Journal of Advanced Research in Applied Sciences and Engineering Technology 28, Issue 2 (2022) 1-25

SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied
Sciences and Engineering Technology

https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

A comprehensive review of recent progress of nanofluid in engineering application: Microchannel heat sink (MCHS)

Yew Wai Loon[1], Nor Azwadi Che Sidik[1,*]

[1] Malaysia-Japan Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100, Kuala Lumpur, Malaysia

ABSTRACT

Nanofluid is a new class of heat transfer fluid that is introduced to enhance the heat transfer performance in various heat exchanging systems. Prior to invention of nanofluid, water is the most common fluid used to extract heat generated from the systems. The application of water has reached thermal bottleneck since it can only enhance the heat transfer performance up to a certain extent. The suspension of nanoparticles with enhanced thermal conductivity provides augmentation in heat transfer performance. Since then, nanofluids have received great interest from scientists and researchers due to significant higher thermal conductivity. Due to enhanced thermophysical properties, nanofluids can be incorporated into high heat transfer device such as solar thermal conversion system, heat exchanger, and electronic equipment. Understanding the factors that influence the heat transfer performance is extremely important for appropriate selection and implementation of nanofluids. The influence of nanoparticles material, nanoparticles size, nanoparticles concentration, nanoparticles shape and surfactant are reviewed systematically to provide a comprehensive understanding of nanofluids. The review aims to extensively discuss the application of nanofluids in engineering application such as microchannel heat sink (MCHS). Finally, the review aims to update the readers about the current progress of nanofluids along with challenges of nanofluids in engineering field.

Keywords:
Microchannel heat sink; Nanofluid;
Surfactant; Thermal Conductivity

Received: 25 July 2022 Revised: 27 September 2022 Accepted: 1 October 2022 Published: 16 October 2022

1. Introduction

The energy crisis issues have been debated over the century, and the primary objective is to achieve continuous and uninterrupted energy sources. The current global energy sources are dominated by traditional non-renewable sources, while renewable sources only accounts for small share. According to Centre for Climate and Energy Solutions, in the year of 2020, about 29% of the world electricity generation was from renewable energy [1]. From this, the energy management has arrived into two distinct approaches, either to conserve the conventional energy resources or to reduce the dependency on conventional energy resources and develop more efficient system to harvest renewable energy. The former approach has received considerable attention from scientists and researchers, which lead to development of energy efficient systems to reduce the energy usage.

---

[*] *Corresponding author.*
E-mail address: azwadi@utm.my

https://doi.org/10.37934/araset.28.2.125

Extensive effort has been expended to accelerate the development of energy efficient systems. In fact, previous work has identified that the consumption of energy in industrial sectors are about 37%, and this indicates that reducing energy usage is certainly a good initiative [2]. The energy consumption of conventional energy system is unacceptably high due to low efficiency of the system. Owing to poor performance of the system, a large portion of useful energy is not properly utilised. It is therefore necessary to improve the efficiency of energy system in order to conserve the conventional energy sources. The effort to improve the efficiency can be achieved by adopting thermal energy system management. By definition, thermal management is the practice of controlling the temperature of a system to remain within specific limit based on thermodynamics and heat transfer knowledge.

Heat and mass transfer can be accomplished when there is presence of flow passage or flow channel. The heat and mass transfer can be described as the process of exchanging thermal energy and mass by various forms such as conduction, convection, and radiation. In flow channel, the heat and mass transfer usually take place in a simultaneous manner, which is through conduction and convection. Conduction refers to the transfer of heat through a solid medium. Conduction occurs when the inner surface of flow channel is heated up, where the heat is being transported through the solid medium to the outer surface of flow channel. Convection refers to the transfer of heat from the surface of solid body to fluid. Convection occurs when the outer surface of flow channel is heated up, where the heat is being transported away by the ambient air of the surrounding.

In recent years, there is an increasing trend in development of high integration density electronic equipment and components. In addition, the advancement in technology enables the manufacturers to build small and compact components such as microelectronic or nano electronic devices. However, miniaturisation of the components and increase in power consumption requires proper thermal management to sustain its performance [3]. The continuous operation of electronic devices produce varying amount of heat which need to be dissipated away. The conventional cooling method is not suitable to be employed to remove heat from the electronic devices owing to its very low heat removal rate. Microchannel heat sink (MCHS) appears to be an innovative solution to address this issue [4]. The high surface area and high compactness of MCHS fulfil the cooling demand of electronic devices [5]. Figure 1 below shows the microchannel heat sink developed by Tuckerman and Pease [6].

Heat dissipation in microchannel heat sink can be attained by using active cooling technique. Active cooling technique is the application of pump to force fluid to steadily circulate around the flow passage, with the intention to draw away the high heat flux. The conventional fluids employed in microchannel heat sink are water and ethylene glycol. In recent years, the technology has emerged which led to rapid development of microelectronic devices. The heat generation in these devices has increased exponentially, and the conventional fluids are not able to meet the cooling demand for practical application. Therefore, alternative method, such as new class heat transfer fluid is being explored to tackle the thermal management challenges. The advance heat transfer fluid, which is known as nanofluid, is now extensively used in microchannel heat sink to improve its cooling performance.

Our central problem is worth reiterating here, that is to improve the heat transfer characteristic in microchannel heat sink. The implementation of nanofluid is shown to be more effective in dissipating heat in comparison to pure water. Much of the research has therefore focused on enhancing the performance of microchannel heat sink through nanofluid. To the best of author knowledge, the recent review paper of microchannel heat sink only discussed on the heat transfer correlations [4], heat sink configurations [7], manufacturing processes [8]and application of nanofluid [9]. Although the application of nanofluid is discussed, the influence of nanoparticle size, nanoparticles shape, and surfactant on performance of microchannel heat sink are not included in the review. The present review therefore attempts to extensively explore and summarise the influence of nanofluid in heat transfer performance of the heat sink.

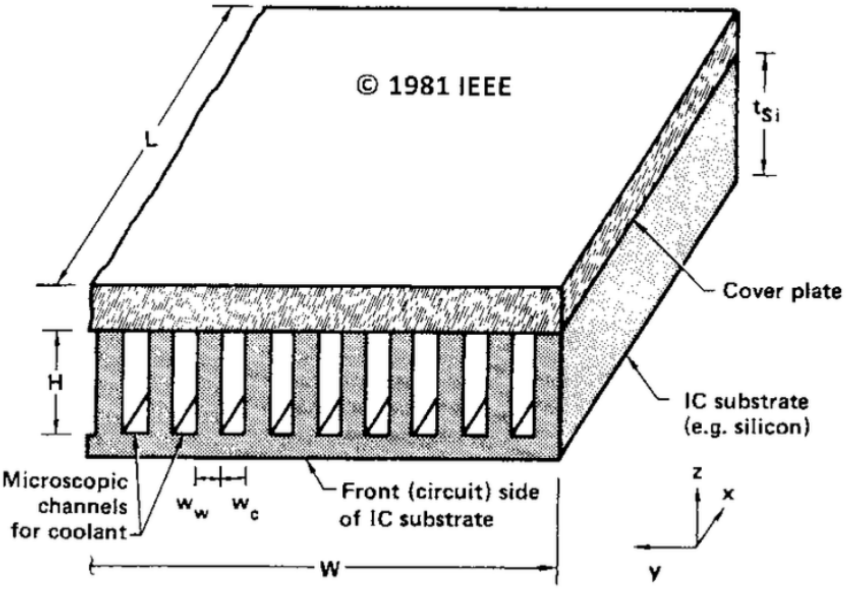

Fig. 1. Schematic diagram of microchannel heat sink [6]

2. Nanofluid

2.1 Potential of nanofluid

The past decade has seen an increase in the use of nanofluid in many heat transfer equipment. A low heat transfer performance is observed in this equipment when conventional heat transfer fluids are used. The limitation of conventional heat transfer fluids is mainly because of the poor thermal conductivity to transmit heat. In past thirty decades, scientists and researchers have successfully realised the concept to improve the thermal conductivity of fluid by suspending particles into it. The novel work has brought revolution in the heat transfer application, where the new class heat transfer fluid might become substitution to conventional heat transfer fluids in future. The nanofluid produced has been tested and it possessed enhanced thermophysical properties compared to pure water. The apparent reason for the enhanced properties is attributed to the much higher thermal conductivities of particles than pure water.

Prior work should focus on examining the potential of nanofluid before considering the application in heat transfer equipment. The emergence of nanotechnology made it possible to produce ultrafine particles in the size of nano scale. The suspension of nano size particles remarkably improve the thermal conductivity of base fluid. Moreover, the thermal conductivity of base fluid can be altered by the volume fraction, shape, and size of nanoparticles. The degree of improvement in thermal conductivity can be manipulated by selecting optimum parameters for each factors mentioned. This suggest that nanofluid has potential for application in heat transfer equipment, since its properties can be altered to meet the cooling demand. Table 1 presents the potential application of nanofluid in microchannel heat sink. Comparing the results of nanofluid with pure water, there is a marked improvement in heat transfer performance.

Table 1
Potential application of nanofluid in MCHS

Author	Geometry	Working fluid	Remarks
Junmei *et al.*, [10]	Rectangular	Al_2O_3/H_2O H_2O	Comparison is made between aluminium oxide nanofluid and pure water to determine the effectiveness of employing nanofluid to improve the overall performance of MCHS. The thermal resistance of MCHS using nanofluid is lower than pure water which implies that it is reliable and able to contribute to improve the overall performance. The temperature distribution of MCHS is more uniform using nanofluid than pure water because increment in thermal conductivity increase the heat removal capability. The pumping power of MCHS is higher using nanofluid than pure water due to increase in dynamic viscosity. The suggested inlet velocity is not more than 2 m/s to save pumping power.
Saidu *et al.*, [11]	Rectangular	Fe_3O_4/H_2O H_2O	Comparison is made between iron oxide nanofluid and pure water to determine the fluid flow and heat transfer performance of MCHS at uniform inlet velocity. The temperature in the heat sink top wall is lower using nanofluid than pure water because it has higher dynamic viscosity and lower heat capacity which promotes better heat transfer. The Nusselt number of iron oxide nanofluid with different volume fraction and pure water are compared and 0.8% volume fraction shows the highest Nusselt number. The iron oxide nanofluid with 0.8% volume fraction exhibits the highest heat transfer performance due to higher thermal conductivity and Nusselt Number.
Snoussi *et al.*, [12]	Rectangular	Al_2O_3/H_2O Cu/H_2O H_2O	Comparison is made between aluminium oxide nanofluid, copper nanofluid and pure water to determine the cooling efficiency and heat transfer characteristics of MCHS. The pressure drop is significantly higher using nanofluid than pure water due to increase in viscosity and the pressure drop increases about 24% for volume fraction from 0% to 2%. The increment in heat flux in MCHS has a positive impact in improving the heat transfer coefficient of nanofluid but a weak effect in improving heat transfer coefficient of water. The 2% volume fraction of aluminium oxide nanofluid and copper nanofluid provides 14% and 20% increase in heat transfer coefficient compared to pure water.
Krishna *et al.*, [13]	Rectangular	$CuAl_2O_3/H_2O$ Cu/H_2O Al_2O_3/H_2O H_2O	Comparison is made between hybrid nanofluid, copper oxide nanofluid, aluminium oxide nanofluid and water to determine coolant that offer better heat and pumping performance. The hybrid nanofluid with 2% volume fraction showed an increase in 7.54% and 14.87% for Nusselt number compared with copper oxide nanofluid and aluminium oxide nanofluid. The hybrid nanofluid offer better heat transfer compared to other coolant as there is changes in thermophysical properties and motion of nanoparticles due to hybridisation. The pumping power for different nanofluids are higher compared to pure water due to addition of nanoparticles which alter the effective density and lead to higher pressure difference.

