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Numerical Prediction of Laminar Nanofluid Flow in Rectangular Microchannel

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ABSTRACT

Numerical simulation of laminar nanofluid flow in three-dimensional (3D) straight rectangular microchannel heat sink is carried out. In this study, the behavior and the effect of using pure water and Fe_3O_4-H_2O_4 as working fluids in the microchannel are examined. Fe_3O_4-H_2O_4 with volume fraction range of 0.4% - 0.8% are used in this simulation to evaluate the cooling performance of microchannel heat sink. Fluent, a Computational Fluid Dynamic (CFD) software is used as the solver of simulation. A rectangular microchannel with hydraulic diameter of 86 μm and length of 10mm under the boundary condition of constant heat flux and uniform inlet velocity is set on this analysis. Results of present work using Fe_3O_4-H_2O_4 as coolant are expected to give higher efficiency of heat transfer in microchannel heat sink in comparison to pure water.

Keywords:
Nanofluid, laminar flow, CFD, Fe_3O_4-H_2O_4

1. Introduction

The severe need by user for greater IC speeds, functionality and minimization has fuelled an extraordinary acceleration in chip power dissipation. Amongst all the problems facing by the chip and computer designers is none other than more burning than the soaring levels of power flowing through the integrated circuits. Thermal demands are continuously on the rise. Increasing process speeds (up to 2.5 GHz), decreasing product sizes and styling requirements cause higher and higher heat loads on the products and consequently thermal management is becoming a critical bottleneck to system performance. The National Electronic Technology Roadmap, 1997 has acknowledge the expectation that the Moore' law improvements in the semiconductor technology will continue into the second decade of the 21st century [1]. Due to these enhancements, the chip level heat fluxes have gone up tremendously.

The heat dissipated by silicon chips has increased from 10-15 W/cm^2 in the year 2000 to 100 W/cm^2 in the year 2006. High heat fluxes of the order of 102-103 W/cm^2 are also found in opto-electronic equipment, high performance super computers, power devices, electric vehicles and

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advanced military avionics [2]. As now the thermal design power of the last versions of processors for high performance calculation is about 100-130 W/cm^2.

These significant developments of power of microprocessors and other electronic components by simultaneous reduction of their surface area contribute to critically high the heat flux generation. An increase in the heating density of these components has been a severe problem affecting the performances and reliability of the electrical devices. The advance cooling technology using microchannels were proposed by [3] for cooling very large scale integrated (VLSI) circuitry. The concept of microchannel heat sink applied in cooling system is important due to high-density electronics packaging requires new advancement in thermal management.

Cooling becomes one of the top technical challenges facing high-tech industries. Since conventional methods of cooling such as forced convection air cooling fails to dissipate away the astronomical volumetric heats from the very small surfaces of electronic chips and circuits, new solution need to be present to overcome these matters. The small physical size of electronic equipment and limitations of air cooling systems have caused an increase of interest in high-performance liquid cooling systems. A liquid coolant is pumped through the microchannels of the heat sink to extract the heat from the source such as electronic chip on which it I mounted. In most cases, water is used as a coolant. But water is well known as heat transfer fluids which have low thermal conductivity that greatly limits the heat exchange efficiency. Other base fluids like engine oil and ethylene glycol also have low thermal conductivity.

Promising result was obtained if using nanofluids as a coolant. Nanofluids can be used to improve heat transfer and energy efficiency by addition of solid phase into the base fluid. Nanofluids can be considered next generation heat transfer fluids as they offer exciting new possibilities to enhance heat transfer compared to pure liquids. Nanofluids are expected to have superior properties compared to conventional heat transfer fluid.

The used of nanofluids as a coolant for microchannel heat sink on semiconductor and electrical field is found out more effective and researches on this application are increase from time to time. Before nanofluids was first discovered, most of the researches focused on conventional methods of cooling such as forced convection air-cooling and using fin to dissipate away the excessive heats from the microchannel heat sink. Most of the researches focused on the material properties of microchannel heat sink can enhance the heat transfer. In this paper, the evolution of microchannel heatsink together with the application of nanofluids to enhance the heat transfer will be discussed. After that, a numerical method to simulate laminar nanofluid flow in a rectangular type of microchannel is proposed.

2. Introduction to Microchannel

The concept of the microchannel heat sinks was first introduced in 1981 by Tuckerman and Peas [3]. They demonstrated that the microchannel heat sinks, consisting of micro rectangular flow passages, have a higher heat transfer coefficient in laminar flow regime than in turbulent flow through macro size channels. Therefore, a significantly high heat flux can be dissipated by using such a microchannel heat sink. There are two main configurations for the application of microchannel cooling which are direct cooling and indirect cooling. Direct cooling requires a direct contact between the surface to be cooled and the coolant fluid as illustrated in Fig. 1a. This scheme reduces the thermal resistance between the surface and the coolant and thus, enhances the cooling effectiveness. However, electrical and chemical compatibility between the coolant and device itself needs to be ensured for this system to work [4]. An alternative to the above configuration is the use of a metallic heat sink to conduct the heat away from the device to a coolant which is forced through circular or noncircular grooves in the heat sink. Such an indirect cooling configuration shown in Fig. 1b allows for a greater flexibility in coolant selection at the cost of increased thermal resistance between the device and the heat sink due to the heat diffusion resistance in the heat sink itself [5].

