Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Heat Transfer Analysis in Microchannel Heatsink by using Different Nanoparticle Concentration of h-BN

Muhammad Ashraf Abd Halim[1,*], Nor Azwadi Che Sidik[1], Kamyar Shameli[2]

[1] Department of Mechanical Precision Engineering, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia
[2] School of Medicine, Institute of Virology, Technical University of Munich, 81675 Munich, Germany

ARTICLE INFO

Article history:
Received 29 August 2021
Received in revised form 4 December 2021
Accepted 19 December 2021
Available online 27 December 2021

Keywords:
Microchannel; nanoparticle; nanofluids; hexagonal boron nitride

ABSTRACT

In this study, performance of microchannel heat sink using nanofluid as coolant was addressed. In the recent years, nanoparticles are used in basic research and technological applications due to their improved physical and thermal properties compared to their bulk counter-parts. Nanofluids are consisted of nanoparticles which ranged from 1 to 100 nm in size, suspended in the base fluid. In this work, h-BN nanofluid was synthesized, with water as their base fluid with different concentrations to improve the thermal efficiency of the cooling fluid. Heat transfer rate was high when nanofluids were used as coolant than the base fluids like water. A microchannel made of copper and nanofluid by mixture of hexagonal boron nitride (h-BN) and water as base fluid were used as a coolant. The h-BN particle volume fraction was in the range of 0.0001 % to 0.001 %.

1. Introduction

Microchannels have become very popular in application where very high heat transfer rates were necessary. Its development trend as electronic equipment become more advanced and smaller in size with continuing innovations. It faces thermal engineering challenges from high level of heat generation and the reduction of available surface area for heat removal. In the absence of sufficient heat removal, the working temperature of this component may exceed a desired temperature level which then increases the critical failure rate of the equipment. Therefore, an advanced electronic equipment with high heat generation is required as an efficient and compact device to provide proper cooling operation [1,17,18]. In order to meet the cooling requirement, the need to increase the product of heat transfer coefficient (h) and heat transfer surface area (A) for a device is of focus, since the heat transfer coefficient is related to the channel hydraulic diameter [2]. The heat transfer surface area can be increased by incorporating microchannels on the device surface.

Microchannel heat transfer has the potential of cooling high power density microchips. These chips have machined microchannels through which cooling fluid like water is circulated. The cooling

* *Corresponding author.*
E-mail address: azwadi@semarakilmu.com.my

liquid removes heat by single phase forced convection. Flow within the microchannel is considered as a fully developed laminar flow with constant heat flux. Therefore, heat sinks with larger surface area with highly conductive material and more coolant flow are key parameters to reduce the base temperature [3].

Nanofluids are relatively a new class of engineered liquids comprised of nanoparticles dispersed within base fluids. Nanofluids have better thermophysical properties compared to their base fluids.

2. Literature Review

Tuckerman and Pease [1] (Figure 1) first suggested the use of microchannels for high heat flux removal, which employed the direct circulation of water under laminar condition through microchannels heat sinks fabricated in silicon wafer. This heat sink is simply a substrate with numerous small channels and fins are arranged in parallel such that heat is efficiently carried from substrate to coolant. They managed to produce large aspect ratio heat sink with channel width in the order of 50 µm. Heat flux as high as 790 W/cm^2 was achieved with the chip temperature maintained below 110°C.

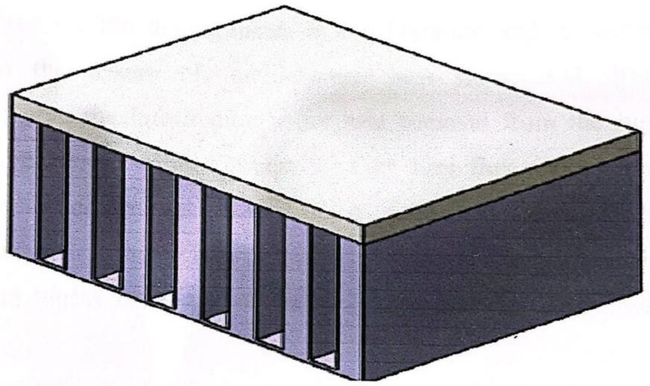

Fig. 1. The design proposed by Tuckerman and Pease [1]

Hassan *et al*. [2] gave the information about microchannel, which are used in computers for cooling of high powered IC's. The heat generated by the electronic component is transferred to the coolant by forced convection. Laminar flow is the best for heat removal through microchannel, due to the development of the thin thermal boundary layer. Hong and Cheng [4] analysed the fluid flow characteristic and heat transfer in offset strip-fin microchannel heat sinks at different size of strip-fin for electronic cooling purpose as in Figure 2. They successfully demonstrated the breakup of boundary layer and enhancement of heat transfer using the proposed design.

