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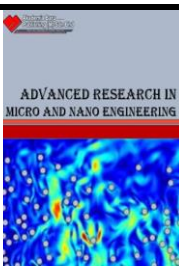

Nanofluid-Infused Microchannel Heat Sinks: Comparative Study of Al_2O_3, TiO_2, and CuO to Optimized Thermal Efficiency

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ABSTRACT

Nanofluid technology advancements have significantly improved cooling performance by utilising distributed nanoparticles, showing promise as an effective method for heat removal. These nanomaterials offer unique opportunities to cool electrical appliances. Nanofluids, akin to conventional fluids, exhibit thermophysical properties such as viscosity, specific heat, and fluid behaviour, ranging from laminar to turbulent. The thermal behavior of nanofluids is influenced not only by concentration but also by nanoparticle size, shape, material, and base fluid parameters. This study focuses on investigating the thermal behaviour and cooling efficiency within a straight single microchannel heat sink (MCHS), utilising water-based nanofluids—Al_2O_3, TiO_2, and CuO. A series of experiments were conducted on the MCHS with varying nanoparticle concentration percentages in a rectangular channel measuring 6 mm (W) x 10 mm (H) x 30 mm (L). Computational Fluid Dynamics (CFD) simulations using Fluent model the channel's behaviour, applying a heat flux of 45,000 W/m2 at the base of the aluminium microchannel heat sink. The study examines Reynolds numbers ranging between 2000 and 2300 across inlet velocities from 0.0405 m/s to 0.04658 m/s. Prior research indicates a positive correlation between higher Reynolds numbers and improved nanofluid cooling performance. The projected conclusion based on existing literature suggests that Al_2O_3, with increased particle concentration, is likely to outperform other nanofluids in terms of Reynolds number. Reported viscosities of Al_2O_3 increase as nanoparticle concentration rises. Additionally, higher Reynolds numbers correspond to greater pressure drops in the microchannel heat sink. The investigation underscores the potential of nanofluids in improving thermal conductivity and cooling performance. The concentration-dependent behaviour of Al_2O_3 and its influence on Reynolds number further support its potential superiority among other nanofluids.

Keywords:
Thermal properties; velocity; flow characteristics; nanofluid; microchannel heatsink

1. Introduction

Nanofluid innovation is a significant academic area of investigation that involves materials science, nanotechnology, and thermal engineering. Using nanofluid innovation, coolants (water,

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ethylene glycol, oil, and so on) are changed into a future group of coolants with better thermal performance. According to studies, nanofluids containing various nanomaterials have unique thermal properties than ordinary working fluids (density, specific heat, viscosity, thermal conductivity, thermal diffusivity, and so on). Nanofluids with low quantities of nanoparticles added to working fluids have a thermal conductivity of 15–40% better than base liquid in practice [1]. Nanofluids can be used in applications that need high heat fluxes and convective heat transfer.

1.1 Nanofluids as Coolants

Optimal microsystem cooling is required in modern mechanical, chemical, and biomedical engineering for excellent power and compact gadget design. Even yet, for microsystems that generate massive heat fluxes, restricting rate of heat transfer can be a serious stumbling barrier [2,3]. One solution to this problem is to use new coolants that have better thermal performance than forced air fluids like oil, water, or ethylene glycol. Adding metallic nanoparticles (NPs) to liquids at small volume fractions, for example, creates a unique fluid–particle mixture that has the potential to considerably boost heat transfer rates. As a consequence, the resultant nanofluid, which is a diffuse NP solution in liquids, is being considered as a potential solution to the microsystem chilling issue. Nanofluids containing various types of NPs, such as metal oxide particles and carbon nanotubes, were created in a variety of base fluids, including water, ethylene glycol, and oil, to evaluate their thermal characteristics and heat transfer performance under various situations. Most experimental experiments indicated increased thermal conductivities and viscosities above the base fluids, while the results were mixed. In particular, current experimental evidence suggests that nanofluid flow has improved heat transfer performance and a little higher pressure drop than the base fluid [4].