Microchannels are very fine channels of the width of a normal human hair and are widely used for electronic cooling purposes. In a MCHS, multiple microchannels are stacked together as shown in Fig. 1 (b) which can increase the total contact surface area for heat transfer enhancement and reduce the total pressure drop by dividing the flow among many channels. Liquid or gas is used as a coolant to flow through these microchannels.

The large surface area of MCHS enables the coolant to take away large amounts of energy per unit time per unit area while maintaining a considerably low device temperature. Using these MCHS, heat fluxes can be dissipated at relatively low surface temperatures [6].

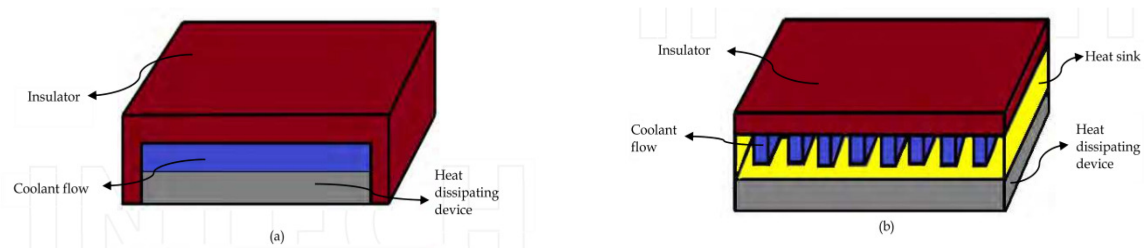

Fig. 1. Schematic diagram of the (a) direct cooling and (b) indirect cooling [6]

2.1 Experimental and Numerical Study of Fluid Flow and Heat Transfer in Microchannels

Flow studies in microchannels have been reported by several research groups. In order to drive the development of compact and efficient thermal management technology for advanced electronic devices, cooling devices have to be in light-weight, small in size and of high performance. The comprehensive review of friction factor data in microchannels with liquid flows is presented by Kandlikar and Steinke [7] . They indicated that entrance and exit losses need to be accounted for while presenting overall friction factors losses in microchannels. Most of the data that accounted for friction factor loss show good agreement with the conventional theory. They also provided a new procedure for correcting measured pressure drop to account for inlet and outlet losses.

In addition, three-dimensional fluid flow and heat transfer phenomena inside heated microchannels were investigated by Toh *et al.* [8] . They solved the steady laminar flow and heat transfer equations using a finite-volume method. It was found that the heat input lowers the frictional losses and viscosity leading to an increase in the temperature of the water, particularly at lower Reynolds numbers.

Peng and Peterson [9] experimentally investigated the flow characteristics of water flowing through rectangular microchannels with hydraulic diameters ranging from 133 to 367 μm and width to height ratios from 0.333 to 1. For Reynolds numbers ranging between 8 and 800, they observed higher friction factors with respect to the macroscale predictions. The main result obtained in these works is that the friction factor and the Reynolds number do not seem to be inversely proportional, as indicated by the conventional theory for laminar flow. The authors proposed empirical correlations in order to calculate the friction factor in laminar and in turbulent regime.

The numerical analysis of three-dimensional fluid flow and heat transfer in a rectangular micro-channel heat sink using water as the cooling fluid was analysed in another study by Qu and Mudawar

[10]. They used same channel geometry used in the experimental work done and validated their work with Kawano *et al.* [11], width of 57 µm and a depth of 180 µm with 10 mm long. For the microchannel heat sink investigated, it is found that the heat flux and Nusselt number have much higher values near the channel inlet and vary around the channel edge, approaching zero in the corners. Flow Reynolds number affects the length of the flow developing region. For high Reynolds number of 1400, fully developed flow may not be significant inside the heat sink. Result also showed that increasing the thermal conductivity of the solid substrate reduces the temperature at the heated base surface of the heat sink, especially near the channel outlet.

Numerical simulation to investigate the conjugate fluid flow and heat transfer phenomena in a microchannel for microelectronic cooling was done by Wong [12]. A rectangular microchannel with hydraulic diameter of 86 mm together with water as a coolant is used in the simulation. The investigation was conducted with consideration of temperature dependent viscosity and developing flow, both hydro dynamically and thermally. The results indicate a large temperature gradient in the solid region near the heat source. The result also prove that silicon is a better microchannel heatsink material compared to copper and aluminum, based on higher average heat transfer. A higher aspect ratio in a rectangular microchannel gives higher cooling capability due to high velocity gradient around the channel when channel width decreases.

In another work by Chein and Chuang [13] conducted an experiment on microchannel heat sink performance studies using nanofluids. The carried out simple theoretical analysis that indicated more energy and lower MCHS wall temperature could be obtained under the assumption that heat transfer could be improved by the presence of nanoparticles. CuO-H_2O nanofluid has been used as a coolant to experimentally study the heat performance of silicon trapezoidal shaped MCHS. They found that nanofluid-cooled MCHS could absorb more energy than pure water-cooled MCHS when the flow rate was low. However, for high flow rates, the heat transfer was dominated by the volume flow rate and nanoparticles did not contribute to the extra heat absorption. The experimental result also indicated that only slightly increase in pressure drop due to the presence of nanoparticles in MCHS operation.

Lee and Mudawar [14] studied experimentally the micro-channel cooling benefits of water-based nanofluids containing small concentrations of Al_2O_3 for single-phase and two-phase heat transfer. It has been found that high thermal conductivity of nanoparticles is shown to enhance the single-phase heat transfer coefficient, especially for laminar flow. Higher heat transfer coefficients were achieved mostly in the entrance region of microchannels. They also found that higher concentrations also produced greater sensitivity to heat flux. The results show that nanoparticles are not suitable to be used in two-phase because nanoparticles caused catastrophic failure by depositing into large clusters near the channel exit.