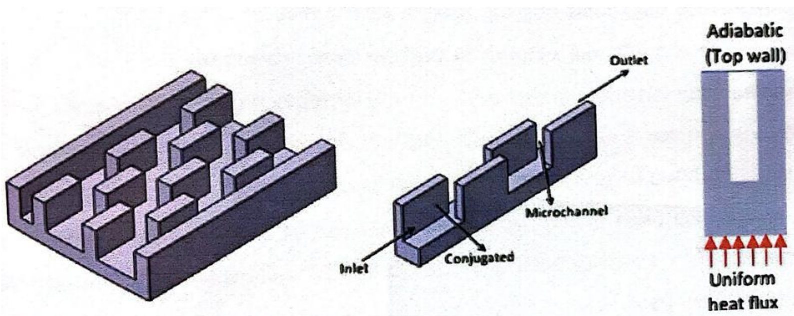

Fig. 2. The design that has been proposed by Hong and Cheng [4]

Sobhan and Garimella [5] indicated that before predictions of flow and heat transfer rates in microchannel can be made with confidence, careful experiments were needed to resolve the discrepancies in the literature and to provide practical information on the design of microchannel heat sinks. Kandlikar and Grande [6] highlighted about heat removal from the high heat flux devices also gave flow boiling concept for high heat flux cooling applications in minichannel and microchannels. Flow boiling was superior to single-phase liquid cooling from two main considerations, namely a high heat-transfer coefficient during flow boiling and higher heat removal capability for a given mass-flow rate of the coolant.

Poh-Seng Lee *et al*. [7] discussed the experimental results of rectangular microchannel and considered a microchannel width from 194 - 534 µm, with the channel depth being nominally five times the width in each case. Each test piece was made of copper and contained 10 microchannels in parallel. The experiments were conducted with deionized water with the Reynolds number ranging from approximately 300 - 3500.

2.1 Preparation of Nanofluid

Nanofluids are moderately new class of designed fluids containing nanoparticles scattered inside base liquids. Because of their capability to increase rate of heat transfer, nanofluids has been a great intrigued since their presentation by Choi [8]. The most frequently applied method to prepare nanofluid is the two-step method. Despite this method enables relatively easy steps in industrial implementation and mass production because of nanoparticles have high surface energy and their difficulty in dispersion, the agglomerations are formed leading to stability problems. Extra treatments are applied to these suspensions to prevent rapid coagulation and sedimentation of nanoparticles. To obtain well dispersed solutions, methods such as ultrasonic vibration, pH control and surfactant additives have been used to prepare the nanofluids [9].

Since the scattering quality is very subjective to the nature of nanoparticles and their respective interaction with the base liquid, a blend of such treatments can be executed at the production process. The stability level can be defined based on different measurements such as observing the change in mean aggregate size, zeta potential or transport properties along time. Numerous research groups have studied that thermal conductivity enhancement of nanofluids is beyond the expectations by effective medium theories and there is a high dependency on particle loading, particles size, shape and temperature. There are various mechanisms that might explain this behaviour, such as Brownian motion of nanoparticles within the fluid, percolation theory and the nano-layer structures [10]. While such an increase in thermal conductivity enhances heat transfer capacity by using nanofluids, similar increase observed for viscosity might limit it in cases where flow velocity is reduced. In the literature, it has been observed that different researchers have observed different conduct in terms of viscosity and thermal conductivity increase with different base fluids and nanoparticle additives [11].

Boron nitride (BN) has similar lattice structure to carbon and hexagonal form of BN, hBN, and is similar to graphite. With its high chemical stability and thermal conductivity, it is a very suitable candidate material for nanofluids. BN nanofluids have been introduced recently, however there are limited studies focusing on hBN nanofluids in the literatures [12,13].

2.2 Analytical Modelling
2.2.1 Microchannel heat sink (MCHS) model

Based on Figure 3, the top surface is assumed to be insulated. Thermal resistance is measured to configure the rate of heat transfer.

