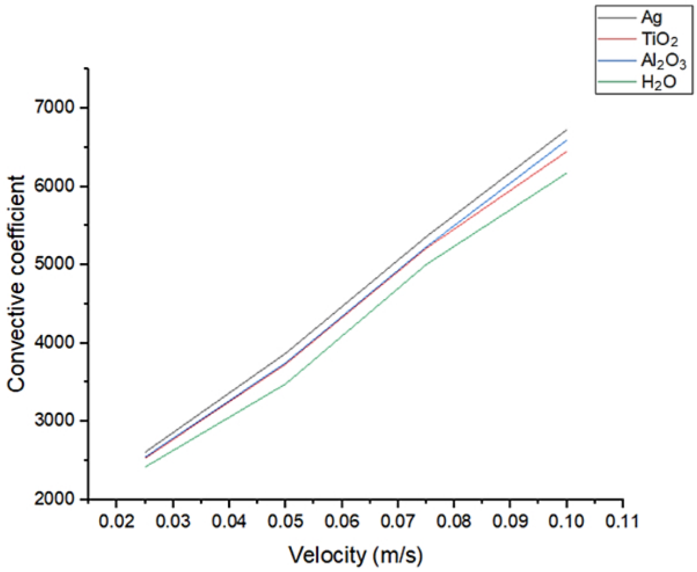


Figure 8. Heat transfer coefficient versus flow velocity.

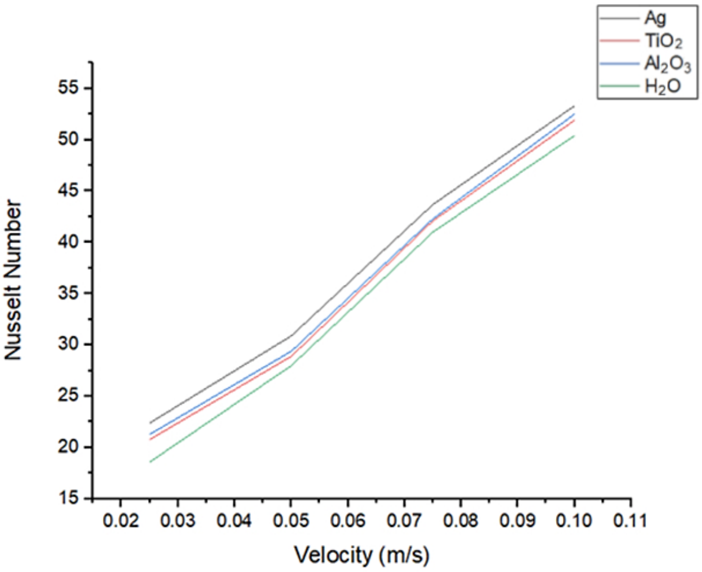


Figure 9. Nusselt Number versus flow velocity.

Thermal Resistance

The variation of thermal resistance of heat sink versus flow velocity ranging from 0.02 m/s–0.1 m/s at 0.50% volume fraction of nanofluid is shown in Figure 10. Thermal resistance is low when nanofluid relative to standard fluid water is used as a cooling fluid, hence it is easier to expel the heat energy away from heat sink when nanofluid is employed relative to water. From Figure 10, it can be noticed that the thermal resistance is lowest for Ag-H_2O nanofluid at a flow at a velocity of 0.1 m/s.

CONCLUSIONS

Following conclusions are drawn from the numerical study:

- Ag-water cooling fluid has better heat transfer coefficient value of 6727 W/m^2K than the standard fluid and slightly over the TiO_2-water 6448 W/m^2K and Al_2O_3-water 6593 W/m^2K at 0.1 m/s. The percentage increase is 8.919% relative to water for Ag-water nanofluid.
- The temperature of the microprocessor chip is at its minimum while using Ag-water, measuring 431 K, compared to the normal fluid water which has a temperature of 436.7 K at a velocity of 0.1m/s.
- Absolute thermal resistance observed lowest for the Ag-water (0.1897 K/W).