In another research done by Mohammed *et al.* [15] studied the impact of using various types of nanofluids on heat transfer and fluid flow characteristics in triangular shaped microchannel heat sink (MCHS). An aluminium MCHS performance is examined using water as a base fluid with different types of nanofluids such as Al_2O_3, Ag, CuO, diamond, SiO_2, and TiO_2 as the coolants with nanoparticle volume fraction of 2%. The result shows that diamond-H_2O are recommended to achieve overall heat transfer enhancement whereas Ag–H_2O nanofluids water is recommended to achieve low pressure drop and low wall shear stress.

Fani *et al*. [16] studied the spherical nanoparticles size effects on thermal performance and pressure drop of a nanofluid in a trapezoidal microchannel-heat-sink (MCHS). Eulerian–Eulerian two-phase numerical approach is utilized for forced convection laminar, incompressible and steady three dimensional flow of copper-oxide nanoparticles with water as base fluid at 100 to 200 nm diameter and 1% to 4% volume concentration range. They observed that with an increase in nanoparticles diameter, average Nusselt number of base fluid decreases more than that of the nanoparticles and this signifies that base fluid has more efficacy on thermal performance of copper-oxide nanofluid.

Interesting study by Tsai and Chein [17] analytically addressed the performance of rectangular shaped MCHS using Cu–H_2O and carbon nanotube-water (CNT–H_2O) nanofluids as coolants. The velocity and temperature distributions in the MCHS were obtained by modeling the MCHS as a porous media where the results for both distributions were then used to evaluate the thermal resistance that characterizes MCHS performance. It was found that the nanofluid reduced the temperature difference between the MCHS bottom wall and bulk nanofluid compared with that from pure fluid. This temperature difference produces a reduction in conductive thermal resistance while for convective thermal resistance, was found to increase when nanofluid is employed as the coolant due to the increase in viscosity and decrease in thermal capacity. They also found that using nanofluid the MCHS performance can be enhanced when the porosity and aspect ratio are less than the optimum porosity and aspect ratio.

Promising results were achieved by Bhattacharya et al. [18] who presented numerical study of conjugate heat transfer in rectangular microchannel using Al_2O_3-H_2O nanofluid. The result confirmed that the use of Al_2O_3-H_2O nanofluid improved the thermal performance of a microchannel heat sink.

3. Nanofluids

Conventional heat transfer fluids used in heat exchangers are mainly water, ethylene-glycol and oil. The drawback of conventional fluids is low heat transfer performance; this effect the heat transfer enhancement efficiency to be lower, besides, foils heat exchanger to have smaller dimensions. In order to enhance the thermal conductivity of the conventional fluid and heat transfer characteristics, the solid particles are suspended into the base fluid used in the heat exchangers. Adding particles into the base fluid enhances the thermal conductivity, because the thermal conductivity of the solid metal particles is higher than the base fluid. Nanofluids contain a small fraction of solid nanoparticles in base fluids.

The term “Nanofluid” was first proposed by Choi in 1995. He defined nanofluids as fluids containing particles of sizes below 100 nm. Nanofluids can be classified in different aspects: Base fluid, particle material, particle size, particle concentration, dispersant and pH-value of the nanofluid. In some cases, dispersants are used to stabilize the particles in the nanofluid and prevent the particles from sedimenting. The materials used to manufactured nanoparticles can generally be grouped into metallic i.e. copper [19], metal-oxide (i.e. CuO and Al_2O_3 [20]), chalcogenides (sulphides, selenides and tellurides [21] and other particles, such as carbon nanotubes [22].

3.1 Preparation of Nanoparticle and Nanofluids

Nanoparticles in most materials are made in the form of powders. In powder form, nanoparticles dispersed into host liquids to form nanofluids for specific applications. Nanofluids are produced by dispersing nanometer-scale solid particles into base liquid. Since nanofluids are not simply liquid-solid mixture, delicate preparation of nanofluids is vital because nanofluid need some special requirement to meet such as even and stable suspension, durable suspension, low or negligible agglomeration of particles and no chemical change of the fluid. Nanofluids can be produced by two techniques: a one-step technique and a two-step technique. The one-step technique the nanoparticles are simultaneously made and directly dispersed into the base fluid. The two-step technique starts with nanoparticles, produced by one of the physical or chemical synthesis techniques, and proceeds to disperse them into a base fluid. The table below summarized the methods used in producing nanofluids with its advantages and disadvantages.

Table 1
Method in producing nanofluids with its advantages and disadvantages

Methods	Single-Step Method	Two-Step Method
Description	Direct evaporation which called VEROS (vacuum evaporation onto a Running oil substrate). Original idea separation of particles from the fluids to produce dry nanoparticle but difficult to separate particle from the fluids to produces dry nanoparticles. Further develop using high pressure magnetron sputtering for the preparation of suspension.	Nanoparticle was first produced and then dispersed the base fluids. Ultrasonic equipment is used to intensively disperse the particle and reduce the agglomeration of particle. Extensively used in the synthesis of nanofluids because the availability of commercial nano powders supplied.
Advantage	Nanoparticle agglomeration is minimized. This increases the stability of the suspensions and uniform dispersion into the host liquids.	Work very well for oxide Nanoparticle. It is easily and economically produced.
Disadvantages	Only low vapour pressure fluid compatible with such process.	Less successful with metallic particle

3.2 Thermal Conductivity of Nanofluids

The primary assessment of the heat transfer potential of nanofluids is to consider its thermal conductivity. Nanofluids have offered challenges to thermal engineers and attracted many researchers over the past decade to determine the reasons for anomalous enhancement of thermal conductivity in them [23]. According to past review works [24, 25], the thermal conductivity of nanofluids depends on parameters including the thermal conductivities of the base fluid and the nanoparticles, the volume fraction, the surface area, and the shape of the nanoparticles, and the temperature. Until now, there is no reliable formula to predict thermal conductivity of nanofluids satisfactorily.