Table 1 (Cont.)
Potential application of nanofluid in MCHS

Author	Geometry	Working fluid	Remarks
Mushtaq [13]	Rectangular, Rectangular with sudden expansion	Cu/H_2O Al_2O_3/H_2O C/H_2O H_2O	Comparison is made between copper nanofluid, aluminium oxide nanofluid, diamond nanofluid and water to determine the influence of different coolant on cooling performance of MCHS. The heat transfer performance using different types of nanofluid is significantly higher compared to pure water as nanofluid possesses higher thermal conductivity. Copper nanofluid is the coolant that provides the highest cooling performance among others and it is due to the addition of copper particles which has highest thermal conductivity. The nanofluid is suggested to be used in different geometrical configuration because it is able to provide enhancement in overall performance of MCHS.
Weerapun [15]	Zigzag	SiO_2/H_2O H_2O	Comparison is made between silicon oxide nanofluid and water to determine the thermal and hydraulic performance of different coolant in MCHS with multiple zigzag flow channels. The surface temperature of MCHS is affected by the heat transfer capability of coolant and nanofluid with 0.6% volume fraction provides highest heat transfer performance. The Nusselt number of nanofluid is higher than pure water and it increases with increasing particle concentration. The heat transfer using nanofluid is about 8% better than pure water. There is no significant pressure drop when using nanofluid compared with pure water and the findings conclude that nanofluid is potential to be applied in MCHS.

2.2 Definition of nanofluid

The term “nanofluid” is used to describe a fluid that consists of solid nanoparticles with average size of less than 100 nm suspended on it [16]. The term “nanofluid” is redefined later which include any nano-sized particles of metallic, non-metallic and polymeric mixed with non-carcinogenic base fluid [17]. Previously, geometrical modification is the only way to enhance the heat transfer performance of various heat exchanging systems. For such reason, researchers have keen interest to improve the heat transfer performance to overcome the limitation. Liquid cooling is one of the methods used to accelerate the heat transfer process from heat exchanging systems. The conventional fluid used such as oil, water, and water-glycol do not possess high thermal conductivity. A researcher, named Maxwell came out with the idea to enhance the thermal conductivity of fluid by adding solid particles into conventional fluids [18]. Researchers and scientists found that suspension of metal particles of millimetre or micrometre size is capable to enhance the heat transfer process. The metal particles such as silver and copper are used because they exhibit much higher thermal conductivity (about 400 to 500 times) than the base fluid. However, the drawback of using milli or micron size particles is that it caused sedimentation and aggregation which results in corrosion or blockage in heat exchanging systems. Later on, researchers and scientist work on improving the thermal conductivity of fluid by using nano size particles. A researcher, named Choi succeeded in development of the new class of heat transfer fluids by suspending nano size solid particles into base fluid [19].

2.2 Classification of Nanofluid

2.2.1 Nanoparticle material

Nanofluid is categorised into various classes based on the types of nanoparticles suspended into the base fluid. The common types of nanoparticles are metallic, non-metallic (carbon based or nanocomposites) and combination of both which is hybrid nanofluid [20]. The nanofluid can be formed from metallic nanoparticles of single element such as copper (Cu), silver (Ag), aluminium (Al), and iron (Fe). Besides that, the nanofluid can be formed from metallic oxide nanoparticles of single element such as copper oxide (CuO), aluminium oxide (Al_2O_3), titanium oxide (TiO_2), and silicon oxide (SiO_2). Other than that, the nanofluid can be formed from two or more different metals nanoparticles such as copper zinc (Cu-Zn), iron nickel (Fe-Ni), silver copper (Ag-Cu) and these combinations are known as metallic alloy nanoparticles. In addition, the nanofluid can be formed from multielement oxides nanoparticles such as copper zinc iron oxide ($CuZnFe_4O_4$), nickel ferrite ($NiFe_2O_4$), and zinc ferrite ($ZnFe_2O_4$). Moreover, the nanofluid can be formed from metal carbides or metal nitrides nanoparticles such as silicon carbide (SiC), boron carbide (B_4C), zirconium carbide (ZrC), silicon nitride (SiN), titanium nitride (TiN), and aluminium nitride (AlN). Last but not least, the nanofluid can be formed from carbon nanoparticles such as graphite (C), carbon nanotube (CNT), and diamond (C). The Table 1 below shows the thermal conductivity of different nanoparticles that are commonly used.

Table 2
Thermal conductivity of common nanoparticles [21], [22]

Materials		Thermal conductivity (W/mK)
Metals	Aluminium (Al)	205
	Copper (Cu)	385
	Gold (Au)	314
	Iron (Fe)	79.5
	Silver (Ag)	406
Metal oxide	Aluminium oxide (Al_2O_3)	40
	Copper oxide (CuO)	76
	Iron oxide (Fe_2O_2)	7
	Tin oxide (SnO_2)	36
	Zinc oxide (ZnO)	29

2.2.2 Nanoparticle base fluid

Nanofluid is categorised into various classes based on the types of base fluid used. The common types of base fluid are water-based, aqueous based, and non-aqueous based [23]. An example of non-aqueous base fluid are ethylene glycol (EG) and oils. The selection of base fluid for nanofluid is solely depend on the field of application. For instance, oil based nanofluids are used as coolant in manufacturing industries for high temperature usage whereas water based or EG based nanofluids are used as coolant in pipes or channels [24]. The selection of base fluid is critical as it plays a major role in enhancing the thermal conductivity of nanofluid. It is because nanofluid is produced by using large volume fraction of base fluid and small volume fraction of nanoparticles. Hence, the composition of base fluid is dominant over nanoparticles in nanofluid and proper evaluation is necessary to select the most suitable base fluid. In general, the nanofluid will exhibit higher thermal conductivity when it is prepared using base fluid with higher thermal conductivity. Likewise, the nanofluid will exhibit lower thermal conductivity when it is prepared using base fluid with lower thermal conductivity. However, this is not the exact case every time because its behaviour may subject to change according to different condition. For instance, the suspension of nanoparticles in ethylene glycol shows higher enhancement in thermal conductivity than water although the thermal conductivity of water is three times higher than ethylene glycol [25]. Researchers and scientists have identified that such behaviour is related to the degree of dispersibility of nanoparticles in base fluids. The dispersibility refers to the uniform distribution of nanoparticles in the base fluid to form a homogenous solution. A researcher attempts to explain the “base fluid effect” by relating it to interfacial thermal resistance of base fluid [26]. The ethylene glycol base fluid has lower interfacial thermal resistance than water and thus provides better wettability. Hence, ethylene glycol appears to be more compatible for nanoparticles to be suspended in it compared to water. A recent study has been performed to study the effects of suspending aluminium oxide (Al_2O_3) nanoparticles in ethylene glycol and distilled water [27]. It is found that the concentration of nanoparticles has a significant influence in thermal conductivity of ethylene glycol based nanofluid. In contrast, it is found that the temperature of distilled water has a significant influence in thermal conductivity of distilled water based nanofluid. Therefore, ethylene glycol based nanofluid is favoured in application where concentration is changed constantly whereas distilled water based nanofluid is favoured in application where temperature is changed constantly.

2.3 Advantages of Nanofluid

The nanofluid is prepared by suspending nano size particles into base fluid to form a colloidal suspension. The primary advantage of suspending nanoparticles into conventional fluids is significant enhancement in effective thermal conductivity of the fluid. The effective thermal conductivity is a term that is introduced to provide an accurate representation of the nanofluid behaviour. In brief, the “effective” term implies that the thermal conductivity of nanofluid which consists of nanoparticles and base fluid is affected and not only thermal conductivity of base fluid is affected [28]. The effective thermal conductivity depends on the volume fraction of nanoparticles where higher volume fraction provides more increment. The enhancement in effective thermal conductivity of nanofluid is more likely to improve the heat transfer performance in various heat exchanging systems. Besides that, the nanoparticles provide large surface area to volume ratio between the particles and the surrounding fluid. Due to large surface area of nanoparticles, there is presence of more heat transfer surface between the particles and the surrounding fluid [29]. Consequently, the higher heat transfer surface of nanofluid promotes heat transfer more effectively than milli or micron size particles. Thus, there is no downside to shift from using milli or micron size particles to nano size particles as it provides large surface area and improvement in heat transfer performance. Furthermore, the nanoparticles are extremely small in which the agglomeration effect which cause clogging of flow passage is reduced [16]. As stated previously, the milli or micron size particles often cause blockage and make it difficult to be employed in the heat exchanging systems with small flow passage. The invention of nanofluid is able to overcome the limitation because they are extremely small and therefore can flow pass the channels smoothly. Moreover, the suspension of nanoparticles in conventional fluids produce Brownian motion which will lead to better heat transfer performance. It is mainly due to the effect of Brownian motion which increase the interaction and collision between the particles and the surrounding fluid [30]. Brownian motion refers to the collision of molecules with surrounding medium which cause random motion of particles in fluid [31]. Brownian motion influence the thermal conductivity of nanoparticles in two ways such that one way is direct manner and another way is indirect manner. The nanoparticles can facilitate the heat transfer through solid-solid transport of heat between the particles and nano convection between the nanoparticles and the surrounding fluid [32]. The former heat transfer process is known as direct manner and the latter heat transfer process is known as indirect manner. As a result, the performance of nanofluid is believed to surpass the conventional fluid in heat transfer application.