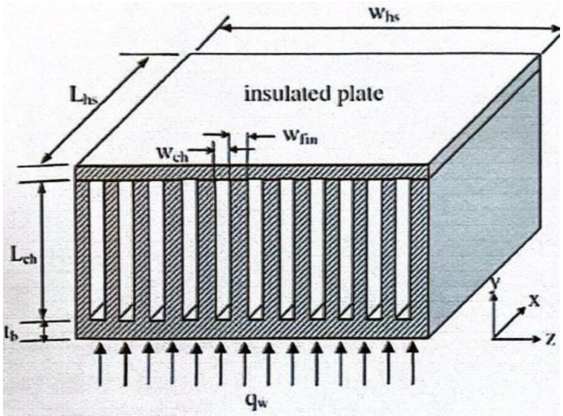

Fig. 3. Schematic diagram of MCHS (Geometric configuration)

Based on the theoretical analysis [14], it can be expressed as,

$$R_{th} = \frac{T_{w,\max} - T_{f,in}}{Q/(W_{hs}L_{hs})} = R_{fin} + R_{cap} + R_{con} = \frac{1}{Nuk_f}\frac{1+\beta}{1+2\alpha\eta}\frac{2\alpha}{1+\alpha}W_{ch} + \frac{L_{hs}}{C_{pf}\mu_f}\frac{2}{\mathrm{Re}}\frac{1+\beta}{1+\alpha} + \frac{t_b}{k_s} \tag{1}$$

α, β, η and Re are defined as,

$$\alpha = \frac{L_{ch}}{W_{ch}}, \beta = \frac{W_{fin}}{W_{ch}}, \eta = \frac{\tanh(m\alpha)}{m\alpha}, \mathrm{Re} = \frac{\rho_f u_m . D_h}{\mu_f} \tag{2}$$

In Eq. (2), m, μ_m and D_h are defined as,

$$m = \sqrt{Nu\frac{1+\alpha}{\alpha\beta}\frac{k_f}{k_s}}, \; u_m = \frac{\dot{V}}{NW_{ch}L_{ch}}, \; D_h = \frac{2W_{ch}L_{ch}}{(W_{ch}+L_{ch})} \tag{3}$$

N in Eq. (3) is given as,

$$N = \frac{W_{hs} - W_{fin}}{W_{ch} + W_{fin}} \tag{4}$$

A pumping power supply was required to drive the coolant in MCHS operation. It is the product of the pressure drop across the microchannel heat sink, Δ_P and volume flow rate. In Eq. (5), the pressure dropped at the channel inlet and exit were neglected because they were usually small compared to that in the microchannel. From Eq. (1) and Eq. (5), N_u and μ are two important parameters for MCHS performance in addition to the microchannel geometry. Both N_u and μ depend on the flow regime and type of coolant used. Assuming laminar and fully developed flow in the microchannel, λ correlation for pure fluid was given as Eq. (5), and for λ in turbulent flow and in macro scales,

$$Pow = \dot{V} \cdot \Delta p = \dot{V}\left(\lambda \frac{L_{hs}}{D_h} \rho_f \frac{u_m^2}{2}\right) \quad (5)$$

2.2.2 Nusselt number and friction coefficient models

Since there was no correlation for turbulent flow in micro scale, we used the macro scale correlation Eq. (7) for turbulent flow. As pointed out by Xuan and Roetzel [15], two approaches can be used to predict the heat transfer of nanofluids.

$$Re = 4(4.7 + 19.64G) \qquad G = \frac{\left(\frac{1}{\alpha}\right)^2 + 1}{\left(\frac{1}{\alpha} + 1\right)^2} \quad (6)$$

$$\lambda = \frac{0.3164}{\mathrm{Re}^{0.25}} \quad (7)$$

The first approach is the conventional model that treats the nanofluid as a single-phase fluid. The heat transfer and friction coefficients were the same as those for pure fluid except that the nanofluid transport properties must be used. That is,

$$Nu = \frac{hD_h}{k_{nf}},\ \mathrm{Re}_{nf} = \frac{u_m \cdot D_h}{\upsilon_{nf}} \quad (8)$$

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_f + \phi(\rho c_p)_p \quad (9)$$

$$\mu_{nf} = \mu_f \frac{1}{(1-\phi)^{2.5}} \quad (10)$$

$$k_{nf} = k_f \frac{k_p + (SH-1)k_f - (SH-1)\phi(k_f - k_p)}{k_p + (SH-1)k_f + \phi(k_f - k_p)} \quad (11)$$