The physical mechanism accounting for the thermal conductivity of nanofluids is not well understood. Maxwell was one of the first investigators of suspended panicles. He considered a very dilute suspension of spherical particles by ignoring the interactions among the particles and made an equation that can be applied for particles with low volume concentrations. A great number of extensions to the Maxwell equation have been carried out since Maxwell's initial investigation.

These extensions take into account various factors related to effective thermal conductivity, including particle shape [26], particle distribution, high volume concentration, particle-shell structure, and contact resistance. A substantial increase in liquid thermal conductivity, liquid viscosity, and heat transfer coefficient, are the unique features of nanofluids. It is well known that at room temperature, metals in solid phase have higher thermal conductivities than those of fluids. Because thermal conductivity is the most vital parameter answerable for enhanced heat transfer many experimental works been reported on this aspect. The transient hot wire method, the steady-state parallel-plate technique and the temperature oscillation technique have been employed to measure the thermal conductivity of nanofluids. Among them the transient hot wire method has been used most extensively according to Wang and Mujumdar [24].

In another work done by Das *et al*. [21], they examined the effect of temperature on thermal conductivity enhancement for nanofluids containing Al_2O_3 (38.4nm) or CuO (28.6nm) through an experimental investigation using temperature oscillation method. They observed that a 2 to 4-fold increase in thermal conductivity can take place over the temperature range of 21^oC to 52^oC. The result suggests the application of nanofluids as cooling fluids for devices with high energy density where the cooling fluid is likely to work at a temperature higher than the room temperature. They also mentioned that the inherently stochastic motion of nanoparticles could be a probable explanation for the thermal conductivity coefficient enhancement since smaller particles show greater enhancements of thermal conductivity with temperature than do larger particles.

In addition, Wang [27] measured the effective thermal conductivity of nanofluids by a steady state parallel-plate technique. The base fluids (water ethylene glycol (EG), vacuum pump oil and engine oil) contained suspended Al_2O_3) and CuO nanoparticles of 28 and 23nm of average diameters, respectively.

Experimental results demonstrated that the thermal conductivities of all nanofluids were higher than those of their base fluids. A comparison with various data indicated that the thermal conductivity of nanofluids increases with decreasing particle size. Results demonstrated 12% improvement of the effective thermal conductivity at 3 vol. percent of nanoparticles as compared to 20% improvement reported by Masuda *et al*. [28].

Additional work by Xie *et al*. [29] measured the thermal conductivity of Al_2O_3 nanoparticle suspensions. The effects of the pH value of the suspension, the specific surface area of the dispersed Al_2O_3 particles, the crystalline phase of the solid phase, and the thermal conductivity of the base liquid on the enhanced thermal conductivity ratio were investigated. The addition of nanoparticles into the fluid led to higher thermal conductivity. The enhanced thermal conductivity increased with an increase in the volume fraction of Al_2O_3. The enhancement increased with an increase in the difference between the pH value and isoelectric point of Al_2O_3· for the suspensions containing the same base liquid, the thermal conductivity enhancements were highly dependent on the specific surface area of the nanoparticles. For the suspensions using the same nanoparticles, the enhanced thermal conductivity ratio decreased with increasing thermal conductivity of the base fluid. While, the crystalline phase of the nanoparticles did not appear to have any obvious effect on the thermal conductivity of the suspensions.

Meanwhile, Xuan and Li [30] presented a study on the thermal conductivity of a nanofluid consisting of copper nanoparticles and base liquid. The measured data showed that the suspended nanoparticles obviously increased the thermal conductivity of the base liquid. Thermal conductivity of the nanofluid increased with increasing volume fraction of nanoparticles. The ratio of thermal conductivity of Cu water to that of the base liquid increased from 1.24 to 1. 78 when the volume fraction of the nanoparticles varied from 2.5 to 7.5%.

While, Lee *et al*. [31] measured the thermal conductivity of nanofluids. The number- weighted particle diameter and the area weighted particle diameter used were 18.6 and 23 .6 nm for CuO, and 24.4 and 38.4 nm for Al_2O_3 respectively. These particles were used with two different base fluids: water and ethylene glycol to get four combinations of nanofluids (CuO in water, CuO in ethylene glycol, Al_2O_3 in water and Al_2O_3 in ethylene glycol). The nanofluids showed substantially higher thermal conductivities than' those of the same liquids without the nanoparticles. The thermal conductivity of suspended CuO in ethylene glycol showed an enhancement of more than 20% at 4% volume fraction of nanoparticles. The thermal conductivity ratios increased almost linearly with an increase in volume fraction. The experimental results revealed that the thermal conductivity of nanofluids depend on the thermal conductivity of both the particles and the base fluids. Table 2 below show several formulas to calculate thermal conductivity of nanofluid.

