Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage: www.akademiabaru.com/ard.html
ISSN: 2289-7984

Utilisation of Nanofluids In Minichannel For Heat Transfer and Fluid Flow Augmentation

Open Access

Nura Mu'az Muhammad[1], Nor Azwadi Che Sidik[1,*]

[1] Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 5 July 2018
Received in revised form 3 October 2018
Accepted 12 November 2018
Available online 20 November 2018

ABSTRACT

Current trend of size reduction of electronic devices and heat exchangers to enhance their performance and energy conservation is pushing the limit of their heat transfer enhancement capabilities. Conventional fluids failed to provide required heat removal from high heat flux generating electronic devices and heat exchangers, due to their inherent low thermal conductivity. Nanofluid is an advance innovative thermal engineering fluid capable of providing outstanding heat transfer improvement than the conventional fluids, thus, increasing thermal system productivity and ensure energy sustainability. Just as the development and progresses in using nanofluids are recognized in literatures, also their medium of transportation i.e Micro (MC) and minichannels (MiC) are also receiving attention from researchers. They differ from conventional channels for having hydraulic diameter in the range of 0.01 – 0.2 mm and 0.2 – 3 mm for micro and minichannels, respectively. In this paper, the design of numerical study of cooling application of high heat flux dissipating devices is proposed using hybrid passive techniques of using nanoparticles as an additive in base fluid and the corrugated (Diverging-converging) minichannel heat sink to determine the performance of heat transfer and flow behaviour. The result expected to be achieved at the end of successful conduct of this research include: declaration of superiority of nanofluid over base fluid on improvement of heat transfer rate, and consequently enhanced convective heat transfer coefficient (HTC), minimal pressure drops which may not necessarily demand more pumping power of working fluid and reasonable level of thermal resistance.

Keywords:
Nanofluid, minichannel heat sink, convective heat transfer, thermal conductivity, hydraulic diameter

1. Introduction

Nanofluid technology is regarded as one of the key emerging technologies that is presently attracting great research efforts in thermal engineering with the aim to provide improve working fluid for efficient thermal dissipation from high heat flux generating devices. Miniaturization which involves reduction of sizes of components without compromise on the heat transfer capability is

* *Corresponding author.*
E-mail address: azwadi@utm.my (Nor Azwadi Che Sidik)

gaining popularity in modern electronic devices and heat exchangers. Rapid technological advances in these areas are continuously pushing the boundaries of heat transfer enhancement, hence, there is need for a dynamic, efficient and sustainable approaches toward heat transfer improvement through a continuous research and development.

Tuckerman and Pearse [1] pioneered the use of micro (MC) and minichannels (MiC) in heat sinks which differ from the conventional channels in terms of channel hydraulic diameters. They postulated that reduction in channel hydraulic diameter can increase heat transfer coefficient. The minichannel is usually within 200µm to 3mm hydraulic diameter based on Kandlikar and Grande classification scheme that distinguished the channels based on manufacturing restrictions and the Knudsen number [2]. Though, microchannel offers higher heat transfer enhancement than minichannel, but its smaller hydraulic diameter leads to increase pumping power and pressure drop, as well as high cost and more sophisticated manufacturing techniques [3], thus, minichannel still receives interest for utilization in heat exchangers and heat sinks, as well as in micro-electro-mechanical system devices. Numerous investigators have measured the thermo-physical properties of nanofluids through experiment [4, 5], whereas some employed well-known predictive correlations through analytical or numerical methods [6-11].

The mechanism that influence thermal and hydrodynamic properties of nanofluids were highlighted by some researchers [5, 12-15] and the common mechanisms observed include: Brownian diffusion/motion that induce migration of nanoparticles, temperature gradient induced particles migration (thermophoresis), solid-like nanolayer formation at the nanoparticles surface, clustering mechanism, and interaction of nanoparticles' surface with base fluid compounds. Buschman et al. [16] observed that the convective heat transfer capability of nanofluid is not anomalous as reported by some researchers. They compiled experiments from five independent research teams studying convective heat transfer and flow of nanofluids in different passages and plate heat exchangers. The result shows that improvement in heat transfer by nanofluids is equivalent to the increase in its thermal conductivity as compared to the base fluid and independent on the concentration or material of nanoparticle.