2.4 Influential factor of performance of nanofluid

2.4.1 Surfactant

Surfactants are active chemical compound that are added into a liquid to reduce its surface tension. Presence of interfacial tension between nanoparticles and base fluid can be lowered when surfactant is added [21]. Addition of surfactant into nanofluid is necessary as it can prevent the sedimentation of nanoparticles. The primary reason of addition of surfactant into nanofluid is to enhance its stability. A small amount of surfactant is able to stabilise the nanofluid for longer time by altering the characteristic of the surface of nanoparticles.

The surfactant is comprised of a head which is hydrophilic (attract water molecules) and a tail which is hydrophobic (repel water molecules). The hydrophilic head is electrically charged and the types of surfactants used can be distinguished based on the charge on the hydrophilic head. A positively charged surfactant is known as cationic surfactant. The examples of cationic surfactants are cetrimonium bromide, benzalkonium chloride, alkyl ammonium chloride and etc. A negatively charged surfactant is known as anionic surfactant. The examples of anionic surfactants are sodium dodecyl sulphate, sodium lauryl ether sulphate, dioctyl sodium sulfosuccinate and etc. A neutrally charged surfactant is known as non-ionic surfactant. The examples of non-ionic surfactants are polysorbates, sorbitans, cocamide and etc. The effect of adding surfactant into nanofluid is that it creates a layer around the nanoparticles such that the surfactant and nanoparticles have same electric charges [21]. The like-charged between surfactant and nanoparticles produce a strong electrostatic repulsion among the nanoparticles so that aggregation does not occur. However, surfactant is not suitable for high temperature application, especially for temperature above 60℃ [33]. It is because high temperature cause degradation and break the bonding between the surfactant and nanoparticles. Since the bonding between them is damaged, sedimentation of nanoparticles is likely to occur and the nanofluid is no longer stable [34].

Kim *et al.*, [35] has performed a study on thermal conductivity of metal oxide nanofluid and found that the nanofluid become unstable without addition of surfactant [35]. As a result, the thermal conductivity of the nanofluid decreased rapidly and only become stable after addition of surfactant. Byrne et.al has performed an experimental study on the CuO nanofluids in microchannels with and without suspension enhancers and found that addition of surfactant is able to enhance the dispersion of nanoparticles in nanofluid and decrease the nanoparticles average size [36]. It is discovered that nanofluid with surfactant has higher heat transfer rates compared to nanofluid without surfactant and pure water. The study also demonstrates that nanofluid without surfactant at 0.1% concentration is highly unstable and more susceptible to agglomeration and settling. Shamsuddin et.al has performed a study on nanofluid cooled microchannel heat sink with carbon nanotube using different types of surfactants and found that CNT nanofluid mixed lignin and sodium polycarboxylate show different dynamic viscosity [37]. Other thermophysical properties such as thermal conductivity, density, and specific heat capacity remain the same while the dynamic viscosity changes according to the type of surfactant used. CNT nanofluid mixed with lignin has a dynamic viscosity of 0.00107259 Ns/m^2 while CNT nanofluid mixed with sodium polycarboxylate has a dynamic viscosity of 0.00138372 Ns/m^2. The addition of surfactant alters the dynamic viscosity of the nanofluid which is considered one of the influential factors that affects the performance of MCHS. The thermal resistance and pumping power are lower when using lignin as surfactant.

2.4.2 Nanoparticle size

Nanofluid contains nanoparticles that ranged from 1 to 100 nanometres (nm) in diameter mixed with base fluid. The nanofluid produced can be varied in size or diameter and it is believed that the size has a significant influence on thermal conductivity and viscosity of nanofluid. A study has been conducted to investigate the influence of specific surface area of nanoparticles on thermal conductivity of nanofluid [38]. As the specific surface area increases, the thermal conductivity ratio increases first and decreases later on. To be exact, the thermal conductivity ratio increases initially and decreases after the specific surface area exceed 25 m^{2}g^{-1}. There is an inverse relationship between the specific surface area and nanoparticle sizes. The specific surface area increases when the nanoparticle sizes decreases and vice versa. The increase in specific surface area causes nanoparticles to have larger interfacial area.

Since heat transfer occurred at particle fluid interface, a smaller nanoparticles size with larger interfacial area has better heat transfer and therefore higher thermal conductivity. Similar remark has been made in other study regarding the influence of nanoparticles surface area on thermal conductivity of nanofluid. It is discovered that the effective thermal conductivity of nanofluid is improved because reduction of nanoparticle sizes caused an increase in thickness of nanolayer [39]. The smaller nanoparticles size provides larger surface area and caused an increase in thickness of nanolayer. Yang et.al has performed a study to investigate the factors that affect the thermal conductivity of aluminium oxide water nanofluid [40]. Aluminium oxide nanoparticles with different sizes such as 20 nm and 40 nm are selected for the study. As expected, the thermal conductivity ratio of 20 nm nanoparticles size is higher than 40 nm nanoparticles size. Such phenomena are related with the force exist within the nanoparticles itself.

The Van der Waals force which is the attraction forces between the molecules is stronger when the nanoparticles size is smaller. As a result, the nanoparticles move frequently such that the interactions of nanoparticles and the surrounding fluid become stronger. Thus, the energy transfer is improved and eventually lead to augmentation in thermal conductivity. A study of CNT nanofluid with different nanoparticles size is conducted to determine the thermal conductivity enhancement [41]. The larger specific surface area due to smaller nanoparticles is associated with higher water molecules near the surface of CNT nanoparticles. The water molecules are attached on the CNT nanoparticles to form an interfacial layer which can enhance the thermal conductivity of nanofluid. Wang et.al has performed a numerical study to determine the effect of different nanoparticles size on heat transfer performance of MCHS with trapezoidal grooves [42]. The nanoparticles size that are employed in this study are 5 nm, 10 nm, 20 nm, 40 nm, and 80 nm. The Brownian diffusion and thermophoretic diffusion are greater when smaller nanoparticles are suspended. Greater diffusion leads to more aggressive Brownian motion which in turn provides greater enhancement in heat transfer. However, the heat transfer rate caused by Brownian diffusion and thermophoretic diffusion are dependent on the nanoparticles size. When the nanoparticles size is smaller than 20 nm, much heat can be transported away by Brownian motion.

In contrast, much heat can be transported away by thermophoresis when the nanoparticles size is greater than 20 nm. Comparisons are made between heat transfer coefficient and various volume concentration with different particle size. It is deduced that increased in volume concentration increased the heat transfer coefficient whereas increased in particle size decreased the heat transfer coefficient. Yue *et al.*, [42] has performed a numerical study to determine the effect of particle diameter of nanoparticles on hydraulic and thermal performance of manifold MCHS [42]. It can be observed that the temperature of solid and fluid regions is higher and the temperature variation across the surface is also higher when the diameter of nanoparticles is larger. The higher temperature observed in these regions imply that the heat transfer coefficient is lower. Furthermore, the viscosity and thermal conductivity of nanofluid decrease with larger diameter of nanoparticles. At fixed volume fraction, the number of nanoparticles available in the nanofluid is lesser for larger diameter of nanoparticles. The induced shear stress caused by nanoparticles and the surrounding fluid is lesser which results in lower viscosity. On the other hand, the thermal conductivity is influenced by the effect of Brownian motion and surface area of nanoparticles. The effect of Brownian motion is weakened as the diameter of nanoparticles is increased. The surface area of nanoparticles is lesser as the diameter of nanoparticles is increased. Less thermal energy is allowed to transfer when surface area is decreased. Consequently, the thermal conductivity is decreased for larger diameter of nanoparticles. Mohammadpour *et al.*, [44] has performed a numerical study to investigate the effect of suspension of alumina particle with different diameter sizes in microchannel [44]. The diameter sizes of alumina particle that are chosen for the study are 50 nm, 75 nm, and 100 nm. The study is concerned about the effect of nanoparticle diameter on temperature distribution at the bottom of MCHS. The result revealed that nanoparticle of 50 nm has highest local temperature reduction. The local temperature reduction at the bottom is almost similar to the case of nanoparticle of 50 nm when nanoparticle of 75 nm is used. As the nanoparticle size is increased to 100 nm, the cooling effect is reduced and the variation of temperature at the bottom is roughly 2 K. Also, the vortices profile shows that secondary particle vortex propagates towards the microchannel outlet with nanoparticle of 50 nm. Therefore, the presence of vortices promotes better heat transfer and uniform temperature distribution.

2.4.3 Nanoparticle concentration

Concentration is a common term used to express the amount of substance present in another given amount of substance. Nanoparticle concentration is used to state the amount of nanoparticles present in the known amount of base fluid. Two usual terms used by researchers to describe the nanoparticle concentration are mass fraction and volume fraction. It is represented as dimensionless quantity to express the composition of nanoparticles in nanofluid where mass fraction is the percentage of nanoparticles by weight (wt%) and volume fraction is the percentage of nanoparticles by volume (vol%). The mass fraction is defined as the ratio of mass of nanoparticles over total mass (mass of nanoparticles and mass of base fluid). The volume fraction is defined as the ratio of volume of nanoparticles over total volume (volume of nanoparticles and volume of base fluid).

To obtain the volume of nanoparticles, the mass of nanoparticles can be divided by the density of nanoparticles. Kanti et.al has performed an experimental study using coal fly ash nanoparticles suspended in water to determine its effectiveness in heat transfer application [45]. The thermal conductivity of fly ash nanofluid as function of volume fraction is investigated. Various volume fractions range from 0.1 to 0.5 are evaluated in the study. The thermal conductivities show different improvement compared with base fluid at 30 ℃. The improvements are 1.13%, 2.42%, 3.72%, 4.85%, and 5.98% for volume fractions of 0.1, 0.2, 0.3, 0.4 and 0.5 respectively. Arasu et.al has performed an experimental study using titania water nanofluid and titania silver water nanocomposite fluid to investigate the thermal conductivity enhancement [46]. The thermal conductivity of titania water nanofluid for temperature of 35 ℃, 40 ℃, 50 ℃, and 60 ℃ improved by 2.3%, 9.98%, 8.3% and 8.53% as the volume fraction is increased from 0.1% to 0.4%. The thermal conductivity of titania silver water nanocomposite fluid for temperature of 35 ℃, 40 ℃, 50 ℃, and 60 ℃ improved by 9.1%, 9.4%, 9.73% and 20.5% as the volume fraction is increased from 0.1% to 0.4%. From the results, nanocomposite fluid showed better enhancement in terms of thermal conductivity compared to nanofluid.