In the study by Xuan and Li [16], two formulae proposed to correlate the experimental data for nanofluid heat transfer coefficient (Nusselt number) in laminar and turbulent circular tube flow are given as,

$$Nu_{nf} = 0.4328\left(1.0 + 11.285\phi^{0.754} Pe_d^{0.218}\right)\mathrm{Re}_{nf}^{0.333}\ \mathrm{Pr}_{nf}^{0.4} \quad (12)$$

3. Methodology

This section focussed on the methodology or the process that were involved throughout this experiment. This section (Figure 4) provides detail, clear and understandable statements describing every step that was taken in carrying out this experiment.

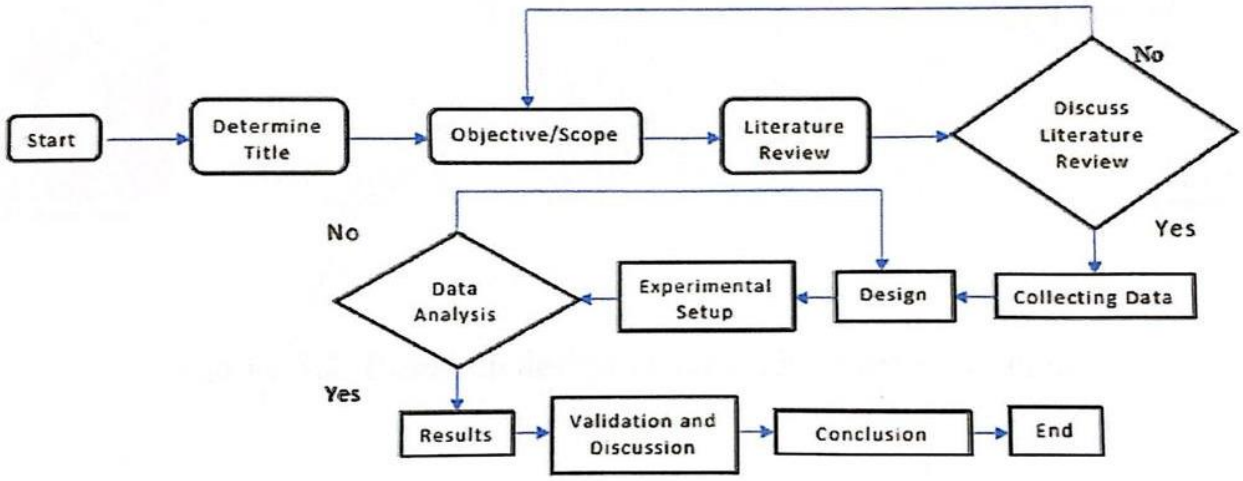

Fig. 4. Flowchart of research

3.1 Experimental Setup of MCHS

Nanofluid from the inlet tank was sucked with the help of digital pump. The water flow rate was fixed at 40 ml/min for all concentration of nanofluids that were prepared. A manifold made from acrylic material for holding the heat sink securely in place and it's have transparency for good aesthetic view. The cover plate on the heat sink top surface formed closed microchannels. A silicon sealant in the housing maintained a leak proof seal. Inlet plenum was manufactured in such a way that the air should be removed from the manifold during the flow. For getting the temperature readings at different location, thermocouples (K Type) were mounted at inlet plenum, outlet plenum, heater surface and substrate.

For finding the pressure drop across the microchannel, two pressure ports were provided. One port is in inlet plenum and another is at outlet plenum. The pressure drop across the microchannel was measured using software with a high speed USB output pressure transducer. Power supply was used to control the temperature of heater under the microchannel. Thermocouples that has been installed was used to read the temperature at different points around the microchannel. Nanofluid that passes through the microchannel will flow out to the outlet tank.