1.2 Stability of Nanofluid

Nanoparticles are usually agglomerated in powder form and are typically turned into nanoscale by dispersing them in liquids using different techniques such as sonication and homogenisation. Although nanoparticles dispersed in the fluid are separated, their high surface energy often leads to agglomeration and deposition [5,9]. Nanoparticles also have a strong tendency to migrate to the interface of different phases and therefore tend to adsorb on the solid surface they encounter in the nanoflow [6,7]. In the particular case of porous media, the adsorption of nanoparticles is a critical factor as the solid surface is abundant in such systems. The adsorption and deposition are two main limiting factors in nanoparticle applications, making the applications economically unfavourable [8,11]. This means that nanoparticles adsorption/deposition is sometimes a positive factor and therefore beneficial in specific applications. For example, in the wettability alteration process, the adsorption of nanoparticles on the solid surface helps change the wettability in a good way [10]. These retention phenomena, deposition and adsorption, can be somehow controlled by manipulating the physical and chemical properties of the liquid media, the particles, and the solid surface. As such, depending on the application, the properties can be adjusted accordingly.

1.3 Nanofluid in Heat Exchanger for Saving Energy

The Nusselt number exhibits a nearly 90% increase when compared to the Al_2O_3/water nanofluid. Gupta's research revealed that the use of hybrid nanofluid resulted in a 124 percent enhancement in the efficiency of a heat exchanger. This improvement led to a reduction in energy consumption and a decrease in the overall cost of the heat exchanger. The relationship between effectiveness and pressure drop (Dp) as a function of Reynolds number (Re) is depicted in Figure 1 and 2 [12,13].

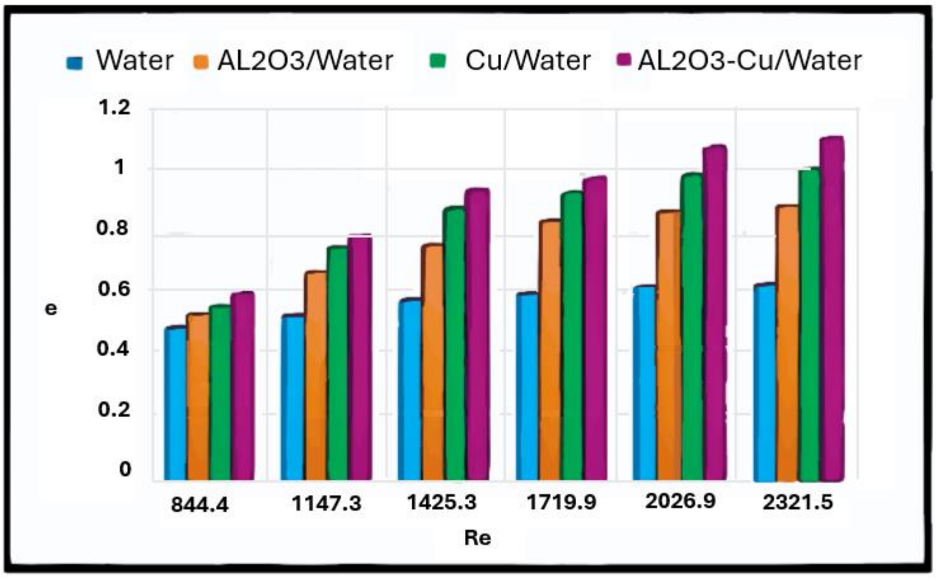

Fig. 1. Effectiveness (e) v/s Reynolds number (Re) [9]