Therefore, suspension of silver nanoparticles into the nanofluid is practical since it further improved the thermal conductivity of the existing nanofluid. Interestingly, the thermal conductivity is almost the same for nanocomposite fluid at 0.1% volume fraction and nanofluid at 0.4% volume fraction. Thus, the same enhancement in thermal conductivity can be achieved with four times less volume fraction when silver nanoparticles of 9.5 wt% is added into titania water nanofluid. Rabiei et.al has performed a numerical study using graphene platinum water nanofluid to investigate the performance of a cylindrical microchannel heat sink equipped with wavy fins [47].

The heat transfer coefficient is evaluated along the microchannel and it is found that the increased in mass fraction of nanoparticles cause an increased in heat transfer coefficient. Similarly, the increased in mass fraction of nanoparticles reduced the thermal resistance of MCHS. The mass fraction of 0% and 0.1% nanoparticles are used to evaluate the temperature distribution of MCHS. It can be observed that using 0.1% mass fraction of nanoparticles has the lowest maximum temperature and this can be ascribed to the enhancement in thermal conductivity due to higher concentration of nanoparticles. Souby *et al.*, [48] has performed a numerical study using binary or ternary hybrid nanofluid to investigate the thermohydraulic performance of rectangular MCHS [48]. The effect of volume concentration of nanofluid on temperature distribution along the bottom wall of MCHS are studied. The wall temperature is much lower when using higher concentration of nanofluid. The CuO/MgO/TiO_2 water ternary nanofluid showed a better cooling capability than MgO/TiO_2 water binary nanofluid. It is because employing ternary nanofluid showed a more uniform temperature distribution, as observed from the temperature contour. The ternary nanofluid achieved a reduction of 28.18 K in temperature and 33.7% in thermal resistance, whereas the binary nanofluid achieved a reduction of 16.63 K in temperature and 18.96%% in thermal resistance. Thus, combination of several types of nanoparticles to produce ternary nanofluid is promising since it offered the highest heat transfer rate. Jamshidmofid and Bahiraei has performed a numerical study using hybrid nanocomposite to determine the effect of utilising novel hybrid nanofluid on performance of MCHS that is equipped with sinusoidal cavities and rectangular ribs [49]. By increasing the nanoparticles volume fraction from 0% to 0.2% and Reynolds number from 100 to 500, the average wall temperature of MCHS reduced from 331 K to 309 K. The raising of nanoparticles volume fraction and Reynolds number allowed more heat to be transported away from wall to the adjacent fluid. The convection heat transfer coefficient is improved which results in lower wall temperature. In addition, the thermal resistance of MCHS is investigated at various Reynolds numbers and concentrations. The raising of nanoparticles volume fraction and Reynolds number caused decline in thermal resistance. Thus, the lowest thermal resistance is obtained when the nanoparticles volume fraction is 0.2% and Reynolds number is 500.

2.4.4 Nanoparticle shape

Nanoparticles can have a variety of shapes such as cylindrical, spherical, platelet, blade, brick and etc. The shapes of nanoparticles can be further classified into different aspect ratios. High aspect ratio implies that the nanoparticles length is longer than its width. Example of high aspect ratio of nanoparticles are nanotubes, nanorods, and nanowires with shapes such as helices, zigzags and belts. Low aspect ratio implies that the nanoparticles length is shorter than its width. Example of low aspect ratio of nanoparticles are those with spherical, cubic, prism, oval shape and etc. Most of the previous studies have found that nanoparticle shape that offered higher surface area to volume ratio generally possessed higher thermal conductivity. Maheshwary *et al.,* [50] has performed a study to investigate the effect of nanoparticles shape on thermal conductivity of titania water nanofluid. The shapes that are used to prepare the titania water nanofluid are spherical, cubic, and rod. The suspension of different shapes of nanoparticles into base fluid have considerable effect on thermal conductivity of nanofluid. It is because different shapes of nanoparticles have different surface area. In fact, heat transfer is directly proportional to surface area when other variables are kept constant. Therefore, a higher surface area corresponds to higher heat transfer. The cubic shape nanoparticles have the highest thermal conductivity since it has the highest surface area.

Zheng *et al.,* [51] has performed a study to investigate the influence of nanoparticles properties on thermal conductivity of nanofluid. Three different shapes of nanoparticles including spherical, planar, and bar shape are studied. The surface area to volume ratio for spherical, planar and bar shape are 3, 7.061, and 4.375 respectively. The thermal conductivity enhancement ratio for spherical, planar and bar shape are 1.15, 1.21, and 1.23 respectively at 0.01 nanoparticles volume fraction. From the results, it is discovered that higher surface area to volume ratio leads to higher thermal conductivity enhancement ratio. However, the contribution of nanoparticles shape for thermal conductivity enhancement is limited to a certain extent. As the nanoparticles volume fraction is larger than 3%, the influence of nanoparticles shape is not that significant to alter the thermal conductivity of nanofluid. For this reason, suspension of different shapes of nanoparticles in nanofluid exhibit almost similar enhancement. Monavari *et al.,* has performed a numerical study using boehmite nanofluid to determine the effect of different nanoparticles shape on thermohydraulic performance of MCHS [52].There are five nanoparticle shapes examined in the study including platelet, blade, cylinder, brick and oblate spheroid. The heat transfer coefficient for nanoparticles with platelet shape is the highest, follow by cylinder, blade, brick, and oblate spheroid shape. Unexpectedly, the relative thermal conductivity for nanoparticles with platelet shape is the lowest. The velocity magnitudes for different nanoparticles shape are evaluated and nanoparticles with platelet shape has the highest velocity. Owing to higher velocity, the nanoparticles with platelet shape attains the maximum heat transfer coefficient. The bottom wall temperatures for several nanoparticles shapes are observed and it is found that the results are in good agreement with each other. Since the nanoparticles with platelet shape has the maximum heat transfer coefficient, the bottom wall temperature must be the lowest. The temperature contour indicates that the nanoparticles with platelet shape has the lowest maximum temperature at the bottom wall.

Shasavar *et al* has performed a numerical study using boehmite alumina nanofluid to determine the nanoparticle shape effect on thermal performance of helical MCHS [53]. There are five nanoparticle shapes examined in the study including platelet, blade, cylinder, brick and spherical. The convective heat transfer coefficient records the highest and lowest enhancement when using platelet shape and spherical shape respectively. The flow regime is identified as a parameter that influence the cooling performance of nanofluid. In laminar regime, the convective heat transfer coefficient is improved about 25% using nanoparticles with platelet shape at Reynolds number of 500. In turbulent regime, the convective heat transfer coefficient is improved about 22.5% using nanoparticles with platelet shape at Reynolds number of 5000. In this case, the nanofluid found its application more suitable in laminar regime than turbulent regime. The thermal resistance which is an indicator of heat transfer performance of MCHS is also evaluated. A lower thermal resistance is desired for better heat dissipation from MCHS to surrounding fluid. The nanoparticles with platelet shape attain the lowest thermal resistance whereas the nanoparticles with spherical shape attain the highest thermal resistance.

2.4.5 Nanoparticle material

Nanoparticles can be categorised into different types of materials such as metal, metal oxide, ceramic, carbon and etc. Examples of metal type nanoparticles include zinc, silver, iron, copper, gold and etc. Metal nanoparticles are sometimes unstable and difficult to be prepared due to formation of oxide or nitride. Examples of metal oxide type nanoparticles include aluminium oxide, zinc oxide, magnesium oxide, silicon oxide, ferrosoferric oxide and etc. Metal oxide nanoparticles have unique properties and better stability and these features make it applicable to many areas. Ferrosofferic oxide is the most unique nanoparticles as it exhibits magnetic property and its behaviour can be altered by magnetic field [54]. Examples of carbon type nanoparticles are carbon nanotube, nano diamond, graphene and etc. Carbon nanoparticles have extremely high thermal conductivities than other kind of nanoparticles and this enables them to be applicable in thermal management. To enhance the heat transfer performance, it is suggested to select the nanoparticles material with higher thermal conductivity.

Comparison is made between different nanoparticles suspended in the same base fluid. Magnesium oxide nanoparticle size is 40 nm while aluminium oxide nanoparticle size is 13 nm. Although the particle sizes are different, magnesium oxide showed higher thermal conductivity enhancement [55]. Past research indicates that smaller nanoparticle size is more advantageous to thermal conductivity enhancement [40], [41]. However, the finding of the current study demonstrates that larger nanoparticle size provides higher enhancement and this result is different from the previous research. A possible explanation for this might be that nanoparticles material with higher thermal conductivity has significant effect compared to nanoparticles size in augmenting base fluid thermal conductivity. A comparative study of different nanoparticles dispersed into ethylene glycol base fluid is performed to examine the thermal conductivity enhancement. The relative enhancement in thermal conductivity compared to base fluid is 5% for copper, 10% for aluminium silver, 13% for iron, 15% for aluminium copper and 72% for carbon nanotube [56]. Certainly, carbon nanotube achieved the highest thermal conductivity among all and this can be explained by the superior thermal conductivity of the material itself. In another major study, the researcher found out that the highest thermal conductivity is achieved despite the suspension of nanoparticle material with lowest thermal conductivity [57].

The finding is also agreed by another researcher with the statement that the thermal conductivity enhancement is higher using fluid with lower thermal conductivity [58]. The thermal conductivity for various nanoparticles such as titanium oxide, copper oxide, aluminium oxide, and ferrosoferric oxide are 11.7 W/mK, 20 W/mK, 36 W/mK, and 7 W/mK respectively [57]. The enhancement of 38% is observed for ferrosoferric oxide, while the enhancement of 30% is observed for the other nanoparticles. The researcher relates it to the effect of nanoparticles alignment and clustering which mainly contribute to enhance the thermal conductivity of ferrosoferric oxide higher than other nanoparticles. Yan et.al have performed a numerical study to determine the effect of different types of nanofluid in trapezoidal cross section MCHS [59]. A careful examination is performed to understand whether the thermal conductivity of nanoparticle material is the reason that influence the performance of MCHS. The thermal conductivity of silicon carbide and titanium oxide are 490 W/mK and 8.4 W/mK respectively. The dispersion of 9% volume fraction of silicon carbide and titanium oxide raised the thermal conductivity of water and attained a value of 0.809 W/mK and 0.771 W/mK respectively. The cooling effect of two nanofluids are compared and silicon carbide nanofluid dissipates heat better. Based on this result, it is clear and concise that silicon carbide nanofluid provides better heat transfer performance and this is mainly due to slightly higher thermal conductivity than another nanofluid. Khetib *et al.*, have performed a numerical study to investigate the effect of addition of aluminium oxide and copper oxide nanoparticles in wavy MCHS [60]. The results showed that addition of nanoparticles have positive contribution to MCHS performance, compared to pure water.