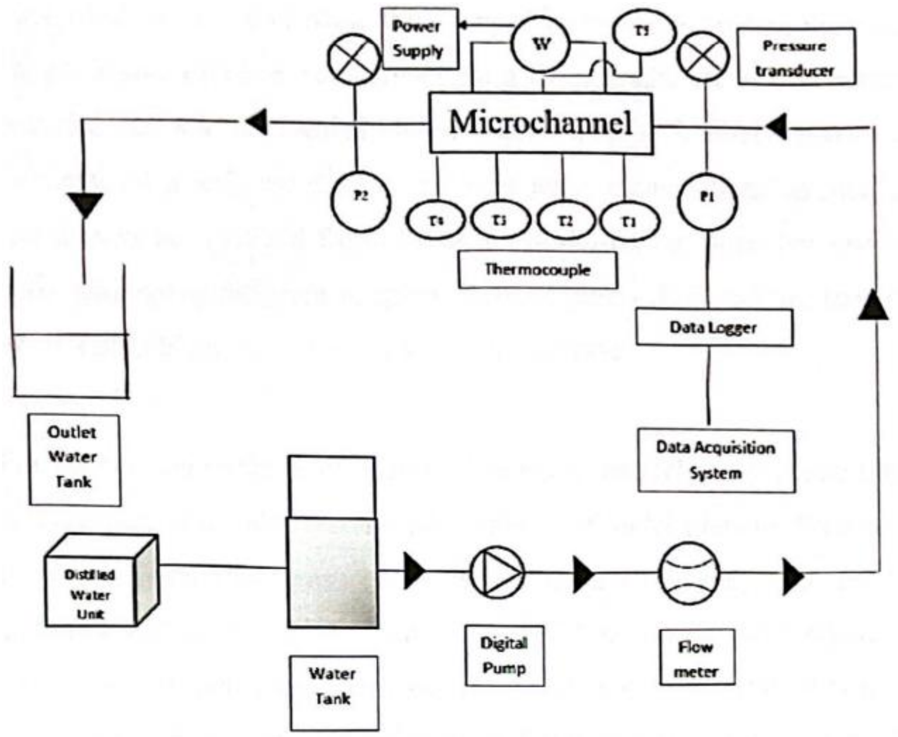

Fig. 5. Schematic diagram of experiment setup

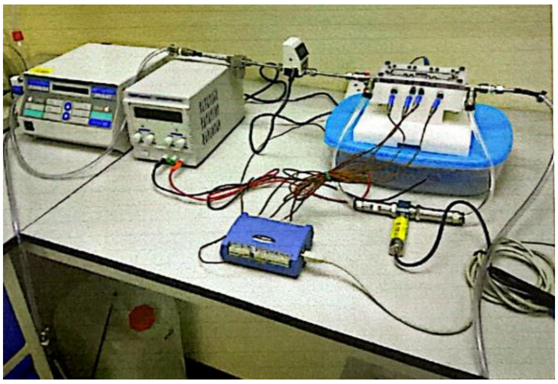

Fig. 6. Experiment setup to test the heat transfer in microchannels

3.2 Apparatuses

Figure 7 shows the Omega FPUS-MT peristaltic pump motor. This pump was used to pump the nanofluid from inlet tank to the microchannel. The volume flow rate was set at 40 ml/min.

Fig. 7. Omega FPU5-MT peristaltic pump

Based on Figure 8, the regulated DC power supply was applied to control the temperature of the heater under the microchannel. The voltage was set at 31.1 V and the current at 0.529 A.

Fig. 8. Regulated DC power supply

Figure 9 shows the thermocouples that have been installed around the microchannel. T1 and T4 in the figure shows the thermocouples used to read the inlet and outlet water temperature. Thermocouples T2 and T3 read the channel inlet and channel outlet temperature while the thermocouple at the top of the channel recorded the temperature at the middle of the channel. Pl is the inlet pressure and P2 is the outlet pressure which was then used to calculate the pressure drop.

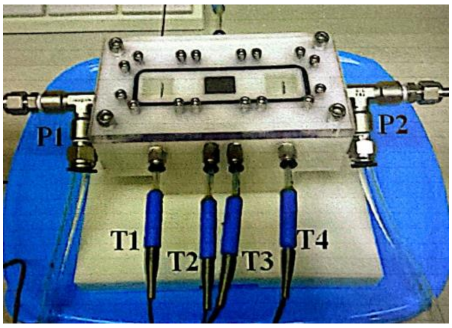

Fig. 9. Thermocouples

Data logger as shown in Figure 10 was used to record the temperature reading of the thermocouples. The thermocouples were connected to the data logger to record the temperature.