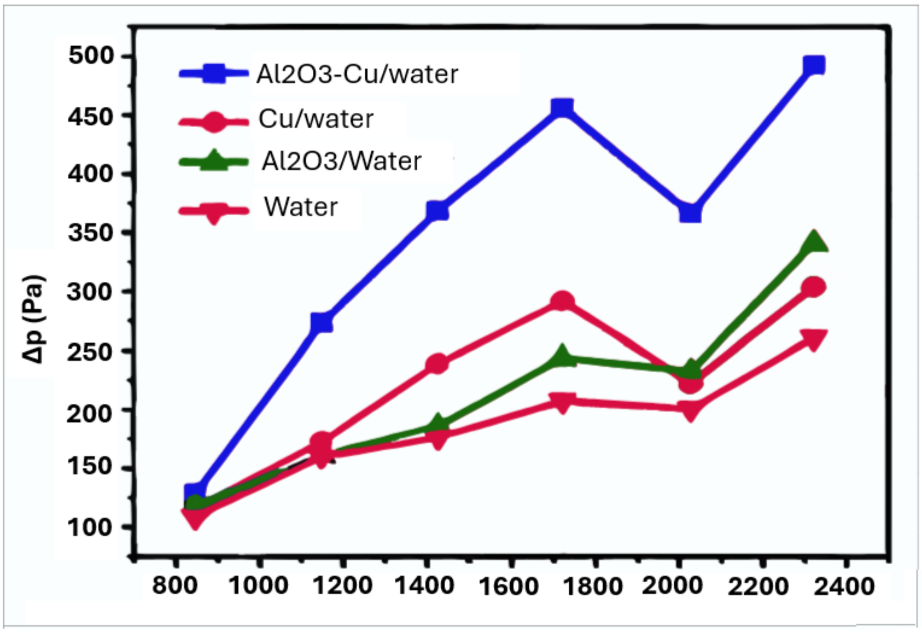

Fig. 2. Pressure drop (Dp) v/s Reynolds number (Re) [9]

1.4 Heat Transfer Coefficient (Micro-Channel Heat Sink)

The findings of the dimensionless heat transfer coefficient across the microchannel heat sink (MCHS) are displayed in Table 1, which aims to determine the thermal efficiency of using different nanofluid types in MCHS. Recent findings indicate that all types of nanofluid-cooled MCHS show enhanced heat transfer capabilities compared to fully water-cooled MCHS [14,15]. The water-based nanofluid containing silica exhibits the best heat transfer coefficient, then followed by SiO_2, CuO, TiO_2, Ag, and Al_2O_3.

Table 1
Dimensionless heat transfer coefficient across the microchannel heat sink (MCHS)

Dh (µm)	K (µm)	h (µm)	l (µm)	Lch (µm)	S (µm)	β
230	280	430	452	10000	500	36.07

1.5 CFD Simulation on Single-Microchannel Heat Sink

A computational fluid dynamics (CFD) simulation study was undertaken by [16] to investigate the pressure drop and velocity across a single flow microchannel heat sink. A channel was defined as a dimension that is smaller than 1.0 milimeter and larger than 100.0 micrometre. The simulation programme was utilised to forecast the velocity in the microchannel. Furthermore, three separate models were employed to conduct simulations in order to ascertain the fluid dynamics within the microchannel. In order to enhance heat transfer in a microchannel heat sink, it is imperative for researchers to simultaneously investigate the impacts of several factors, including channel dimensions, morphology, fluid properties, pressure gradient, and other relevant variables. The heat transfer coefficient in a microchannel is subject to variation based on factors such as the size of the channel, its cross section, geometry, fluid properties, and the flow pattern of the fluid [17,19]. Due to the absence of heat dissipation through fluid convection in a microchannel heat sink, the region of high temperature is expected to be located in close proximity to the edge of the microchannel. Due to the significant heat transfer, it is expected that the region with lower temperature will be located within the central region of the microchannel [18].

2. Materials and Methods

2.1 Material Selection

This section will provide an overview of the materials utilised in the current investigation. Aluminium and copper are the primary materials for the single microchannel heat sink (MCHS). Working base fluids and nanofluids commonly include water, Al_2O_3, TiO_2, and CuO. The criteria to be considered for material selection include thermal conductivity, density, specific heat capacity, shear modulus, Young's modulus, and bulk modulus for solid types. Liquids will be evaluated based on their thermal conductivity, density, viscosity, Nusselt number, pressure drop, and specific heat capacity. The materials utilised in this investigation and implemented in the Single-Microchannel Heat Sink (MCHS) are presented in Tables 2, 3, and 4.

Table 2
Materials utilised and implemented in the Single-Microchannel Heat Sink (MCHS)

Name	Aluminium
Material Type	Solid
Thermal Conductivity, W/mK	234
Density, kg/cm^3	2.70
Specific Heat Capacity, J/kgk	897
Shear Modulus, Gpa	26.1
Young’s Modulus, Gpa	70.3
Bulk Modulus, Gpa	75.5

Table 3
Materials utilised and implemented in the Single-Microchannel Heat Sink (MCHS)

Name	Water
Material Type	Liquid
Thermal Conductivity, W/mK	0.6
Density, g/cm^3	998.2
Specific Heat Capacity, J/kgk	4182

Table 4
Properties of Nanofluid

Material Type	Al_2O_3	TiO_2	CuO
ρ (kg/m^3)	3970	4156	6500
κ (W/m.K)	40	8.4	32.9
Cp (J/kg.K)	765	692	551
Reseacher	Adham [1]	Adham [1]	Kaushik and Panwar [12]

2.2 Microchannel Heatsink

The microchannel heatsink (MCHS) used for this study is Aluminum. For modelling, the microchannel heat sink specimen will be sketched and extruded to create a three-dimensional model using the CAD program. Figure 3 and 4 shows the dimensions of the microchannel heat sink. The Table 5 illustrated the properties of Aluminum.