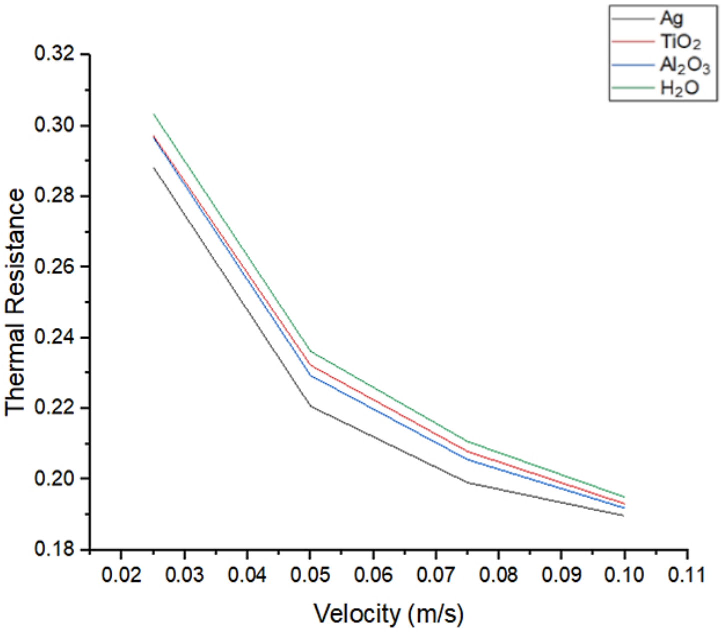


Figure 10. Thermal resistance of heat sink versus flow velocity.

The numerical findings indicate that incorporating nano-scaled Ag particles into the standard fluid has an impact on the exercise, increases the heat entraining potential of cooling fluid circulating in flow micro-channels, hence it is preferable for overall enhancement in heat transfer.

Acknowledgments

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REFERENCES

1. Kim K, Won M, Kim J, Back B. Heat pipe cooling technology for desktop PC CPU. Appl Therm Eng. 2003;23:1137–1144. doi: 10.1016/S1359-4311(03)00044-9.
2. Wang Y, Vafai K. An experimental investigation of the thermal performance of an asymmetrical flat plate heat pipe. Int J Heat Mass Transfer. 2000;43:2657–2668. doi: 10.1016/S0017-9310(99)00300-2.
3. Zhao Z, Avedisian C. Enhancing forced air convection heat transfer from an array of parallel plate fins using a heat pipe. Int J Heat Mass Transfer. 1997;40:3135–3147. doi: 10.1016/S0017-9310(96)00348-1.
4. Lin S, Sefiane K, Christy J. Prospects of confined flow boiling in thermal management of

microsystems. Appl Therm Eng. 2002;22:825–837. doi: 10.1016/S1359-4311(01)00124-7.