Fig. 10. Data logger

3.3 Preparation of Nanofluid

Nanofluid was prepared by mixing the selected nanoparticles with the selected base fluid. In this case, the nanoparticle was hexagonal boron nitrite (h-BN) and water as the base fluid. Amount of the nanoparticles required to form the specific volume concentration was calculated earlier before preparation. The formula is as shown below in Eq. (13).

$$m_{np} = \frac{\rho_{np} \times C \times V_{bf}}{100 - C} \tag{13}$$

High precision laboratory balance was used to measure the needed amount of nanoparticle to form nanofluid. Then the nanoparticle was added to 1.5 litres of water to form the different volume concentrations respectively. These solutions were stirred using mechanical stirrer for 30 mins at 310 rpm. To maintain the stability of the solution, they were sonicated using ultrasonic homogeniser for another 30 mins. Table 1 shows the thermophysical properties that have been calculated for water, nanoparticle and also different volume concentration of nanofluid. Table 2 however, lists the thermophysical properties of nanoparticle, base fluid and nanofluid.

Table 1
Mass of nanoparticle to prepare nanofluid

Vol. fraction (%)	Vol. of base fluid (g)	Density of nanoparticle (kg/m3)	Vol. of nanoparticle	Mass of nanoparticle (g)
0	0.0015	2290	0	0
0.0001	0.0015	2290	1.50015E-07	0.3435
0.00025	0.0015	2290	3.75094E-07	0.8590
0.0005	0.0015	2290	7.50375E-07	1.7184
0.00075	0.0015	2290	1.12584E-06	2.5782
0.001	0.0015	2290	1.5015E-06	3.4384

Table 2
Thermophysical properties of nanoparticle, base fluid and nanofluid

	Density (kg/m^3)	Thermal Conductivity k(W/m.K)	Viscosity (Pa.s)	Specific heat capacity Cp (J/kg.K)
Water	997	0.608	0.00089	4.186
0.0001	997.001293	0.6081824	0.0008990223	4.1860
0.00025	997.0032325	0.608456	0.000890556	4.1860
0.0005	997.006465	0.608912	0.000891113	4.1862
0.00075	997.0096975	0.609368	0.000891669	4.1863
0.001	997.01293	0.609824	0.000892225	4.1864

The formula to calculate the thermophysical properties of nanofluid are as shown below,

Thermal conductivity,

$$k_{nf} = k_f \frac{k_p + (SH-1)k_f - (SH-1)\phi(k_f - k_p)}{k_p + (SH-1)k_f + \phi(k_f - k_p)} \tag{14}$$

Viscosity,

$$\mu_{nf} = \mu_f \frac{1}{(1-\phi)^{2.5}} \tag{15}$$

Thermal capacity,

$$(\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_p \tag{16}$$

3.4 Apparatuses to Prepare Nanofluid

Figure 11 Ultrasonic homogeniser was used for 30 mins for every 1.5 litres solution to maintain the stability of the nanofluid.

Fig. 11. Ultrasonic homogeniser

4. Results and discussions

The results from the experiment were recorded and have been calculated based on their Nusselt number, performance factor and also average pressure drop. Hence, the graphs were plotted for Nusselt number against volume fraction, performance factor against volume fraction and also average pressure drop against volume fraction.

4.1 Nusselt Number

Based on Table 3 and Figure 14, the Nusselt number had the highest reading at the volume fraction 0.0001 % and decreased slightly as the volume fraction increased. This shows that efficiency of heat transfer is the best during the volume fraction 0.0001 % based on the experimental study.

Table 3
Result of Nusselt number

Volume fraction (%)	Nusselt number
0	1664.98
0.0001	2080.6
0.00025	1848.59
0.0005	1511.35
0.00075	1510.22
0.001	1383.33

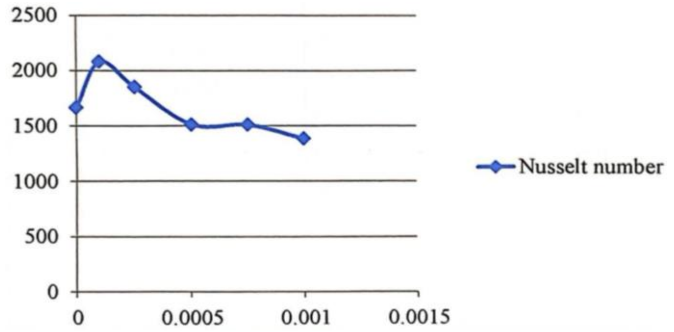

Fig. 14. Graph of Nusselt number against volume fraction

4.2 Average Pressure Drop

Pressure drop from the entire experiment was recorded using the USB pressure transducer. The pressure readings were obtained in Excel spreadsheets. The average pressure reading was calculated as follow in Table 4 below. Based on Figure 12, the average pressure drop was the highest at the 0 % volume fraction and had the lowest pressure drop at the volume fraction 0.0005 %. From the experimental result, it indicated that the pressure drop was low using nanofluid compared to base fluid which was water. However, the pressure drop at the highest volume fraction was high. This was due to particle deposition that increased the wall roughness.