Many researchers have shown remarkable achievement of nanofluids in their works, such as in heat exchangers [17-19], electronic cooling [20], thermo-electric generators (TEG) [21, 22], solar energy harvest [23], refrigeration and energy recovery [24, 25] and other applications. Some researchers compiled extensive review of literatures in relation to utilisation of nanofluid in minichannel as passive means of heat transfer enhancement [26-31]. It is the view of the authors of this work that, there are recent advances that needs to be highlighted to avail researchers in the field with state-of-the-art techniques and methods for further research on heat dissipation in electronic micro-devices and heat exchangers in industries. The objective of this paper is to propose a systematic approach in conducting a numerical research on hydrothermal performance analysis using nanofluid and minichannel as hybrid techniques for heat transfer enhancement.

2. Methodology

Comprehensive review of related works and expression of researches conducted in this area was conducted to have a better understanding of the concepts involve in the study of the hydrothermal analysis of nanofluids in minichannel thermal devices with emphasis on heat transfer enhancement mechanisms and techniques employed, and achievement of thermal improvement. First, a classification of nanofluid was discussed, then the techniques used in heat transfer enhancement as well as methods (either experimental or numerical) employed in the study were overviewed.

2.1 Classification of nanofluids.

Nanofluids are normally produced by dispersing powdered nanoparticles (NP) into the base fluid in two distinct methods, these include one step and two methods. Various Nanoparticle materials used in nanofluids production include: metals (Cu, Ag, Au), oxide ceramics (Al_2O_3, CuO), nitride ceramics (AlN, SiN), carbide ceramics (SiC, TiC), semiconductors (TiO_2 and SiO_2) and carbon-based (Carbon nanotubes and Graphene). In addition, combination of two or more nanofluids provides a hybrid nanofluid, which shown a better enhancement than the individual nanofluids that formed it, though with increased viscosity which sometimes reduces the level of enhancement.

Most researchers observed that, nanofluid has higher surface to volume ratio than the base fluid, hence, adding nanoparticles (NPs) usually in size of 1 – 100 nm in a base fluid can considerably improve heat transfer rate and consequently enhanced convective heat transfer coefficient (HTC), however, with a drawback on pressure drop, which subsequently demands more pumping power of working fluid. Other important factors of consideration include long-term stability and agglomeration of nanoscale to macroscale particles, which may block and erode the minichannel surface. Nanofluid is usually produce either through single step or two step methods. Extensive review was conducted on synthesis and production of nanofluids [32].

2.1.1 Metallic nanofluid

Metallic nanoparticles can be dispersed into a carrier fluid to form an improved thermal fluid. Few researchers used metallic NPs such as: Bahiraei and Heshmatian [33] dispersed spherical silver NP of 40 – 50 nm in water (Ag-H_2O) to evaluate hydrothermal characteristics and entropy generation of a biological nanofluid in a liquid block heat sink for cooling of an electronic processor. The result at concentration of 1% and Reynolds number of 500, indicates temperature reduction of 2.21°C for the NP against water. Investigation of corrugation effect on the flow and thermal characteristics of Au-H_2O nanofluid in the wavy channel was conducted by [34] using concentration of 0% - 5% and Re 250-1500. They highlighted that use of wavy channel with 90° phase shift is not desirable to dissipate heat from the devices. Triangular channel gave better enhancement, then by sinusoidal at 45°, 90° and 135° phase shift.

Nikkam et al. [35] conducted an experimental study through fabrication and characterization of spherical Silver NP of 25-29 nm to determine relevance of base fluids (Deionised water, pure water, Ethylene Glycol and the mixture of water-EG) on thermophysical properties of nanoparticle. Using concentration of 1%, 1.5% and 2wt.% and operating temperature of 20°C, they obtained a highest HTC enhancement of 12.4% with only 6.1% increase in viscosity observed for 2 wt% of Ag-H2O/EG nanofluid, which indicated the preference of this base-fluid above all other colloids in thermal performance.