The thermal resistance is greatly reduced using nanofluid as the cooling fluid and the least thermal resistance is obtained using aluminium oxide nanofluid. The temperature distribution at the bottom of the MCHS is evaluated and it is observed that using aluminium oxide nanofluid provides better temperature uniformity. It is obvious that the aluminium oxide nanofluid performs much better than other cooling fluid, and the reason for this is due to higher thermal conductivity of the nanoparticle base material. The use of aluminium oxide nanofluid therefore appears to be promising alternative to pure water. Kalteh et.al have performed a numerical study to investigate the forced convection heat transfer of aluminium oxide and copper nanofluid in double layered MCHS [61]. At a flow rate of 4.57 ml/min and particle volume fraction of 0.03, the average Nusselt number increased by about 29.41% and 9.87% for copper nanofluid and aluminium oxide nanofluid with respect to pure water. The Nusselt number is used as an indicator to study the enhancement of heat transfer due to convection over conduction. Since the copper nanofluid possessed the highest Nusselt number, it provides greater heat transfer enhancement in MCHS. The thermal properties such as thermal conductivity of copper nanoparticle is examined, and it is found that copper nanoparticle has the highest thermal conductivity. Therefore, the use of nanoparticles with higher thermal conductivity is capable to increase the heat transfer efficiency.

2.5 Application of nanofluid in microchannel heat sink (MCHS)

Thermal energy refers to the energy contained within a system due to movement of particles. In industrial systems and consumer products, thermal energy is transferred into or out of the system, either to supply energy into the system or to extract energy out of the system. According to second law of thermodynamics, the useful energy in the system is always less than the input energy. Some form of the energy is converted into thermal energy and is rejected to the environment. The thermal energy extracted out of the system is the result of waste heat, because this form of energy is not utilised to produce work. Given the rise of usage of these devices, there is an essential need to improve the heat transfer performance and reduce energy loss that lower the efficiency of system. Currently, the major challenge restricting the use of high heat flux system is the low heat removal rate from these devices.

A few examples of high heat flux system are electronic circuits, solar energy system, air conditioning system, and micro-electromechanical systems (MEMS). Intensification of heat transfer is the only technique to facilitate heat removal from these devices, with the aim of lowering the maximum temperature. The two methods to improve heat transfer performance are active method and passive method. As the name suggest, active method requires the use of external energy to sustain the enhancement, whereas passive method does not require the use of energy to accomplish the same outcome. The source of external energy is derived from a fan or a pump, and this will incur additional cost to adopt active method. Passive method, on the other hand, is more economical to be employed because intensification of heat transfer can be achieved by modification of fluid property, surface shape, geometry, and etc.

Conventional heat transfer fluids such as water, oil, and ethylene glycol are often used in heat transfer system, despite some disadvantage such as low thermal conductivity. The low thermal conductivity of heat transfer fluid restrained heat transmission from heat source to fluid, causing less amount of heat being transported away. Considering this, it is sensible to disperse solid particles into the heat transfer fluid to raise the intrinsic thermal conductivity. The concept to disperse solid particles has been practiced for a long time, starting with the use of millimetre or micrometre sized particles. The use of these particles did not yield promising results, as it led to some severe problem such as poor suspension stability. The reason for outcome is mainly because the milli or micron size particles are fairly large.

Table 2
Application of nanofluid in MCHS

Author	Nature of work	Geometry	Flow regime	Reynolds number	Nanofluid type	Remarks
Ahmed *et al.,* [62]	Experimental	Rectangular double layer Triangular double layer	Laminar	50 - 300	Al_2O_3/H_2O SiO_2/H_2O 0.3 - 0.9% vol	At fix pumping power of 0.1 W and channel number of 24, both nanofluid show decrease in thermal resistance when the volume concentration is increased. At different pumping power, both nanofluid show increase in pressure drop when the volume concentration is increased. It is worthwhile to note that aluminium oxide shows 16.1% pressure drop when the volume concentration is increased from 0 - 0.9%. Aluminium oxide has the lowest thermal resistance but silicon oxide is more preferred due to lower pressure drop.
Ardah *et al.,* [63]	Numerical Single phase	Straight double layer	Laminar	50 - 400	Al_2O_3Cu/H_2O $Al_2O_3SiO_2/H_2O$ 0 - 5% vol	At fix Reynolds number, the addition of hybrid nanoparticles in water will lower the bottom wall temperature. At higher nanofluid concentration, uniformity in bottom wall temperature is achieved. The maximum temperature reduction in bottom wall is 9.2℃ and 6.2℃ using alumina silica nanofluid and alumina copper nanofluid. Alumina silica nanofluid has lower thermal resistance and therefore it demonstrates better heat transfer performance. The increment in nanofluid concentration has significant effect in pumping power where alumina silica nanofluid requires 95% more pumping power.
Wang *et al.,* [64]	Numerical Single phase	Rectangular with pin fins Rectangular with vortex generators	Laminar	340 - 640	Al_2O_3/H_2O Distilled water 1 - 4 % vol 20 - 40 nm	At 4% volume fraction of nanofluid, the effect of different nanoparticle diameters on overall performance factor and total thermal resistance are evaluated. It is deduced that the nanoparticle diameter that is

						smaller (20 nm) tends to improve the thermal conductivity and lead to augmentation of overall performance. 20 nm nanoparticle provides 5.7% and 5.1% improvement in overall performance factor and total thermal resistance compared to distilled water. It is found that nanoparticles with smaller diameter and higher concentration provides higher heat transfer performance.
Adio *et al.*, [65]	Numerical Single phase	Interrupted with fillets Interrupted chamfers Interrupted inverted fillets	Laminar	100 - 700	Al_2O_3/H_2O H_2O 0.5 - 4% vol	At fix Reynolds number of 100, the increment of nanoparticle concentration from 0 to 4% provides an improvement of 43.69% in convective heat transfer coefficient. At all Reynolds number evaluated, the thermal resistance is lowered when using aluminium oxide nanofluid compared to pure water. At higher Reynolds number and concentration, the bottom surface temperature of MCHS is decreased and uniformity in temperature is achieved. The PEC of MCHS is evaluated and it shows that using nanofluid is more preferred than pure water although pressure drop is higher.
Adio *et al.*, [66]	Numerical Single phase	Manifold rectangular ribs Manifold semi-circular ribs Manifold forward triangular ribs Manifold backward triangular ribs	Laminar	100 - 400	CuO/H_2O 0.5 - 4% vol	At Reynolds number of 400 and 4% volume fraction, the MCHS show more uniform temperature distribution. The increment in nanofluid concentration along with Reynolds number provides the highest reduction in surface temperature. Also, it is less likely that hotspot is formed on MCHS substrate because the maximum substrate temperature is lowest when the Reynolds number and nanofluid concentration is highest. The PEC of MCHS is evaluated and it shows that nanofluid at 4% volume fraction and Reynolds number of 100 provides 6.5% enhancement compared to pure water.
Ali *et al.*, [67]	Numerical Single phase	Rectangular without fin	Laminar	100 - 350	Al_2O_3/H_2O 0 - 3% vol	At all Reynolds number, the addition of nanoparticles has an effect on the Nusselt number. However, the effect is not too

		Rectangular with rectangular fin Rectangular with twisted fin Rectangular with zigzag fin				significant as the Nusselt number only increases slightly. To be concise, the Nusselt number at 1%, 2% and 3% volume fraction and Reynolds number of 350 show an increment of 0.19%, 1.31% and 0.67%. At highest nanofluid volume fraction, the temperature difference between fluid inlet and bottom wall average temperature is the lowest. This is mainly because higher thermal conductivity and lower specific heat capacity of nanofluid allows heat to be absorbed faster.
Mukesh Kumar, Arun Kumar [68]	Numerical Single phase	Circular	Laminar	200 - 600	Al_2O_3/H_2O H_2O 0.25 - 0.75% vol	At all Reynolds number, the thermal resistance of MCHS decreases with increasing in nanofluid concentration. The heat transfer coefficient of nanofluid is increased about 12%, 26% and 40% at 0.25%, 0.5% and 0.75% volume fraction compared to pure water. The thermal resistance is lowered about 11%, 25% and 39% at 0.25%, 0.5% and 0.75% volume fraction compared to pure water. It is also observed that power dissipation of electronic components is lowered by 20% using 0.75% volume fraction nanofluid. Hence, it is evident that nanofluid is suitable to be used in electronic system.
Elbadawy, Fayed [69]	Numerical Single phase	Rectangular with single stack Rectangular with double stack	Laminar	200 - 1500	Al_2O_3/H_2O 0.01 - 0.05% vol	At all nanofluid volume fractions, the temperature of fluid rises along the channel length. This is mainly because the heat is absorbed by the fluid when it flows along the channel. However, when nanoparticles volume fraction is increased, the temperature distribution is decreased which implies that higher volume fraction improves the heat transfer coefficient resulting in enhancing cooling performance. This is useful because the required area for heat transfer is reduced for same cooling load. At Re = 1500 and 0.05% volume fraction, 62.6% reduction in channel volume is achieved.