Table 4
Result of average pressure drop

Volume fraction (%)	Pressure drop
0	40.51
0.0001	21.97
0.00025	29.71
0.0005	15.16
0.00075	27.03
0.001	33.34

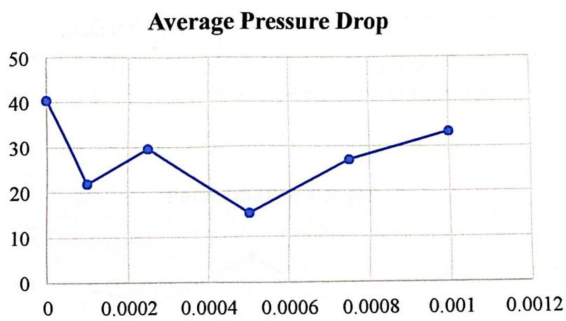

Fig. 12. Graph of pressure drop against volume fraction

4.3 Performance Factor

Performance factor in heat transfer is the ratio of the change in the heat transfer rate to change in friction factor. Based on Table 5 and the graph in Figure 13, the performance factor had the highest value for nanofluid compared to base fluid. This showed that the performance in heat transfer in nanofluid was better compared to base fluid. However, all the performance factor was above the value 1 which indicates that it had a high Nusselt number. High Nusselt number indicate that it has better efficiency in heat transfer.

Table 5
Results of performance factor

Volume fraction (%)	Performance factor
0	1
0.0001	1.490562
0.00025	1.355354
0.0005	1.77612
0.00075	1.247437
0.001	1.120486

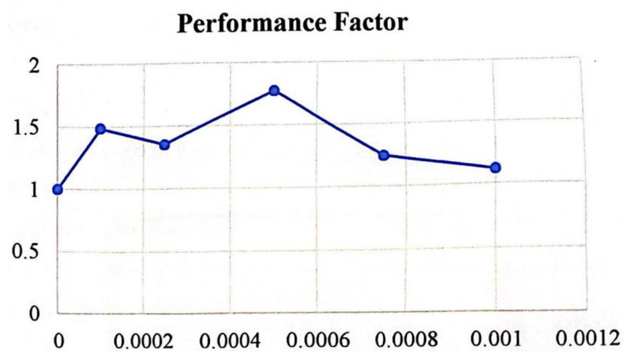

Fig. 13. Graph of performance factor against volume fraction

5. Conclusions

The performances of MCHS utilizing nanofluids as coolants were studied. A theoretical prediction had been carried out followed by an experimental analyses. Theoretical predictions have indicated that microchannel heat sink that has been cooled out using nanofluid can absorb more heat compared to microchannel that were cooled out using base fluid like water.

By conducting the experiment, it showed that nanofluid have a better performance factor in the term of efficiency to absorb heat compared to base fluid. However, the Nusselt number from experimental analyses showed a higher value for base fluid compared to nanofluid. This differed from the theoretical prediction. Experimental analyses might have some errors caused by the surrounding and also errors in conducting the experiment.

Acknowledgement

The authors would like to thank Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia for the support given in conducting the research.

References

[1] Tuckerman, David B., and Roger Fabian W. Pease. "High-performance heat sinking for VLSI." *IEEE Electron device letters* 2, no. 5 (1981): 126-129. https://doi.org/10.1109/EDL.1981.25367

[2] Hassan, I., P. Phutthavong, and M1 Abdelgawad. "Microchannel heat sinks: an overview of the state-of-the-art." *Microscale thermophysical engineering* 8, no. 3 (2004): 183-205. https://doi.org/10.1080/10893950490477338

[3] Kandlikar, Satish G., and William J. Grande. "Evaluation of single phase flow in microchannels for high heat flux chip cooling—thermohydraulic performance enhancement and fabrication technology." *Heat transfer engineering* 25, no. 8 (2004): 5-16. https://doi.org/10.1080/01457630490519772