In another work. Bahiraei and Heshmatian [36] used Silver-Graphene (Ag/HEG) to investigate the efficacy and entropy generation of a novel hybrid NF in three different liquid blocks made up of an aluminium for CPU cooling with Re of 500, 750 & 1000. They observed that, the novel distributor liquid block exhibited superior efficacy from both thermal performance and irreversibility rates. Moreover, nanofluid has sharp advantage over pure water in the liquid blocks cooling. Hence, the hybrid nanofluid has good potential for cooling improvement in electronics. Azwadi and Adamu [37] investigated the effect of Silver-Graphene (Ag/HEG) and Copper-oxide Graphene (CuO/HEG) nanofluids in a circular channel under constant heat flux within turbulence regime using concentration of 0.4 – 1 vol%. and Re 10000 - 120000. At 1vol.%, enhancement of 34.34% and 38.72% were obtained for Ag/HEG at Reynold numbers of 60000 and 40000, respectively. similarly, 35.95%

and 43.96% were obtained for CuO/HEG at the same Reynolds number and concentration respectively. Other researchers that employed metallic nanofluids in their works include: Ag-HEG [38, 39] and Cu-H_2O [40, 41].

2.1.2 Non-Metallic nanofluid

Alumina (Al_2O_3), Titania (TiO_2) and Silica (SiO_2) are the commonest used nanoparticles, with Alumina as the most widely preferred by most of the researchers due to its lower density and viscosity as well as increased reactivity when compared with other conventional micron-sized particles. Stability and rheology of Alumina as nanoparticle was carried out by [42], while formulation of metal-oxide nanofluids and their thermo-physical properties, mechanisms, and heat transfer performance was reviewed by [43] and concluded that, the interactions between metal oxide NPs and glycol resulted in reduced viscosity of nanofluids due to interfacial hydrogen bonding formation, and the lower the viscosity of the base fluids, the higher the thermal conductivity improvement due to Brownian motion induced convection.

Bahiraei and Heshmatian [44] investigated multi objective optimization of energy efficiency of liquid block for electronic cooling using Alumina nanofluid with variable sizes of 40 - 100 nm at volume fractions of 1 - 4 % and Re 400 - 1000. They observed that, the nanofluid concentration and particle size effects on the surface temperature is larger than that on the pumping power, whereas the Reynolds number shows rather similar effect on the two objective functions with optimum values found to be 666, while the concentration attained maximum value of 0.4% and the particle size has its minimum value of 40nm. Dominic et al. [45] used similar nanofluid of 40 nm particle size, volume fraction of 0.5% and 0.8% and at Re of 700 – 3300 to investigate heat transfer and pressure drop between wavy divergent and wavy cross-sections and reported that, in the laminar regime, the heat transfer performance of divergent wavy minichannels was 9% higher and the pressure drop was 30–38 % lesser than that of the wavy minichannels having constant cross-section. The performance factor of divergent wavy minichannels was 110–113 % for nanofluids compared to 115–126 % for water. Zhou et al. [46] confirmed Alumina enhanced the heat transfer performance and the average saturated flow boiling HTC of specified concentrations of nanofluid respectively increased by 11.2%, 15.4% and 18.7% in comparison with deionized water.

TiO_2 (Anatase and Rutile) are two classes of Titania, and were used by [47] to investigate steady state laminar flow regime analysis for heat transfer performance of inline and staggered pin fin heat sinks. The results show that TiO_2(R)/H2O nanofluids exhibited 16.46% higher enhancement in contrast to 15.27% for TiO_2(A)/H_2O nanofluids in staggered and inline pin fin heat sinks. Minimum base temperature at a power of 192 W attained is 29.4°C using TiO_2(R)/H_2O nanofluid with staggered pin fin heat sink. Naphon and Nakharintr. [48] dispersed TiO_2 of 21 nm size in distilled water to analysed heat transfer performance of nanofluid for cooling of MiCHS at Re 200. HTC for the heat sink with w=1.5 and 2mm, averagely appreciates by more than 27% for the nanofluids in contrast to the de-ionized water of 42.3%. [49] investigated convective heat transfer characteristics of aqueous TiO_2 nanofluid under laminar flow conditions.