Experimental investigations and theoretical determination of effective thermal conductivity and viscosity of magnetic Fe_3O_4/water nanofluid are reported by Sundar [32]. The nanofluid was prepared by synthesizing Fe_3O_4 nanoparticles using the chemical precipitation method, and then dispersed in distilled water using a sonicator. Both experiments were conducted in the volume concentration range 0.0% to 2.0% and the temperature range 20 °C to 60 °C. The thermal conductivity and viscosity of the nanofluid were increased with an increase in the particle volume concentration. Viscosity enhancement was greater compared to thermal conductivity enhancement under at same volume concentration and temperature. Theoretical equations were developed to predict thermal conductivity and viscosity of nanofluids without resorting to the well-established Maxwell and Einstein models, respectively. The proposed equations show reasonably good agreement with the experimental results.

3.3 Viscosity of Nanofluids

Viscosity is important in designing nanofluids for flow and heat transfer applications because the pressure drop and the result in pumping power depend on the viscosity. Some of the experimental research for nanofluids viscosity such as viscosity of Al_2O_3 nanoparticles in water reported that the fluids have higher viscosity near their freezing point and fairly low viscosity near their boiling temperature, showing that viscosity is a strong function of the temperature. They mentioned that the relative viscosity was almost constant for all nanofluids independent of temperature for particle volume fraction lower than 4%. However, the difference became more for higher particle fraction, e.g. for 7% and 9%, where temperature and particle volume fraction dependence can be observed [33]. In general, in any flow, layers move at different velocities and the fluids have frictional forces between molecules. These forces represent the flow resistance which can be measured as viscosity. Compared with the experimental studies on thermal conductivity of nanofluids there are limited rheological studies. Li et al. [34] measured the viscosity of water with CuO nanoparticle suspensions using a capillary viscometer. Results showed that the apparent viscosity of nanofluids decreased with increasing temperature. A study by Wang and Choi [35] also measured the relative viscosity of Al_2O_3-water and Al_2O_3-ethylene glycol nanofluids. Results showed similar trend of increase of relative viscosity with increased solid volume fraction for the two nanofluids. That means the desirable heat transfer increase may be offset by the undesirable increase in pressure drop. Nanofluids with high concentration and large size nanoparticles have high interaction and thus increase the flow resistance and decrease the heat transfer enhancement. Table 3 gives a summary of nanofluid viscosity model proposed by several authors. The tabulated viscosity can be generally applied for determining the viscosity of nanofluids.

3.4 Effect of Temperature on Nanofluids

One important contribution on nanofluids was the discovery [36] of a very strong temperature dependence of nanofluids with the same Al_2O_3 and CuO particles as those used by Lee et al. [37]. Using the temperature oscillation technique, they measured the thermal conductivity of oxide nanofluids over the temperature range of 21ºC - 50ºC. The results revealed an almost threefold increase in conductivity enhancement (i.e., 10% became ~30%) for copper oxide and alumina nanofluids. The effectiveness of the Brownian motion decreases with an increase in the bulk viscosity and increase with increasing fluid temperature as noted by Koo and Kleinstreuer [38].

3.5 Effect Particle Size on Nanofluids

The effects of several important factors such as particle size on the effective thermal conductivity of nanofluids have not been studied adequately. It is important to do more research so as to ascertain the effects of these factors on the thermal conductivity of wide range of nanofluids. The size of nanoparticles is in the range of 1-100 nm for nanofluids. The smaller in particle size higher will be the enhancement. Since the surface to volume ratio will be higher for small diameter particles which results in uniform distribution of particles gives and the best enhancement. On the other hand, even when the particle size of CuO was smaller than that of Al_2O_3 the deterioration in heat transfer was greater with Al_2O_3. This is because the particle density of CuO is higher than Al_2O_3 [79].

Table 2
Analytical models on thermal conductivity of nanofluids [24]

Author	Formula (k_{eff}/k_b)	Remarks
Maxwell [39]	$\frac{k_p + 2k_b + 2(k_p - k_b)\emptyset}{k_p + 2k_b - 2(k_p - k_b)\emptyset}$	Relates the thermal conductivity of spherical particle, base fluid and solid volume fraction
Hamilton [40]	$\frac{k_p + (n-1)k_b - (n-1)(k_b - k_p)\emptyset}{k_p + (n-1)k_b - (k_b - k_p)\emptyset}$	For non-spherical particles, kp/kb > 100, n is an empirical shape factor (n = 3/ψ, ψ is the sphericity)
Wasp [41]	$\frac{k_p + 2k_b + 2(k_p - k_b)\emptyset}{k_p + 2k_b - 2(k_p - k_b)\emptyset}$	Special case of Hamilton and Crosser's model with ψ = 1
Bruggeman [42]	$\frac{1}{4}\left[(3\emptyset - 1)\frac{k_p}{k_b} + (2 - 3\emptyset) + \frac{1}{4}\sqrt{\Delta}\right.$	Δ =[(3ϕ−1)2(kp/kb)2+(2−3ϕ)2 +2(2+9ϕ −9ϕ2)(kp/kb)]
Yu and Choi [43]	$\frac{k_{pe} + 2k_b + 2(k_{pe} - k_b)(1-\beta)^3\emptyset}{k_{pe} + 2k_b - 2(k_{pe} - k_b)(1+\beta)^3\emptyset}$, $1 + \frac{n\emptyset_{eff}A}{1 - \emptyset_{eff}A}$	A modified Maxwell and Hamilton–Crosser model, respectively
Xuan et al [44]	$\frac{k_p + 2k_b - 2(k_b - k_p)\emptyset}{k_p + 2k_b + 2(k_b - k_p)\emptyset} + \frac{\rho_p\emptyset_{cp}}{2k_b}\sqrt{\frac{k_bT}{3\pi r_c\eta}}$	Includes effect of the random motion of the suspended nanoparticles as well as the interfacial interactions
Jang and Choi [45]	$k_b(1-\emptyset) + k_b\emptyset + 3c\frac{d_b}{d_b}k_bRe^2d_ppr\emptyset$	four modes: collisons between fluid molecules, thermal diffusion of nanoparticles, collisons between nanoparticles due to Brownian motion and thermal interaction of dynamic nanoparticles with base fluid molecules
Xue [46]	$\frac{1 - \emptyset + 2\emptyset\frac{k_p}{k_p - k_b}ln\frac{k_p + k_b}{2k_b}}{1 - \emptyset + 2\emptyset\frac{k_b}{k_p - k_b}ln\frac{k_p + k_b}{2k_b}}$	For CNTs-based nanofluids and including the axial ratio and the space distribution