Table 5
Physical properties of MCHS

Name	Alumnium
Material Type	Solid
Thermal Conductivity, W/mK	202.4
Density, kg/m^3	2719
Specific Heat Capacity, J/KgK	871

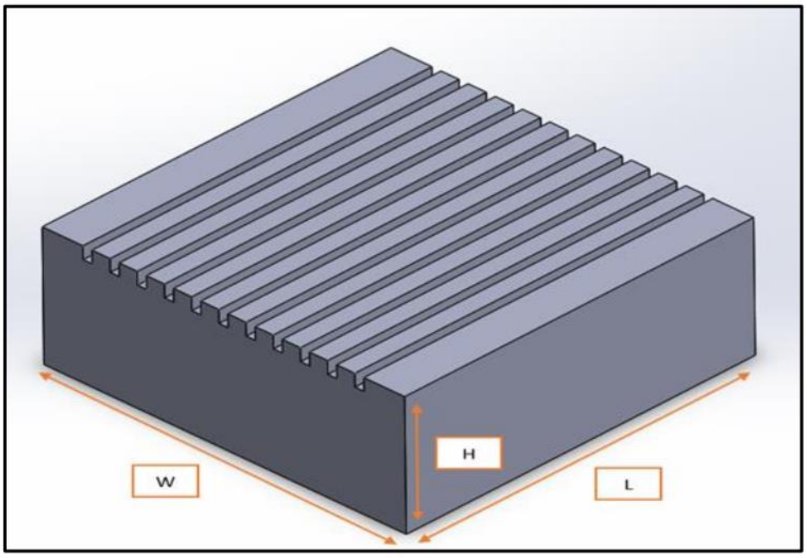

Fig. 3. Structure for full of the microchannel

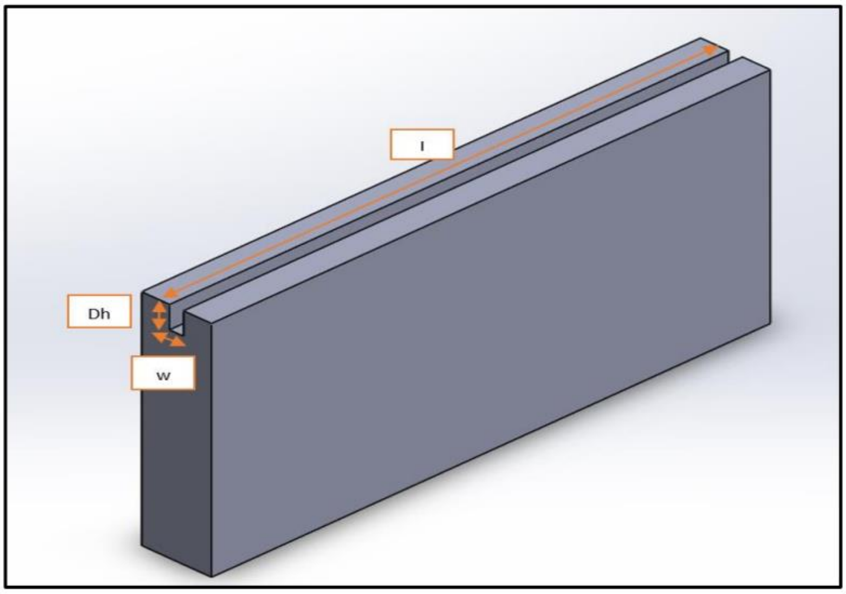

Fig. 4. Structure for single channel of the heat microchannel heat sink

2.3 Numerical Simulation and Boundary Condition

The CFD simulation of MCHS is conducted using the ANSYS Fluent programme. ANSYS Fluent is a versatile computational fluid dynamics (CFD) software that utilises finite volume (FVM) analysis on a collocated grid. The case of the mesh file is read. In order to enhance the quality of simulation, it was necessary to scale the model in order to mitigate skewness on the meshed model. This study used a 3D solver operating under steady state conditions. The simulation's boundary condition is depicted in Table 6.