Kahani [70]	Numerical Single phase	Rectangular	Laminar	100 - 300	Al_2O_3/H_2O 0 - 1% vol	At Re = 300, the average Nusselt number ratio increases from 1.23 to 1.36 as the nanofluid volume fraction is increased from 0.25% to 1%. The increment of average Nusselt number is due to the suspension of nanoparticles which improves the heat convection coefficient. The size of nanoparticles also has considerable effect on average Nusselt number. When the nanoparticles size changes from 100 nm to 10 nm, the average Nusselt number increases. The reduction of nanoparticles size disrupts the Brownian motion which improves the thermal performance of fluid flow and lead to better MCHS performance.
Pourfattah *et al.,* [71]	Numerical Two phase	Manifold	Laminar	25 - 100	CuO/H_2O 0.02 - 0.04% vol	At all Reynolds number, the increment of nanoparticles volume fraction leads to increment of Nusselt number. The higher heat transfer coefficient and lower specific heat capacity of nanofluid contributes to enhancement of Nusselt number. The improvement of heat transfer coefficient in nanofluid is mainly attributed by increment of particles motion in the base fluid. The heat transfer coefficient is highest when the nanofluid is 0.04 volume fraction. The PEC of MCHS is evaluated and the maximum performance is achieved at 0.02% volume fraction as higher volume fraction has higher pressure drop.
Kumar *et al.,* [72]	Numerical Single phase	Double layer tapered	Laminar	100 - 500	Al_2O_3/H_2O 2 - 7% vol 10 - 40 nm	At all Reynolds number and same volume fraction of nanofluid, the Nusselt number increases and thermal resistance decreases when the nanoparticles diameter is reduced. The thermal performance is enhanced as nanoparticles diameter is reduced because there is increase in surface area to volume ratio which will lead to improvement in thermal conductivity of nanofluid. The improvement in thermal

						conductivity is also cause by Brownian motion and liquid layering of nanofluid. The thermal performance of MCHS is the highest using 10 nm diameter nanoparticle and 7% volume fraction.
Arjun and Rakesh [73]	Numerical Single phase	Circular	Turbulent	0.00009 - 11980	Al_2O_3/H_2O 0 - 5% vol	At different flow regime, the heat transfer coefficient of nanofluid shows different improvement. In laminar flow regime, the heat transfer coefficient improved about 15% when using nanofluid from 0% to 5% volume fraction. In turbulent flow regime, the heat transfer coefficient improved about 12% when using nanofluid from 0% to 5% volume fraction. It is suggested that the nanofluid is employed in laminar flow regime than turbulent flow regime as it provides much more enhancement in heat transfer coefficient. The higher heat transfer coefficient provides better heat transfer performance in MCHS.
Reddy and Vinod [74]	Numerical Single phase	Dimple and protrusion	Laminar	100 - 700	CuO/H_2O 0 - 4% vol	At various nanoparticle volume fraction, the relative Nusselt number, relative friction factor, and thermal performance increase along with increment in Reynolds number. However, there is small increment in relative Nusselt number but not noticeable increment in relative friction factor and thermal performance when the volume fraction is increased. As the volume fraction of nanofluid is increased, the convection heat transfer coefficient and dynamic viscosity is increased while the specific heat capacity is decreased. The lower specific heat capacity weakens the heat transfer performance of MCHS.
Junmei *et al.*, [10]	Numerical Single phase	Rectangular	Laminar	0 - 500	Al_2O_3/H_2O 1 - 4.5% vol	At higher nanoparticle volume fraction, the thermal resistance of MCHS is lowered. The MCHS also experiences a uniform temperature distribution on the base surface. However, there is degradation in the heat transfer performance because the increment in nanofluid volume

						fraction only enhance the thermal conductivity but not specific heat capacity. It is suggested that the nanofluid should have higher thermal conductivity, higher specific heat capacity and less dynamic viscosity for improved performance. Overall, the selected nanofluid is not recommended due to high pumping power penalty.

2.6 Limitation and challenges of application of nanofluid

Application of nanofluid in heat transfer equipment is a double-edged sword, although it intensifies the heat transfer performance, it also increases the pressure drop within the system. This presents an even greater challenge because increase in pressure drop indirectly affect the operating expenses for thermal management practice. In heat and mass transfer, pressure drop is undesirable because it will interrupt the steady flow of fluid. The undesirable condition, if left unattended, will affect the normal operation of the cooling system to dissipate heat away. However, the pressure drop can be recovered with the use of pump, but additional cost is required to increase pumping power to compensate the pressure loss. While the benefit of utilising nanofluid in the heat transfer equipment is significant enhancement in thermal performance, the negative consequence such as pressure drop should not be foreseen.

Developing a clear understanding of fundamental reason that increase the pressure drop in heat transfer equipment is essential. Apart from increasing thermal conductivity, addition of nanoparticles into base fluid also increase viscosity. Thus, to achieve high heat transfer rate, it is required to suspend higher volume fraction of particles into base fluid. However, excessive particles loading lead to enhancement in viscosity of base fluid, which is accompanied by an increase in pressure drop. The viscosity determines the flowability of the base fluid, as high viscosity denotes more resistance for steady flow of fluid. To counter the situation, high pumping power is needed to maintain the flow within the system. Other than volume fraction, the viscosity of base fluid is dependent on nanoparticles size, fluid temperature, nanoparticles shape, and nanoparticles material.

Besides that, formation of stable nanofluid has been a main and challenging task, as it ensures the applicability of nanofluid in various engineering field, such as automobile, energy harvest system, electronic cooling, and thermal storage system. The stability of nanofluid is correlated with thermophysical properties (thermal conductivity and viscosity) of nanofluid, where reduction in colloidal stability also lead to reduction in thermophysical properties. One of the properties that influence heat transfer performance is thermal conductivity. Since the stability of nanofluid gradually decreases with passage of time, the performance of nanofluid for heat transfer also decreases. Hence, the adverse effect of unstable nanofluid is weakening of the enhancement effect of nanoparticles. It is therefore important to address the nanofluid stability issue so that nanofluid can be successfully implemented in heat transfer application.

Since nanofluid is a colloidal suspension, it is prone to instability if the suspended particles form sediments. The suspended particles are subjected to various forces such as Van der Waals attractive forces and electrostatic repulsive forces. The existence of Van der Waals attractive forces among the particles of nanofluid increased the tendency to form clusters or agglomeration. The nanoparticles in the base fluid will form aggregates when the solid particles are attracted to each other. Eventually, the aggregates form sedimentation which cause the solid particles to deposit at the bottom of flow channel due to gravitational force. The existence of electrostatic repulsive forces is to oppose the Van der Waals attractive forces because it inhibits the formation of clusters by preventing the particles to be attracted to each other. For stability of nanofluid, the electrostatic forces should be dominant over Van der Waals forces.

3. Conclusion

The application of nanofluid in engineering application such as microchannel heat sink (MCHS) is reviewed comprehensively. The review has included the classification of nanofluid, advantages of nanofluid, and influential factors of performance of nanofluid. Previously, most of the research of microchannel heat sink only focused on one passive technique (geometrical modification) to intensify the heat transfer performance. Recently, the combination of two passive technique (geometrical modification and fluid additive) is of interest of different researchers due to further intensification of heat transfer performance. Therefore, the review is expected to provide an insight for readers to understand the new class heat transfer fluid before implementation in the MCHS. In the review, the potential of nanofluid and application of nanofluid in MCHS are also presented to update readers the current progress of nanofluid.

Based on the review of journals, the following specific conclusions can be achieved:

1. Suspension of nanoparticles in base fluid (water, oil, ethylene glycol) is shown to be effective to enhance the thermal conductivity of base fluid which improves the heat transfer performance of MCHS.
2. To sustain the enhancement effect of nanoparticles, addition of surfactant is necessary because it ensures the stability of nanofluid. Nanofluid without surfactant is prone to instability and more susceptible to agglomeration.
3. The use of smaller nanoparticles size increase the specific surface area which provide larger interfacial area. As a result, the smaller nanoparticles size has higher thermal conductivity and better heat transfer performance compared to larger nanoparticles size.
4. The concentration of nanoparticles is correlated with the effective thermal conductivity of base fluid. Higher concentration of nanoparticles provide higher effective thermal conductivity and therefore higher heat transfer performance.
5. The nanoparticles shape have an influence on effective thermal conductivity of base fluid. Common shapes of nanoparticles are platelet, blade, spherical, cylindrical, brick, and spherical. The platelet shape has the highest effective thermal conductivity due to higher surface area to volume ratio.
6. The nanoparticles material generally possessed different thermal conductivity. The suspension of nanoparticles material with higher thermal conductivity will result in base fluid with higher effective thermal conductivity compared to nanoparticles material with low thermal conductivity.
7. The drawback of nanofluid is high pressure drop and instability. The pressure drop is undesirable in heat transfer equipment as it can increase the cost to supply additional energy to recover the pressure loss. Therefore, it is necessary to examine the optimum concentration of nanofluid that gives moderate pressure drop and provides enhancement in heat transfer. Besides that, the unstable nanofluid can affect the long term practicability of nanofluid in heat transfer equipment. Addition of surfactant is one of the methods that commonly used by researchers to prepare stable nanofluid. However, there are also other methods available to prepare stable nanofluid which is beyond the scope of this review paper.

Acknowledgement

This research was funded by a grant from Ministry of Higher Education of Malaysia (FRGS Grant R.J130000.7824.4X172).

References

[1] Shadman, Saleh, Christina MM Chin, Eng Hwa Yap, Novita Sakundarini, and Sanjayan Velautham. "The role of current and future renewable energy policies in fortifying Malaysia's energy security: PESTLE and SWOT analysis through stakeholder engagement." *Progress in Energy and Environment* 16 (2021): 1-17.

[2] Amran, Mohd Effendi, and Mohd Nabil Muhtazaruddin. "Renewable Energy Optimization Review: Variables towards Competitive Advantage in Green Building Development." *Progress in Energy and Environment* 8 (2019): 1-15.

[3] Japar, Wan Mohd Arif Aziz, Nor Azwadi Che Sidik, Siti Rahmah Aid, Yutaka Asako, and Tan Lit Ken. "A comprehensive review on numerical and experimental study of nanofluid performance in microchannel heatsink (MCHS)." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 45, no. 1 (2018): 165-176.

[4] Sidik, Nor Azwadi Che, Wan Mohd Arif Aziz Japar, and Yutaka Asako. "Entropy generation minimization in sinusoidal cavities-ribs microchannel heat sink via secondary channel geometry." *CFD Letters* 11, no. 7 (2019): 1-10.

[5] Japar, Wan Mohd Arif Aziz, Nor Azwadi Che Sidik, Natrah Kamaruzaman, Yutaka Asako, and Nura Mu'az Muhammad. "Hydrothermal performance in the Hydrodynamic Entrance Region of Rectangular Microchannel Heat Sink." *Journal of Advanced Research in Numerical Heat Transfer* 1, no. 1 (2020): 22-31.

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

[7] Zuo, Jia Wei, Kok Cheong Wong, and Hoon Kiat Ng. "The thermal performance of three-layered microchannel heat sink with tapered channel profile." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 56, no. 1 (2019): 147-156.

[8] Zahmani, Qamar Fairuz, Muhammad Nur Othman, Mohd Faruq Abdul Latif, Siti Nor'ain Mokhtar, Nik Nazri Nik Ghazali, and Ahmad Yusof Ismail. "Numerical Heat Transfer Analysis in Microchannel Heat Sink with Different Aspect Ratio." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 62, no. 2 (2019): 265-273.