Table 3
Summary of nanofluid viscosity model proposed by several authors [47]

Model Name	Effective viscosity models/ Equations	Remarks
Classical models		
Einstein [48]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi$	Valid for spherical particles of low particle volume fraction ∅ ≤0.02.
Krieger and Dougherty (KD) model [49]	$\frac{\mu_{nf}}{\mu_f} = \left[1 - \frac{\phi_p}{\phi_m}\right]^{-\eta\phi_m}$	Based on randomly mono-dispersed hard spheres. Valid for maximum close packed particles of 0.64.
Nielsen [50]	$\frac{\mu_{nf}}{\mu_f} = (1 + 1.5\phi_p)e^{\frac{\phi_p}{(1-\phi_m)}}$	Power law model and more appropriate for particle volume fraction more than 0.02.
Batchelor [51]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\emptyset + 6.5\phi^2$	Considered the effect of Brownian motion. Extension of Einstein model

Models formulated based on classical model		
Eilers [52]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi + [1.5625 + (2.5/\phi_{max})]\,\phi^2$	Based on maximum particle volume fraction. Valid for spheres of 0.5236≤ ϕmax ≤0.7405
De Bruijn [53]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + 4.698\phi^2$	Valid for spherical shaped nanoparticles.
Vand [54]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi + 7.349\phi^2$	Valid for spherical shaped nanoparticles.
Saito [55]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi + 2.5\phi^2$	Reported the viscosity depends on particles volume fraction.
Mooney [56]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi + [3.125 + (2.5/\phi_{max})]\,\phi^2$	Valid for spherical nanoparticles and for 0.5236≤ ϕmax≤0.7405.
Fullman [57]	$\frac{\mu_{nf}}{\mu_f} = 1 + a\frac{1}{\lambda^n}$, $where\ \lambda = \frac{2}{3}d\frac{(1-\phi)}{\phi}$	Depends on the materials characteristics.
Simha [58]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.\phi 5 + [(125/64\phi_{max})]\,\phi^2$	Valid for spherical nanoparticles and for 0.5236≤ ϕmax≤0.7405.
Brinkman [59]	$\frac{\mu_{eff}}{\mu_f} = \frac{1}{(1-\phi)^{2.5}}$	Formulated by two corrections of Einstein's model.
Frankel and Acrivos [60]	$\frac{\mu_{nf}}{\mu_f} = \frac{9}{8}\left[\frac{(\phi/\phi_m)^{1/3}}{1-(\phi/\phi_m)^{1/3}}\right]$	Valid for spherical nanoparticles and for 0.5236≤ ϕmax≤0.7405.
Lundgren [61]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + \frac{25}{4}\phi^2 + 0(\phi^3)$	Formulated from the Taylor and Series. Reduction of Einstein model
Graham [62]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + 4.5\left[\frac{1}{\frac{h}{d_p}\left(2+\frac{h}{d_p}\right)\left(1+\frac{h}{d_p}\right)^2}\right]$	Based on particle volume fraction and inter-particle spacing.
Kitano [63]	$\frac{\mu_{nf}}{\mu_f} = \left[1 - \left(\frac{\phi}{\phi_m}\right)\right]^{-2}$	Based on maximum concentration of two phase mixture.
Pak and Cho [64]	$\frac{\mu_{nf}}{\mu_f} = (1 + 39.11\phi + 533.9\phi^2)$	Developed by taking the room temperature as reference.
Chung Lee Starling (CLS) model [65]	$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + \left(\frac{35}{8} + \frac{5}{4}\beta\right)\alpha^2 + \left(\frac{105}{16} + \frac{35}{8}\beta + \frac{5}{12}\beta^2\right)\alpha^3$	Based on the kinetic gas theory. Considered the interaction between particles
Bicerano [66]	$\frac{\mu_{nf}}{\mu_f} = 1 + \eta\phi + k_H\phi^2$	Considered the viscosity of base fluids and particles.
Wang [35]	$\frac{\mu_{eff}}{\mu_f} = 1 + 7.3\phi + 123\phi^2$	Showed the particle volume fraction is the key factor for improved viscosity.
Drew and Passman [67]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi$	Formulated for dilute suspension of small spherical particles of two phase mixtures.
Tseng and Li [68]	$\frac{\mu_{nf}}{\mu_f} = 13.47e^{35.98\phi}$	Developed for TiO2/water nanofluids