Table 6
Boundary condition values

Name	Variable	Setting
Inlet	Velocitu Magnitude (m/s)	2
Heated Source	Temperature (K)	293
	Heat Fkux (W/m^2)	160000

3. Results and Discussion

3.1 Effect of using Different Nanofluids on Heat Transfer Coefficient

An analysis of the thermal performance of different nanofluids utilised in MCHS is conducted by presenting the results of the dimensionless heat transfer coefficient along the entire length of the microchannel, as indicated in Tables 7, 8 and 9. This enables an analysis of the thermal efficiency associated with the application of MCHS. Compared to MCHS cooled by pure water, various types of nanofluids-cooled MCHS have demonstrated the capacity to enhance heat transfer. The water-based nanofluid containing copper oxide shows the highest heat transfer coefficient value, followed by nanofluids containing TiO_2 and Al_2O_3 [19]. The limited difference in thermal diffusivity between TiO_2 and CuO has impeded the identification of significant distinctions between the two materials. In contrast to TiO_2-H_2O-cooled MCHS, CuO-H_2O-cooled MCHS exhibits a minor elevation, primarily observed at the channel's outflow.

Table 7
Nanofluid Thermal Properties of Al_2O_3-H_2O at 303.15 K

Volume Cons (%)	Thermal Conductivity (W/mK)	Specific Heat Capacity, Cp (J/(kg K)	Density ρ, kg/m^3	Reynold Number, Re	Viscosity, η (Pa.s)
1	0.665	4154.7	1007	13169	0.000612
2	0.686	4120.5	1033	16485	0.000714
3	0.705	4086.2	1059	19809	0.000764
4	0.726	4052	1086	23142	0.000777
5	0.745	4017	1112	26481	0.000079

Table 8
Nanofluid Thermal Properties of TiO_2-H_2O at 303.15 K

Volume Cons (%)	Thermal Conductivity (W/mK)	Specific Heat Capacity, Cp (J/(kg K)	Density ρ, kg/m^3	Reynold Number, Re	Viscosity, η (Pa.s)
1	0.433	3392.7	1087	3700	0.000265
2	0.449	3290.4	1117	4286	0.000293
3	0.465	3240.5	1147	5056	0.000321
4	0.472	3190.8	1177	5702	0.000349
5	0.488	3140.2	1207	6470	0.000377

Table 9
Nanofluid Thermal Properties of CuO-H_2O at 303.15 K

Volume Cons (%)	Thermal Conductivity (W/mK)	Specific Heat Capacity, Cp (J/(kg K)	Density ρ, kg/m^3	Reynold Number, Re	Viscosity, η (Pa.s)
1	0.662	4150.9	1061	12379	0.000611
2	0.682	4112.8	1140	15493	0.00065
3	0.702	4074.8	1220	17493	0.0007
4	0.723	4036.7	1300	19100	0.00074
5	0.744	3998	1378	20291	0.0008

By maintaining a constant velocity of Re = 600 at the entrance of the channel, it is clear that the heat transfer coefficient drops linearly along the channel's length due to the enhancement of a thermal boundary layer in all scenarios [20,21]. This occurs due to the maintenance of the channel's entry velocity at Re = 600. The heat-transfer coefficient exhibits its highest value in close proximity to the front door.