5. Honda H, Wei J. Enhanced boiling heat transfer from electronic components by use of surface microstructure. Exp Therm Fluid Sci. 2001;28:159–169. doi: 10.1016/S0894-1777(03)00035-9.
6. Arik M, Bar-Cohen A. Pool boiling of perfluorocarbon mixtures on silicon surfaces. Int J Heat Mass Transfer. 2010;53:5596–5604. doi: 10.1016/j.ijheatmasstransfer.2010.06.034.
7. Das S, Choi S, Patel H. Heat transfer in nanofluids – a review. Heat Transfer Eng. 2006;27:3–19. doi: 10.1080/01457630600904593.
8. Choi S, Eastman J. Enhancing thermal conductivity of fluids with nanoparticles. Journal of heat transfer. 1995.
9. Duangthongsuk W, Wongwises S. An experimental study on the thermal and hydraulic performances of nanofluids flow in a miniature circular pin fin heat sink. Exp Thermal Fluid Sci. 2015;66:28–35. doi: 10.1016/j.expthermflusci.2015.02.008.
10. Ijam A, Saidur R. Nanofluid as a coolant for electronic devices (cooling of electronic devices). Appl Therm Eng. 2012;32:76–82. doi: 10.1016/j.applthermaleng.2011.08.032.
11. Ijam A, Saidur R, Ganesan P. Cooling of minichannel heat sink using nanofluids. Int Commun Heat Mass Transfer. 2012;39:1188–1194. doi: 10.1016/j.icheatmasstransfer.2012.06.022.
12. Ghasemi SE, Ranjbar A, Hosseini M. Numerical study on effect of CuO-water nanofluid on cooling performance of two different cross-sectional heat sinks. Adv Powder Technol. 2017;28:1495–1504. doi: 10.1016/j.apt.2017.03.019.
13. Chamkha A, Molana M, Rahnama A, Ghadami F. On the nanofluids applications in microchannels: a comprehensive review. Powder Technol. 2018;332:287-322. doi: 10.1016/j.powtec.2018.03.044.
14. Bhattacharya P, Samanta A, Chakraborty S. Numerical study of conjugate heat transfer in rectangular microchannel heat sink with Al2O3/H2O nanofluid. Heat mass transfer. 2009;45:1323–1333. doi: 10.1007/s00231-009-0510-0.
15. Ghasemi SE, Ranjbar A, Hosseini M. Thermal and hydrodynamic characteristics of water-based suspensions of Al2O3 nanoparticles in a novel minichannel heat sink. J Mol Liq. 2017;230:550–556. doi: 10.1016/j.molliq.2017.01.070.
16. Ghasemi S, Ranjbar A, Hosseini M. Experimental and numerical investigation of circular minichannel heat sinks with various hydraulic diameter for electronic cooling application. Microelectron Reliab. 2017;73:97–105. doi: 10.1016/j.microrel.2017.04.028.
17. Kumar PM, Kumar CA. Numerical study on heat transfer performance using Al2O3/water nanofluids in six circular channel heat sink for electronic chip. Materials today:proceedings. 2019;21:194–201. doi: 10.1016/j.matpr.2019.04.220.
18. Jang S, Choi S. Cooling performance of a microchannel heat sink with nanofluids. Appl Therm Eng. 2006;26:2457–2463. doi: 10.1016/j.applthermaleng.2006.02.036.
19. Nebbati R, Kadja M. Study of forced convection of a nanofluid used as a heat carrier in a microchannel heat sink. Energy Procedia. 2015;74:633-642. doi: 10.1016/j.egypro.2015.07.799.
20. Seyed GE, Ali RA. Thermal efficiency evaluation of solar rings in tubes. Eur Phys J. 2016;131:1–13. doi: 10.1140/epjp/i2016-16430-x.
21. Ghasemi SE, Ali RA. Numerical thermal study on effect of porous rings on performance of solar parabolic trough collector. Appl Therm Eng. 2017;118:807–816. doi: 10.1016/j.applthermaleng.2017.03.021.
22. Mohammed H, Gunnasegaran P. The impact of various nanofluid types on triangular microchannels heat sink cooling performance. Int Commun Heat Mass Transfer. 2011;38:767–773. doi: 10.1016/j.icheatmasstransfer.2011.03.024.
23. Al-Rashed MH, Dzido G, Korpys M, Smolka J, Wojcik J. Investigation on the CPU nanofluid cooling. Microelectron Reliab. 2016;63:159–165. doi: 10.1016/j.microrel.2016.06.016.
24. Maganti L, Dhar P, Sundararajan T, Das SK. Heat spreader with parallel microchannel configurations employing nanofluids for near-active cooling of MEMS. Int J Heat Mass Transfer. 2017;111:570–581. doi: 10.1016/j.ijheatmasstransfer.2017.04.032.