[4] Hong, Fangjun, and Ping Cheng. "Three dimensional numerical analyses and optimization of offset strip-fin microchannel heat sinks." *International Communications in Heat and Mass Transfer* 36, no. 7 (2009): 651-656. https://doi.org/10.1016/j.icheatmasstransfer.2009.02.015

[5] Sobhan, Choondal B., and Suresh Garimella. "A comparative analysis of studies on heat transfer and fluid flow in microchannels." *Other Nanotechnology Publications* (2001): 17. https://doi.org/10.1080/10893950152646759

[6] Kandlikar, Satish G., and William J. Grande. "Evaluation of single phase flow in microchannels for high heat flux chip cooling—thermohydraulic performance enhancement and fabrication technology." *Heat transfer engineering* 25, no. 8 (2004): 5-16. https://doi.org/10.1080/01457630490519772

[7] Lee, Poh-Seng, Suresh V. Garimella, and Dong Liu. "Investigation of heat transfer in rectangular microchannels." *International journal of heat and mass transfer* 48, no. 9 (2005): 1688-1704. https://doi.org/10.1016/j.ijheatmasstransfer.2004.11.019

[8] Choi, S. US, and Jeffrey A. Eastman. *Enhancing thermal conductivity of fluids with nanoparticles*. No. ANL/MSD/CP-84938; CONF-951135-29. Argonne National Lab.(ANL), Argonne, IL (United States), 1995.

[9] Ghadimi, A., Rahman Saidur, and H. S. C. Metselaar. "A review of nanofluid stability properties and characterization in stationary conditions." *International journal of heat and mass transfer* 54, no. 17-18 (2011): 4051-4068. https://doi.org/10.1016/j.ijheatmasstransfer.2011.04.014

[10] Murshed, S. M. S., K. C. Leong, and C. Yang. "Thermophysical and electrokinetic properties of nanofluids–a critical review." *Applied thermal engineering* 28, no. 17-18 (2008): 2109-2125. https://doi.org/10.1016/j.applthermaleng.2008.01.005

[11] Wang, Xiang-Qi, and Arun S. Mujumdar. "Heat transfer characteristics of nanofluids: a review." *International journal of thermal sciences* 46, no. 1 (2007): 1-19. https://doi.org/10.1016/j.ijthermalsci.2006.06.010

[12] Li, Yanjiao, Jing'en Zhou, Zhifeng Luo, Simon Tung, Eric Schneider, Jiangtao Wu, and Xiaojing Li. "Investigation on two abnormal phenomena about thermal conductivity enhancement of BN/EG nanofluids." *Nanoscale research letters* 6 (2011): 1-7. https://doi.org/10.1186/1556-276X-6-443

[13] Zhi, Chunyi, Yibin Xu, Yoshio Bando, and Dmitri Golberg. "Highly thermo-conductive fluid with boron nitride nanofillers." *ACS nano* 5, no. 8 (2011): 6571-6577. https://doi.org/10.1021/nn201946x

[14] Knight, Roy W., Donald J. Hall, John S. Goodling, and Richard C. Jaeger. "Heat sink optimization with application to microchannels." *IEEE Transactions on Components, Hybrids, and Manufacturing Technology* 15, no. 5 (1992): 832-842. https://doi.org/10.1109/33.180049

[15] Xuan, Yimin, and Wilfried Roetzel. "Conceptions for heat transfer correlation of nanofluids." *International Journal of heat and Mass transfer* 43, no. 19 (2000): 3701-3707. https://doi.org/10.1016/S0017-9310(99)00369-5

[16] Xuan, Yimin, and Qiang Li. "Investigation on convective heat transfer and flow features of nanofluids." *J. Heat transfer* 125, no. 1 (2003): 151-155. https://doi.org/10.1115/1.1532008

[17] Colangelo, G., E. Favale, M. Milanese, A. De Risi, and D. Laforgia. "Cooling of electronic devices: Nanofluids contribution." *Applied Thermal Engineering* 127 (2017): 421-435.

[18] Zhang, Zhihao, Xuehui Wang, and Yuying Yan. "A review of the state-of-the-art in electronic cooling." *e-Prime-Advances in Electrical Engineering, Electronics and Energy* 1 (2021): 100009.