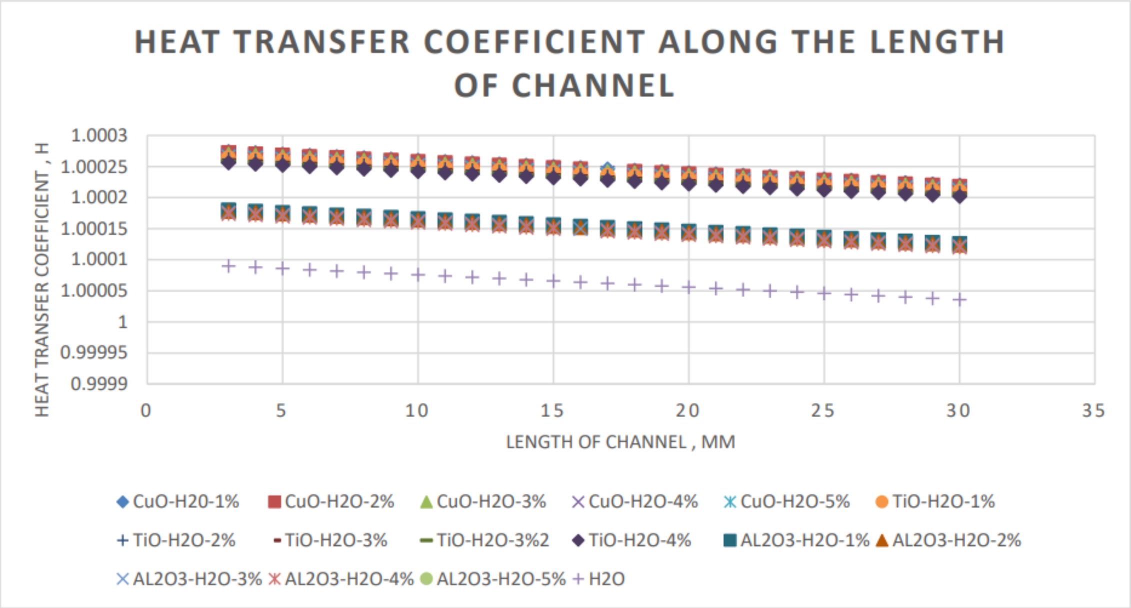

Fig. 5. Heat Transfer coefficient along the length of channel

The difference in dimensionless heat transfer coefficient between the different nanofluids is too tiny, but it follows the trend and is not too distant from the stated values, as shown in Figure 5, which also shows that this difference exists. It shows at figure 5 that CuO-H_2O has the highest heat transfer coefficient compare to TiO_2-H_2O and AL_2O_3-H_2O in term of heat transfer coefficient. The greater the heat transfer coefficient, the greater the amount of heat that is transferred [22,23]. In a broad sense, the heat transfer coefficient for a nanofluid will be greater the higher the thermal conductivity of the fluid. So, in term of cooling the microchannel-heatsink using nanofluid, it shows that better to use CuO-H_2O rather than TiO_2-H_2O and AL_2O_3-H_2O.

3.2 Temperature Gradient of Nanofluid From 15mm (L) Microchannel Heatsink to Outlet At 30mm (L) at 1% To 5% Volume Concentration

The temperature at the centre of the wall material remains constant when a heat flux of 45,000 W/m2 is applied. However, this heat flux leads to a temperature of 303.33K, marking the highest recorded temperature on the microchannel heatsink. Thus, the microchannel heatsink shows a maximum temperature gradient of 0.033 K and a minimum temperature gradient of 0.03 K. Figure 6 shows the temperature gradient data for AL_2O_3-H_2O (with a volume concentration of 1%–5%), CuO-H_2O (with a volume concentration of 1%–5%), and TiO_2-H_2O (with a volume concentration of 1%–5%) from the middle to the outlet.