2.1.3 Hybrid and Carbon nanotubes

Hybrid nanofluid and Carbon based nanorods and flakes like: Carbon Nanotube (Single [50] and multi-walled CNT [51]) and Graphene are receiving interest from researchers. Bahiraei et al. [52] studied thermal and hydraulic characteristics of a non-Newtonian hybrid nanofluid Fe_3O_4 coated with Tetra Methyl Ammonium Hydroxide (TMAH) NPs and Carbon Nanotubes (CNTs) coated with Gum Arabic (GA) having concentrations of 0.1–0.9% and 0–1.35%, respectively. They confirmed adding

NPs leads to further increment in heat transfer rate at lower Reynolds number compared with water, the nanofluid indicated heat transfer enhancement of 53.8% against 28.6% for water at Reynold numbers 500 and 2000 respectively. Shahsavar et al. [53] used similar hybrid nanofluid but with different concentrations of 0.5–0.9% and 0.1 –1.1%, respectively and found that, increasing Fe_3O_4 and CNT concentrations enhances the convective HTC of inner and outer walls, and total entropy generation. Increasing radius ratio from 1/5 to 4/5, at CNT concentration of 1.1% and Fe_3O_4 concentration of 0.7% led to decrease in the heat transfer coefficient of 85.05% and 35.49% for the inner wall and outer wall, respectively.

Diao et al. [54] shows that heat transfer improved with increase in concentration at 0.01% or above but degenerated when concentration falls below 0.01% when they studied the thermo-hydraulic performance of Multi walled CNT (MWCNT) passing through multi-port minichannel (MPMiC). The maximum PEC values of the MWCNT–water nanofluids at 0.01 vol.% for the smooth tubes, microfin (#1) and (#2) are 1.42, 1.37, and 1.32 at Re ≈ 5200, 5300, and 5300, respectively.

Microencapsulated Phase Change Material (MEPCM) is also gaining popularity recently among researchers and [55, 56] compiled extensive reviews on the application of nano and MEPCM in engineering applications. Ho et al. [57] investigated the concurrent presence of hybrid nanofluid made of MEPCM and Alumina for thermal cooling of heat sink, they concluded that, use of hybrid nanofluid significantly improved the heat transfer in the heat sink, and the performance depends on Reynolds no, as pure nanofluid offer better result than hybrid nanofluid at high Reynolds no, hence adjusting Re and concentration of the hybrid nanofluid for a given heat flux can give superb thermal enhancement. In another work, [58] observed that heat dissipation depends on heat flow rates and NP showed 57% enhancement under highest flowrate, whereas MEPCM showed averaged HTC of 51% under low flowrate, and in a similar work [59] they highlighted 52% heat transfer effectiveness has been achieved with the better improvement of thermal resistance obtained with lower flow rate. Other works that used Alumina include. [60-64].

A numerical research performed with different nanofluids to study their heat transfer and flow characteristics through circular minichannel heat sink for cooling was conducted by Sohel et al. [65] using Al_2O_3 -water, CuO -water, Cu -water and Ag -water at 0.5 vol.% to 4 vol.% and reported that, the highest HTC for Ag−water nanofluid was obtained at 9718.96 W/m^2K, which is 29.55% more in contrast to the pure water. In another work [66] analysed entropy generation as function of entropy generation ratio, thermal entropy generation and fluid friction of Copper (Cu), Alumina (Al_2O_3) as the nanoparticle and H_2O, ethylene glycol (EG); reported that Cu-H_2O has 36% highest decreasing entropy generation ratio, which occurred at 6vol%. Cu-H_2O and Cu-EG nanofluid gave the maximum decreasing rates of the fluid friction entropy generation rate are 38% and 35% respectively at 6% volume fraction. It can be construed from the works discussed that, among the NPs, Cu has better enhancements, followed by Al_2O_3 and TiO_2 in terms of heat dissipation capability.

2.2 Heat transfer enhancement techniques

The mechanism used to enhance heat transfer without upsetting the overall thermo-hydraulic performance of the thermal system are simply categorised into active and passive methods. The later involves modifying properties and structure of the heating surface by increasing the effective surface area and residence time of the thermal fluid and has exhibited advance energy efficiency and material saving, hence its commonly used in heat transfer enhancement, while the former, demands some external power input for the heat transfer enhancement, due to energy conservation nowadays, it is rarely employed. Classifications of active and passive methods are depicted in Figure 1.