[9] Majnis, Mohd Fadhil, Mei Mei Chong, Ku Zilati Ku Shaari, and Mohd Azam Mohd Adnan. "Wettability Study of Chitosan Droplet on Surface-Modified PDMS for Microfluidics Application." *Progress in Energy and Environment* 12 (2020): 22-29.

[10] Wu, Junmei, Jiyun Zhao, Jiang Lei, and Bo Liu. "Effectiveness of nanofluid on improving the performance of microchannel heat sink." *Applied Thermal Engineering* 101 (2016): 402-412. doi: 10.1016/j.applthermaleng.2016.01.114.

[11] Sidik, Nor Azwadi Che, Saidu Bello Abubakar, and Siti Nurul Akmal Yusof. "Measurement of Fluid Flow and Heat Transfer Performance in Rectangular Microchannel using Pure Water and Fe3O4-H2O Nanofluid." *Journal of Advanced Research in Applied Mechanics* 68, no. 1 (2020): 9-21. doi: 10.37934/aram.68.1.921.

[12] Snoussi, L., N. Ouerfelli, K. V. Sharma, N. Vrinceanu, A. J. Chamkha, and A. Guizani. "Numerical simulation of nanofluids for improved cooling efficiency in a 3D copper microchannel heat sink (MCHS)." *Physics and Chemistry of Liquids* 56, no. 3 (2018): 311-331. doi: 10.1080/00319104.2017.1336237.

[13] Krishna, V. Murali, and M. Sandeep Kumar. "Numerical analysis of forced convective heat transfer of nanofluids in microchannel for cooling electronic equipment." *Materials Today: Proceedings* 17 (2019): 295-302. doi: 10.1016/j.matpr.2019.06.433.

[14] Hasan, Mushtaq Ismael, and Dhay Mohammed Muter. "Study the micro heat sink with pin fins and different coolants: a comparative study." *International Journal of Engineering & Technology* 7, no. 4 (2018): 4856-4865. doi: 10.14419/ijet.v7i4.25753.

[15] Duangthongsuk, Weerapun. "Thermal and Hydraulic Performances of Nanofluids Flow in Microchannel Heat Sink with Multiple Zigzag Flow Channels." In *MATEC Web of Conferences*, vol. 95, p. 03011. EDP Sciences, 2017. doi: 10.1051/matecconf/20179503011.

[16] Sidik, Nor Azwadi Che, Chow Hoong Kee, Siti Nurul Akmal Yusof, and Ahmad Tajuddin Mohamad. "Performance enhancement of cold thermal energy storage system using nanofluid phase change materials." *Journal of Advanced Research in Applied Mechanics* 62, no. 1 (2019): 16-32.

[17] Akaje, Wasiu, and B. I. Olajuwon. "Impacts of Nonlinear thermal radiation on a stagnation point of an aligned MHD Casson nanofluid flow with Thompson and Troian slip boundary condition." *Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer* 6, no. 1 (2021): 1-15.

[18] Idris, Muhammad Syafiq, Irnie Azlin Zakaria, and Wan Azmi Wan Hamzah. "Heat transfer and pressure drop of water based hybrid Al2O3: SiO2 nanofluids in cooling plate of PEMFC." *Journal of Advanced Research in Numerical Heat Transfer* 4, no. 1 (2021): 1-13. https://doi.org/10.37934/arfmts.88.3.96109

[19] 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.

[20] Wahid, Nur Syahirah, Norihan Md Arifin, Najiyah Safwa Khashi'ie, Rusya Iryanti Yahaya, Ioan Pop, Norfifah Bachok, and Mohd Ezad Hafidz Hafidzuddin. "Three-Dimensional Radiative Flow of Hybrid Nanofluid Past a Shrinking Plate with Suction." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 85, no. 1 (2021): 54-70. https://doi.org/10.37934/arfmts.85.1.5470

[21] Kumar, Aditya, and Sudhakar Subudhi. *Thermal Characteristics and Convection in Nanofluids*. Springer Singapore, 2021. https://doi.org/10.1007/978-981-33-4248-4

[22] Rashidi, Saman, Nader Karimi, Omid Mahian, and Javad Abolfazli Esfahani. "A concise review on the role of nanoparticles upon the productivity of solar desalination systems." *Journal of Thermal Analysis and Calorimetry* 135, no. 2 (2019): 1145-1159. doi: 10.1007/s10973-018-7500-8.

[23] Teh, Yuan Ying, and Adnan Ashgar. "Three dimensional MHD hybrid nanofluid Flow with rotating stretching/shrinking sheet and Joule heating." *CFD Letters* 13, no. 8 (2021): 1-19. https://doi.org/10.37934/cfdl.13.8.119

[24] Waini, Iskandar, Anuar Ishak, and Ioan Pop. "MHD Glauert flow of a hybrid nanofluid with heat transfer." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*86, no. 2 (2021): 91-100.

[25] Zufar, Muhammad, Prem Gunnasegaran, Khai Ching Ng, and Hemantkumar B. Mehta. "Evaluation of the thermal performance of hybrid nanofluids in pulsating heat pipe." *CFD Letters* 11, no. 11 (2019): 13-24.

[26] Elfaghi, Abdulhafid MA, Alhadi A. Abosbaia, Munir FA Alkbir, and Abdoulhdi AB Omran. "CFD Simulation of Forced Convection Heat Transfer Enhancement in Pipe Using Al2O3/Water Nanofluid." *Journal of Advanced Research in Numerical Heat Transfer* 8, no. 1 (2022): 44-49. https://doi.org/10.37934/cfdl.14.9.118124

[27] Agarwal, Ravi, Kamalesh Verma, Narendra Kumar Agrawal, and Ramvir Singh. "Sensitivity of thermal conductivity for Al2O3 nanofluids." *Experimental Thermal and Fluid Science*80 (2017): 19-26. doi: 10.1016/j.expthermflusci.2016.08.007.

[28] Tan, C., S. Zainal, C. J. Sian, and T. J. Siang. "ANSYS simulation for Ag/HEG hybrid nanofluid in turbulent circular pipe." *Journal of Advanced Research in Applied Mechanics* 23, no. 1 (2016): 20-35.

[29] Shameli, Kamyar, Siti Rahmah Aid, Nur Farhana Arissa Jonny, and Yutaka Asako. "Green Synthesis of Gold Nanoparticles Based on Plant Extract for Nanofluid-based Hybrid Photovoltaic System Application." *Journal of Research in Nanoscience and Nanotechnology* 4, no. 1 (2021): 19-34.

[30] Yusefi, Mostafa, Ong Su Yee, and Kamyar Shameli. "Bio-mediated production and characterisation of magnetic nanoparticles using fruit peel extract." *Journal of Research in Nanoscience and Nanotechnology* 1, no. 1 (2021): 53-61. https://doi.org/10.37934/jrnn.1.1.5361

[31] Salleh, Siti Nur Alwani, Norfifah Bachok, Norihan Md Arifin, and Fadzilah Md Ali. "Slip effect on mixed convection flow past a thin needle in nanofluid using Buongiorno's model." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 59, no. 2 (2019): 243-253.

[32] Moosa, Salmah, Anis Nadia Mohd Faisol Mahadeven, and Kamyar Shameli. "Physiochemical synthesis of Silver/Kaolinite nanocomposites and study their antibacterial properties." *Journal of Research in Nanoscience and Nanotechnology* 1, no. 1 (2021): 1-11. https://doi.org/10.37934/jrnn.1.1.111

[33] Wu, Daxiong, Haitao Zhu, Liqiu Wang, and Lumei Liu. "Critical issues in nanofluids preparation, characterization and thermal conductivity." *Current Nanoscience* 5, no. 1 (2009): 103-112. doi: 10.2174/157341309787314548.

[34] Wang, Xiang-Qi, and Arun S. Mujumdar. "A review on nanofluids-part II: experiments and applications." *Brazilian Journal of Chemical Engineering* 25 (2008): 631-648. doi: 10.1590/S0104-66322008000400002.

[35] Kim, Sang Hyun, Sun Rock Choi, and Dongsik Kim. "Thermal conductivity of metal-oxide nanofluids: particle size dependence and effect of laser irradiation." (2007): 298-307. doi: 10.1115/1.2427071.

[36] Byrne, Matthew D., Robert A. Hart, and Alexandre K. da Silva. "Experimental thermal–hydraulic evaluation of CuO nanofluids in microchannels at various concentrations with and without suspension enhancers." *International Journal of Heat and Mass Transfer* 55, no. 9-10 (2012): 2684-2691. doi: 10.1016/j.ijheatmasstransfer.2011.12.018.

[37] Shamsuddin, Hielfarith Suffri, Lee Wei Tong, Normah Mohd-Ghazali, Patrice Estellé, Thierry Maré, and Maziah Mohamad. "Nanofluid-Cooled Microchannel Heat Sink with Carbon Nanotube." (2021): 170-176. doi: 10.5109/4372274.

[38] Xie, Huaqing, Jinchang Wang, Tonggeng Xi, Yan Liu, Fei Ai, and Qingren Wu. "Thermal conductivity enhancement of suspensions containing nanosized alumina particles." *Journal of applied physics* 91, no. 7 (2002): 4568-4572. doi: 10.1063/1.1454184.

[39] Apmann, Kevin, Ryan Fulmer, Alberto Soto, and Saeid Vafaei. "Thermal conductivity and viscosity: Review and optimization of effects of nanoparticles." *Materials* 14, no. 5 (2021): 1291. doi: 10.3390/ma14051291.

[40] Yang, Liu, Kai Du, and Xiao-song Zhang. "Influence factors on thermal conductivity of ammonia-water nanofluids." *Journal of Central South University* 19, no. 6 (2012): 1622-1628. doi: 10.1007/s11771-012-1185-0.

[41] L Chen, Lifei, and Huaqing Xie. "Surfactant-free nanofluids containing double-and single-walled carbon nanotubes functionalized by a wet-mechanochemical reaction." *Thermochimica Acta* 497, no. 1-2 (2010): 67-71. doi: 10.1016/j.tca.2009.08.009.

[42] Wang, Ruijin, Wen Wang, Jiawei Wang, and Zefei Zhu. "Analysis and optimization of trapezoidal grooved microchannel heat sink using nanofluids in a micro solar cell." *Entropy* 20, no. 1 (2017): 9. doi: 10.3390/e20010009.

[43] Yue, Yun, Shahabeddin K. Mohammadian, and Yuwen Zhang. "Analysis of performances of a manifold microchannel heat sink with nanofluids." *International Journal of Thermal Sciences* 89 (2015): 305-313. doi: 10.1016/j.ijthermalsci.2014.11.016.