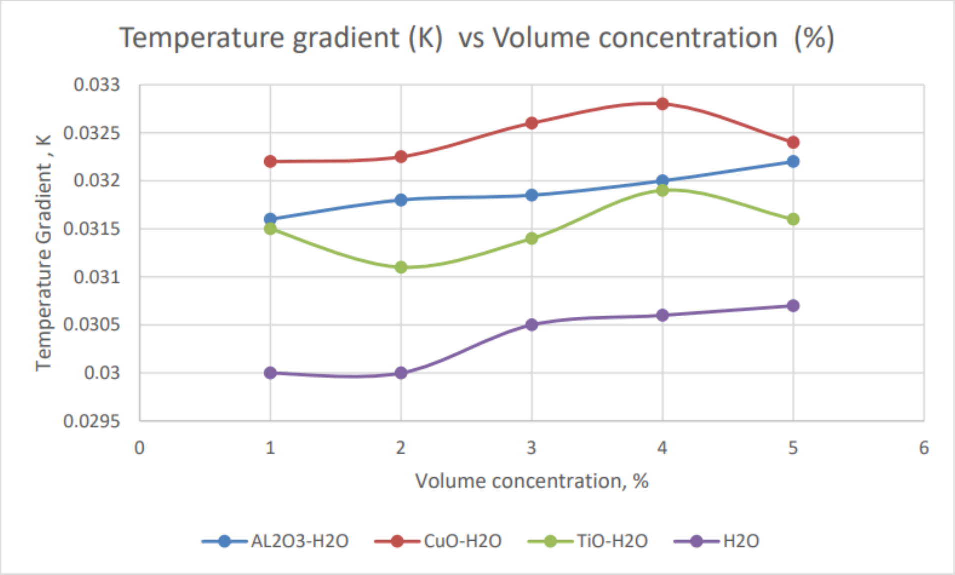

Fig. 6. Temperature Gradient of nanofluids at 1%-5% volume concentration

It shows that the CuO-H_2O (4% volume concentration) has the highest temperature gradient where follow by TiO_2-H_2O (3% volume concentration) and AL_2O_3-H_2O (5% volume concentration). Temperature contour of CuO_2-H_2O at 4% volume concentration of best performing nanofluid in terms of temperature gradient is shown in Figure 7 and the temperature contour for nanofluid at Figure 8 and 9.

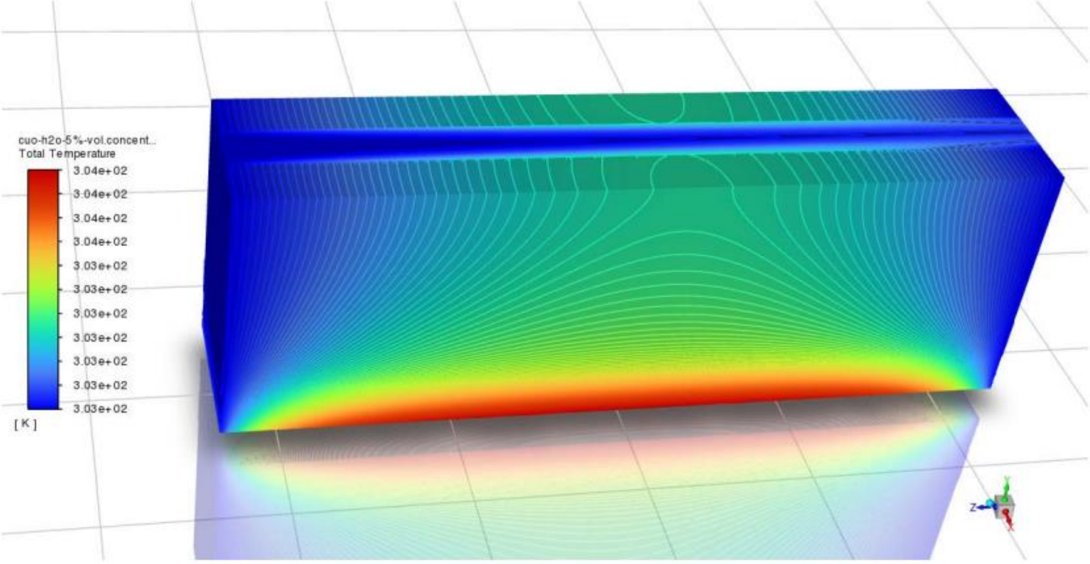

Fig. 7. Temperature contour of microchannel heatsink of CuO_2-H_2O at 4% vol concentration

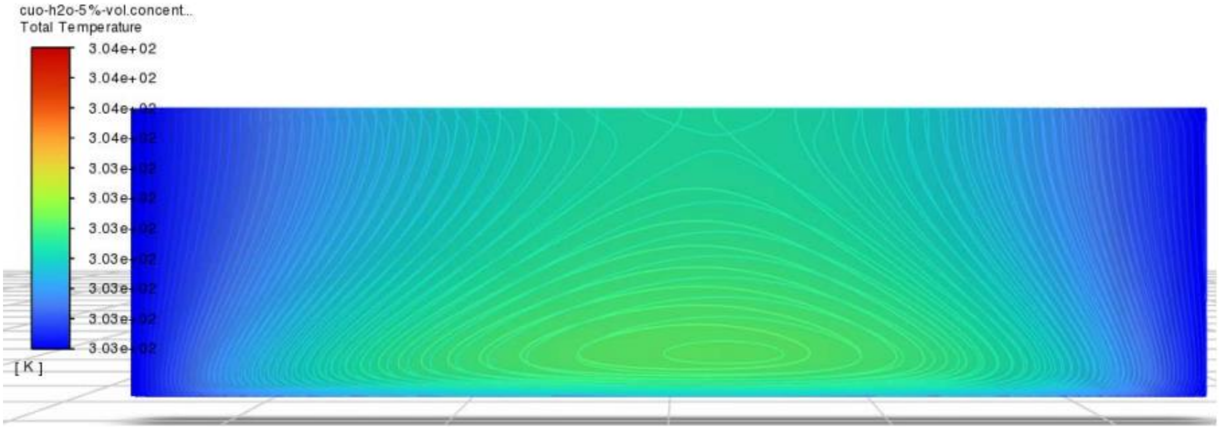

Fig. 8. Temperature contour of nanofluid of CuO-H_2O at 4% volume concentration (Cross section view)