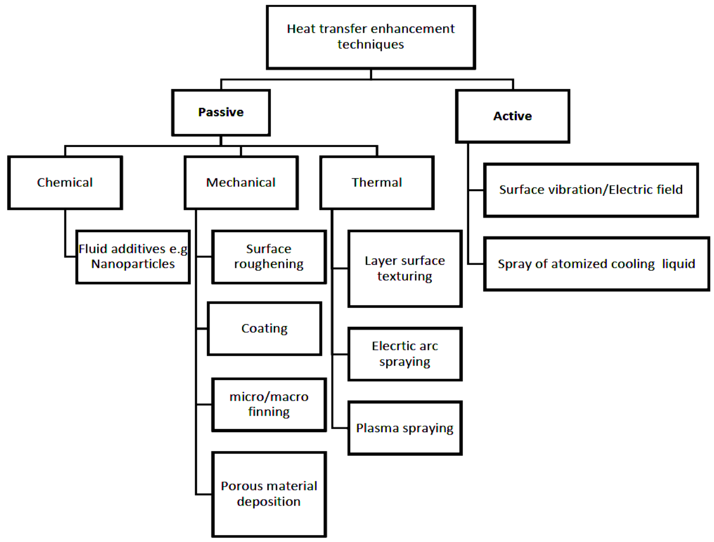


Fig. 1. Heat transfer enhancement techniques

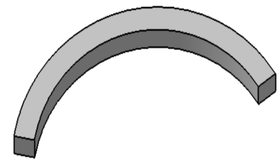
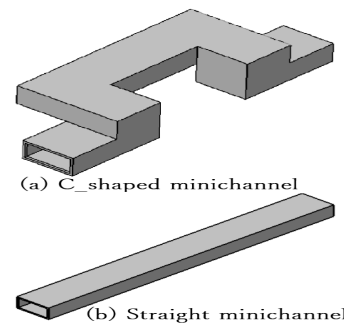
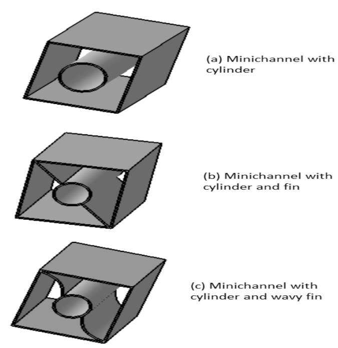
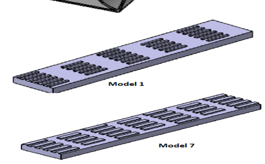
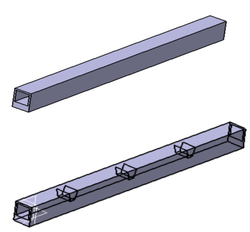
2.2.1 Active method