Maiga [69]	$\frac{\mu_{nf}}{\mu_f} = 123\phi^2 + 7.3\phi + 1$	Derived for Al2O3 /water nanofluids.
White [70]	$ln\frac{\mu_{nf}}{\mu_f} = a + b\left(\frac{T_0}{T}\right) + c\left(\frac{T_0}{T}\right)^2$	Temperature dependant viscosity of Al2O3 nanofluids.
Koo and Kleinstreuer [71]	$\mu_{Brownian} = 5 \times 10^4\beta\rho_m\phi_p\sqrt{\frac{K_bT}{2\rho_p r_p}}\left[\begin{matrix}(-134.63 + 1722.3\phi_p)\\+\\(0.4705 - 6.04\phi_p)T\end{matrix}\right]$	Additional viscosity due to Brownian motion. Valid for CuO nanofluids.
Kulkarni [72]	$ln(\mu_{nf}) = -\left(\begin{matrix}2.8751 +\\53.548\phi - 107.12\phi^2\end{matrix}\right) + \left(\begin{matrix}1078.3 + 15857\phi +\\20587\phi^2\end{matrix}\right)(1/T)$	Temperature dependent model and valid for 5oC-50oC.
Nguyen [73]	$\frac{\mu_{nf}}{\mu_f} = \left(\begin{matrix}2.1275 - 0.0215T +\\0.00027T^2\end{matrix}\right)$	Temperature dependent nanofluids viscosity model and valid for 1%-4%.
Ward (CLS) [65]	$\frac{\mu_{nf}}{\mu_f} = 1 + \eta\phi + (\eta\phi)^2 + (\eta\phi)^3$	An exponential model for ϕ up to 35% of spherical particles.
Chen [74]	$\frac{k_{nf}}{k_f} = \left[1 - \left(\frac{\phi}{\phi_m}\right)\left(\frac{a_a}{a}\right)^{1.2}\right]^{-(\eta)\Phi_m}$	Considered the radii of aggregates. Modified Krieger- Dougherty model.
Avsec [75]	$\frac{\mu_{nf}}{\mu_f} = 1 + \eta\phi_e + (\eta\phi_e)^2 + (\eta\phi_e)^3$	An exponent model and valid for 35% of volume fraction.
Namburu [76]	$\log\mu_{nf} = Ae^{BT}$	Temperature dependent model. Valid for 1-10% of Al_2O_3 nanofluids and -35°C to 50°C.
Masoumi [77]	$\frac{\mu_{eff}}{\mu_{eff}} = 1 + \frac{\rho_N V_B d_N^2}{72C\delta\mu_f}$	Based on the Brownian motion of particles and valid for Al2O3/water nanofluids.
Chandrasekar [78]	$\frac{\mu_{eff}}{\mu_{eff}} = 1 + b\left(\frac{\phi}{1-\phi}\right)^n$	Contribution of Electromagnetic aspects and mechanical – geometrical aspects taken into account.

Compared to micron-sized particles, nanoparticles are engineered to have larger relative surface areas, less 203 particle momentum, high mobility and better suspension stability than micron-sized particles and importantly increase the thermal conductivity of the mixture. In addition, it is reported that as the size of nanoparticle reduce, the Brownian motion will be induced [80]. The most commonly used geo metric shape of the particles is Spherical and cylindrical. The cylindrical particles show an increase in thermal conductivity enhancement due to a mesh formed by the elongated particles that conducts heat through the fluid. This indicates the elongated particles are superior to spherical for thermal conductivity [81]. The size of nanoparticles in the host liquid is too important to the new and compact technology. It can be used in small size system such as nanosystems and micro-passages where the clog is avoid.

3.6 Heat Capacity of Nanofluid

Heat capacity is the ratio of the heat energy absorbed by a substance to the substance's increase in temperature. The quantity of heat required to raise a unit mass of homogeneous material one unit in temperature along a specified path, provided that during the process no phase or chemical changes occur, is known as the heat capacity of the material and has units of joule per Kelvin (J/K). The specific heat capacity is the heat capacity per unit mass (J/kg. K). The specific heat capacities of nanofluids are different from base fluids and increase with the decrement of size and volume concentration. The high specific interfacial area of nanoparticle can absorb liquid molecules to its surface and from liquid layers [82].

4. Heat Transfer Enhancement using Nanofluids in Microchannels

The need for cooling is paramount for maintaining the desired performance, reliability as well as does not exceed allowable temperature. Microchannel heat sink contains many parallel microchannels containing the flow coolant. The heat generated by a device is carried away from the channel walls by the coolant. Air, water, ethylene glycol (EG), and engine oil (EO) are commonly used as coolants in MCHSs. However, the heat transfer performance of these coolants is limited because of their limited thermal conductivity. Hence, to improve heat transfer performance, it is necessary to increase the thermal conductivity of the coolants. This can be achieved by adding an appropriate amount of solid nanoparticles having high thermal conductivity to a base fluid for use as a coolant (i.e., using a nanofluid). Nanofluids were first proposed by Choi and Eastman [83] at the Argonne National Laboratory, USA, who found that nanoparticles raise the thermal conductivity of the coolant, thus improving the heat transfer performance. Several researchers have demonstrated that nanofluids have a higher effective thermal conductivity than pure base fluids and therefore have great potential for heat transfer enhancement [31]. Hence, it becomes desirable to develop an MCHS containing nanofluids for potential application in many electronic devices in order to improve the heat transfer performance.