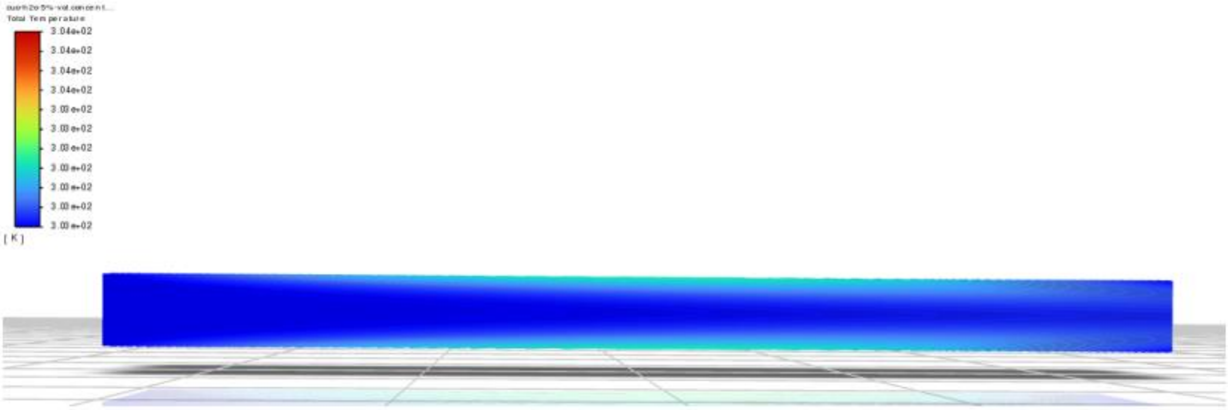

Fig. 9. Temperature contour of nanofluid flow in microchannel-heatsink (Top view)

An increase in the thermal efficacy can be attributed to the volume concentration of the nanofluids. The fluctuation of thermal conductivities with temperature is primarily explained by Brownian motion. Aside from Brownian motion, the thermal conductivity of nanofluid is influenced by the accumulation of particles and changes in viscosity with temperature [24,25]. The enhancement in heat conductivity can be attributed to the phenomenon of Brownian motion. The intensification of nanofluids occurs as the temperature increases. The intensity of Brownian motion is heightened, resulting in an increased influence of microconvection on the rate of heat transfer and an enhancement of the energy conductivity of the nanofluids [26].

4. Conclusion

The investigation carried out to assess the cooling capabilities and thermal characteristics of nanofluids in a microchannel heat sink produced significant and thought-provoking results. The outcomes of several nanofluids were found to vary depending on the parameter configurations. The observations on thermal conductivity revealed a clear relationship between the amount of nanofluid in the volume and improved heat transfer efficiency. Greater concentrations of nanofluid resulted in increased thermal conductivity, consequently enhancing the efficiency of heat transmission within the system. Furthermore, it can be observed that the viscosity properties displayed a similar pattern, increasing in direct proportion to the volume concentration in each form of the nanofluid.

In relation to the examination of temperature gradients, the experimental data exhibited significant differences in performance across various kinds of nanofluids. The nanofluid CuO-H_2O (4%)

demonstrated the greatest level of effectiveness in reducing temperature gradients, showing its greater capacity to dissipate heat in the microchannel heat sink. The following materials, TiO2-H2O (3%) and TiO_2-H_2O (4%), demonstrated significant efficacy in reducing temperature gradients, however they marginally lagged behind the CuO-H_2O (4%) variation. These findings jointly emphasise the impact of volume concentration on thermal conductivity and viscosity, while also shedding light on the small differences in performance observed across various compositions of nanofluorides. The exceptional ability of CuO-H_2O (4%) to dissipate heat highlights its potential for efficient cooling in microchannel heat sinks, emphasising the importance of selecting appropriate nanofluids to optimise thermal management systems.

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