[44] Mohammadpour, Javad, Ann Lee, M. Mozafari, Mehran Rajabi Zargarabadi, and Arun S. Mujumdar. "Evaluation of Al2O3-Water nanofluid in a microchannel equipped with a synthetic jet using single-phase and Eulerian–Lagrangian models." *International Journal of Thermal Sciences* 161 (2021): 106705. doi: 10.1016/j.ijthermalsci.2020.106705.

[45] Kanti, Praveen, Korada Viswanatha Sharma, Ramachandra CG, and W. H. Azmi. "Experimental determination of thermophysical properties of Indonesian fly-ash nanofluid for heat transfer applications." *Particulate Science and Technology* 39, no. 5 (2021): 597-606. doi: 10.1080/02726351.2020.1806971.

[46] Khan, Idrish A. "Experimental validation of enhancement in thermal conductivity of titania/water nanofluid by the addition of silver nanoparticles." *International Communications in Heat and Mass Transfer* 120 (2021): 104910.doi: 10.1016/j.icheatmasstransfer.2020.104910.

[47] Rabiei, Saeed, Raouf Khosravi, Mehdi Bahiraei, Mehdi Raziei, and Amirjavad Ahmadian Hosseini. "Thermal and hydraulic characteristics of a hybrid nanofluid containing graphene sheets decorated with platinum through a new wavy cylindrical microchannel." *Applied Thermal Engineering* 181 (2020): 115981. doi: 10.1016/j.applthermaleng.2020.115981.

[48] Souby, M. Mohamed, Mohamed HS Bargal, and Yiping Wang. "Thermohydraulic performance improvement and entropy generation characteristics of a microchannel heat sink cooled with new hybrid nanofluids containing ternary/binary hybrid nanocomposites." *Energy Science & Engineering* 9, no. 12 (2021): 2493-2513. doi: 10.1002/ese3.982.

[49] Jamshidmofid, Mohammad, and Mehdi Bahiraei. "Thermohydraulic assessment of a novel hybrid nanofluid containing cobalt oxide-decorated reduced graphene oxide nanocomposite in a microchannel heat sink with sinusoidal cavities and rectangular ribs." *International Communications in Heat and Mass Transfer* 131 (2022): 105769. doi: 10.1016/j.icheatmasstransfer.2021.105769.

[50] Maheshwary, P. B., C. C. Handa, and K. R. Nemade. "A comprehensive study of effect of concentration, particle size and particle shape on thermal conductivity of titania/water based nanofluid." *Applied Thermal Engineering* 119 (2017): 79-88. doi: 10.1016/j.applthermaleng.2017.03.054.

[51] Cui, Wenzheng, Zhaojie Shen, Jianguo Yang, Shaohua Wu, and Minli Bai. "Influence of nanoparticle properties on the thermal conductivity of nanofluids by molecular dynamics simulation." *RSC advances* 4, no. 98 (2014): 55580-55589. doi: 10.1039/C4RA07736A.

[52] Monavari, Ali, Jafar Jamaati, and Mehdi Bahiraei. "Thermohydraulic performance of a nanofluid in a microchannel heat sink: Use of different microchannels for change in process intensity." *Journal of the Taiwan Institute of Chemical Engineers* 125 (2021): 1-14. doi: 10.1016/j.jtice.2021.05.045.

[53] Shahsavar, Amin, Milad Rashidi, Mostafa Monfared Mosghani, Davood Toghraie, and Pouyan Talebizadehsardari. "A numerical investigation on the influence of nanoadditive shape on the natural convection and entropy generation inside a rectangle-shaped finned concentric annulus filled with boehmite alumina nanofluid using two-phase mixture model." *Journal of Thermal Analysis and Calorimetry* 141, no. 2 (2020): 915-930.doi: 10.1007/s10973-019-09076-w.

[54] Kumar, Aditya, and Sudhakar Subudhi. "Preparation, characteristics, convection and applications of magnetic nanofluids: A review." *Heat and Mass Transfer* 54, no. 2 (2018): 241-265. doi: 10.1007/s00231-017-2114-4.

[55] Tawfik, Mohamed M. "Experimental studies of nanofluid thermal conductivity enhancement and applications: A review." *Renewable and Sustainable Energy Reviews* 75 (2017): 1239-1253. doi: 10.1016/j.rser.2016.11.111.

[56] Saufi, Muhammad Aiman Bin, and Hussin Bin Mamat. "A Review on Thermophysical Properties for Heat Transfer Enhancement of Carbon-Based Nanolubricant." *Advanced Engineering Materials* 23, no. 10 (2021): 2100403. doi: 10.1002/adem.202100403.

[57] Lenin, Ramanujam, Pattayil Alias Joy, and Chandan Bera. "A review of the recent progress on thermal conductivity of nanofluid." *Journal of Molecular Liquids* 338 (2021): 116929. doi: 10.1016/j.molliq.2021.116929.

[58] Pryazhnikov, M. I., A. V. Minakov, and D. V. Guzei. "Study of transport coefficients of nanodiamond nanofluids." In *Journal of Physics: Conference Series*, vol. 899, no. 3, p. 032020. IOP Publishing, 2017. doi: 10.1088/1742-6596/899/3/032020.

[59] Hou, Yan, Jialin Yang, and Wenqi Zhang. "Numerical study of enhanced heat transfer of microchannel heat sink with nanofluids." In *IOP Conference Series: Materials Science and Engineering*, vol. 721, no. 1, p. 012052. IOP Publishing, 2020. doi: 10.1088/1757-899X/721/1/012052.

[60] Khetib, Yacine, Hala M. Abo-Dief, Abdullah K. Alanazi, S. Mohammad Sajadi, Mohsen Sharifpur, and Josua P. Meyer. "A Computational Fluid Dynamic Study on Efficiency of a Wavy Microchannel/Heat Sink Containing Various Nanoparticles." *Micromachines* 12, no. 10 (2021): 1192. doi: 10.3390/mi12101192.

[61] Kalteh, M., R. Kouhikamali, and S. Akbari. "Numerical simulation of nanofluid heat transfer in a double-layered microchannel heat sink using two phase mixture model." *Journal of Nanofluids* 5, no. 1 (2016): 139-147. doi: 10.1166/jon.2016.1188.

[62] Ahmed, Hamdi E., M. I. Ahmed, Islam MF Seder, and B. H. Salman. "Experimental investigation for sequential triangular double-layered microchannel heat sink with nanofluids." *International Communications in Heat and Mass Transfer* 77 (2016): 104-115. doi: 10.1016/j.icheatmasstransfer.2016.06.010.

[63] Sarvar-Ardeh, Sajjad, Roohollah Rafee, and Saman Rashidi. "Hybrid nanofluids with temperature-dependent properties for use in double-layered microchannel heat sink; hydrothermal investigation." *Journal of the Taiwan Institute of Chemical Engineers* 124 (2021): 53-62. doi: 10.1016/j.jtice.2021.05.007.

[64] Wang, Jin, Kai Yu, Mingzheng Ye, Enyu Wang, Wei Wang, and Bengt Sundén. "Effects of pin fins and vortex generators on thermal performance in a microchannel with Al2O3 nanofluids." *Energy* 239 (2022): 122606. doi: 10.1016/j.energy.2021.122606.

[65] Adio, Saheed A., Timothy A. Alo, Ridwan O. Olagoke, Adedotun E. Olalere, Vasudeva Rao Veeredhi, and Daniel RE Ewim. "Thermohydraulic and entropy characteristics of Al2O3-water nanofluid in a ribbed interrupted microchannel heat exchanger." *Heat Transfer* 50, no. 3 (2021): 1951-1984. doi: 10.1002/htj.21964.

[66] Adio, Saheed Adewale, Adedotun Emmanuel Olalere, Ridwan Olawale Olagoke, Timothy Adefemi Alo, Vasudeva Rao Veeredhi, Daniel RE Ewim, and Olabode Thomas Olakoyejo. "Thermal and entropy analysis of a manifold microchannel heat sink operating on CuO–water nanofluid." *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 43, no. 2 (2021): 1-15. doi: 10.1007/s40430-020-02772-x.

[67] Ali, Abdullah Masoud, Matteo Angelino, and Aldo Rona. "Numerical analysis on the thermal performance of microchannel heat sinks with Al2O3 nanofluid and various fins." *Applied Thermal Engineering* 198 (2021): 117458. doi: 10.1016/j.applthermaleng.2021.117458.

[68] Kumar, PC Mukesh, and CM Arun Kumar. "Numerical study on heat transfer performance using Al2O3/water nanofluids in six circular channel heat sink for electronic chip." *Materials Today: Proceedings* 21 (2020): 194-201. doi: 10.1016/j.matpr.2019.04.220.

[69] Elbadawy, Ibrahim, and Mohamed Fayed. "Reliability of Al2O3 nanofluid concentration on the heat transfer augmentation and resizing for single and double stack microchannels." *Alexandria Engineering Journal* 59, no. 3 (2020): 1771-1785. doi: 10.1016/j.aej.2020.04.046.

[70] Kahani, Mostafa. "Simulation of nanofluid flow through rectangular microchannel by modified thermal dispersion model." *Heat Transfer Engineering* 41, no. 4 (2020): 377-392. doi: 10.1080/01457632.2018.1540464.

[71] Pourfattah, Farzad, Ali Akbar Abbasian Arani, Mohammad Reza Babaie, Hoang M. Nguyen, and Amin Asadi. "On the thermal characteristics of a manifold microchannel heat sink subjected to nanofluid using two-phase flow simulation." *International Journal of Heat and Mass Transfer* 143 (2019): 118518. doi: 10.1016/j.ijheatmasstransfer.2019.118518.

[72] Kumar, Avinash, Sujit Nath, and Dipankar Bhanja. "Effect of nanofluid on thermo hydraulic performance of double layer tapered microchannel heat sink used for electronic chip cooling." *Numerical Heat Transfer, Part A: Applications* 73, no. 7 (2018): 429-445. doi: 10.1080/10407782.2018.1448611.

[73] Arjun, K. S., and K. Rakesh. "CFD analysis of thermal performance of microchannel nanofluid flow at different Reynolds numbers." *Songklanakarin Journal of Science & Technology* 41, no. 1 (2019). doi: 10.14456/sjst-psu.2019.13.

[74] Madhava Reddy, Haritha, and Ananthula Venu Vinod. "CFD simulation of the heat transfer using nanofluids in microchannel with dimple and protrusion." *Indian Chemical Engineer* 61, no. 1 (2019): 40-51. doi: 10.1080/00194506.2017.1418438.