Several recent studies have experimentally examined the use of a nanofluid as a coolant for an MCHS. For example, Xuan and Li [84] proposed a theoretical model describing the heat transfer performance of a nanofluid flowing in a tube and accounting for solid particle dispersion. Zeinali *et al*. [85] investigated the laminar flow forced-convection heat transfer of an Al_2O_3–water nanofluid inside a circular tube with constant wall temperature. They found that increasing the nanoparticle concentration in the nanofluid improved the heat transfer coefficient. Chein and Huang [86] demonstrated that the heat sink performance of silicon microchannels improved greatly when nanofluids were used as coolants. Lee and Mudawar [87] assessed the effectiveness of nanofluids for single-phase and two-phase heat transfer in microchannels. They demonstrated enhancement of the heat transfer coefficient due to the high thermal conductivity of the nanoparticles and proved that nanoparticles have an appreciable effect on thermal boundary layer development. Ho *et al*. [88] investigated the forced convective cooling performance of a copper MCHS with an an Al_2O_3–water nanofluid; they found that the nanofluid-cooled heat sink had a significantly higher heat transfer coefficient, markedly lower thermal resistance at high pumping powers, and a slightly higher friction factor. Liu et al. [89] studied the laminar flow nanofluids consisting of Al_2O_3 nanoparticles and de-ionized water through a copper tube. They observed considerable enhancement of convective heat transfer when the nanofluids were used and proposed that nanoparticle migration and the resulting disturbance of the boundary layer were the main reasons for the enhancement.

Many researchers have performed numerical studies of heat transfer with nanofluids. For example, Chein *et al*. [86] investigated the heat transfer performance of nanofluid-cooled MCHSs and found that they yielded better heat transfer performance than a water-cooled MCHS, and that a higher nanofluid bulk temperature could prevent particle agglomeration. Tsai and Chein [17] analyzed MCHS performance using Cu–H_2O and carbon nanotube-H_2O and a porous media approach. They found that the nanofluid reduced the temperature difference between the bottom-heated wall and the bulk nanofluid. Jang and Choi [90] numerically investigated a nanofluid-cooled MCHS and found that the use of water –diamond nanofluid enhanced the performance by about 10% compared with that of an MCHS with pure water. Li and Kleinstreuer [91] analyzed the thermal performance of nanofluid flow in a trapezoidal microchannel using pure water and a nanofluid. They claimed that the nanofluid measurably enhanced the thermal performance of microchannel flow, although a slight increase in pumping power was required. Specifically, the thermal performance increased with nanoparticle volume fraction, but the greater pressure drop somewhat decreased the beneficial effect.

5. Microchannel Design and Research Methodology

The micro-heat sink model consists of a 10 mm long substrate and dimension of rectangular microchannels have a width of 57 µm and a depth of 180 µm and we consider a rectangular channel of dimension (900µm x 100µm x 10mm) applied constant heat flux of 90W/m^2 from top of the heat sink as shown Fig. 2. The heat sink is made from silicon. The electronic component is taking advantage of symmetry, a unit cell consisting of only one channel and the surrounding solid is chosen as shown by the dashed lines in Fig. 2. Attention is focused on the heat transfer process in a single unit cell. The results obtained can be easily extended to the entire heat sink. Figure 2 also shows the unit cell, the corresponding coordinate system, and some important notations. Dimensions of the heat sink unit cell are given in Table 4. Heat transport in the unit cell is a conjugate problem which combines heat conduction in the solid and convective heat transfer to the cooling fluid. The two heat transfer modes are coupled by the continuities of temperature and heat flux at the interface between the solid and fluid.

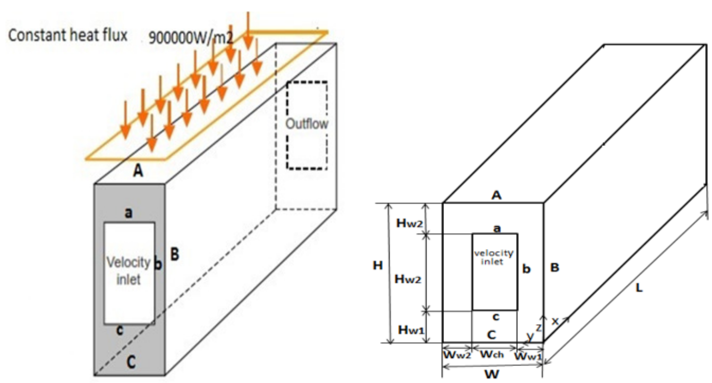

Fig. 2. Schematic of unit cell rectangular microchannel heatsinks

Table 4
Dimension of the physical model

W_{w1}	W_{ch}	W_{w2}	H_{w1}	H_{ch}	H_{w2}	L
21.5µm	57µm	21.5µm	270µm	180µm	450µm	10mm

Nano fluid as heat transfer enhancement fluid exhibits a unique properties of enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid. The thermophysical properties of nanofluids are calculated as

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p \tag{1}$$

$$\left(\rho c_p\right)_{nf} = (1-\varphi)\left(\rho c_p\right)_{bf} + \varphi\left(\rho c_p\right)_p \tag{2}$$

$$\left(\frac{k_p+2k_b+2(k_p-k_b)\varphi}{k_p+2k_b-2(k_p-k_b)\varphi} k_{bf}\right) \tag{3}$$

$$\mu_{nf} = \mu_{bf}\,(1+2.5\varphi) \tag{4}$$

6. Expected Findings and Conclusions

This paper was set to propose a numerical study on laminar nanofluid flow in rectangular microchannel. It is expected that by inclusion of nanoparticle to conventional coolant, the microchannel heatsink is capable in removing more heat to the surrounding.

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