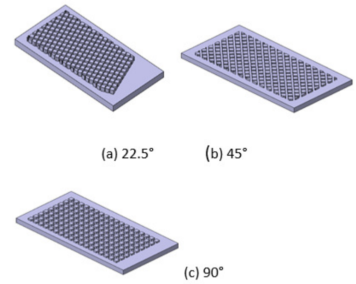
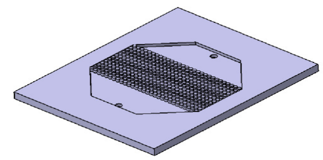
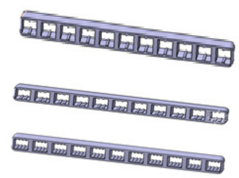
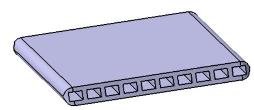
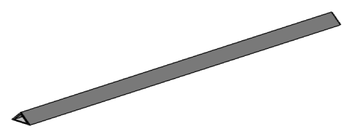
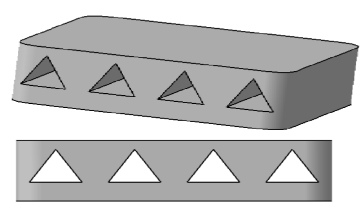
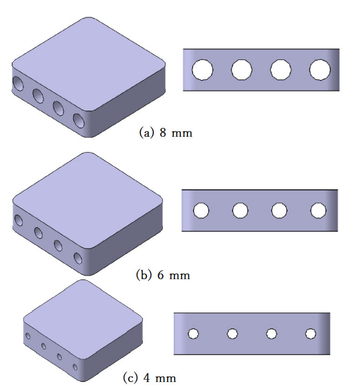
Few available researches that employed active method include; Ozbey et al. [67] investigated the magnetic actuation of ferrofluid with dynamic magnetic fields in small channel. Mohammadpourfard [68] investigated hydro-thermal behaviour of magnetic nanofluid (ferrofluid) Fe_3O_4-kerosene, and found that the Nusselt no is about 36% and 56% by applying the magnetic field in the peak point for an aspect ratio of 1 and 4, respectively. Naphon and Klangchart [69] studied numerically the effects of outlet port position on the heat transfer and flow on the jet liquid impingement characteristics in the mini-channel heat sink. They observed that the flow rate in each zone of the heat sink differs due to the velocity maldistribution and the positions of the outlet port have substantial impact on the fluid flow through the entire heat sink and temperature distribution. Thus, in thermal cooling of heat sink, observing temperature non-uniformity is vital. Other researchers that employed active methods include [70-72].

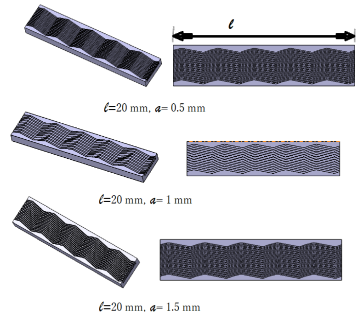
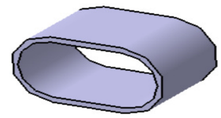
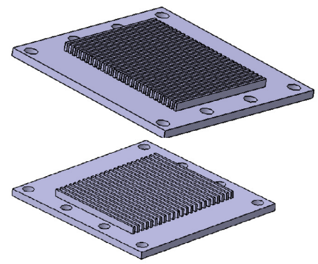
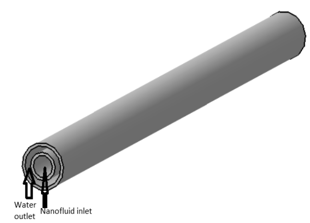
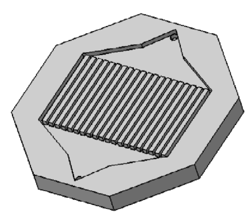
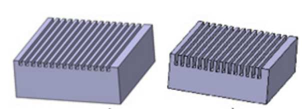
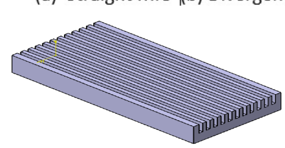
2.2.2 Passive method

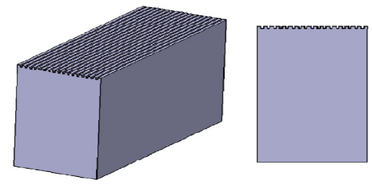
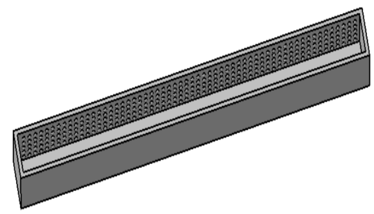
Dominic *et al*. [73] observed that passive method for forced convective heat transfer enhancement can be achieved through: decrease in thickness of thermal boundary layer, increase in fluid interruption, and increase in velocity gradient near a heat transfer wall. In addition, investigators observed that reduction of hydraulic diameter and higher heat transfer surface area per unit fluid volume of nanoparticles can effectively remove excess heat and improves heat transfer coefficient (HTC), thus, a lot of methods were introduced by changing minichannel geometrical parameters, such as: channel number, aspect ratio, cross-sections and path configurations. Table 1 illustrate some of the works that employed passive method of heat transfer enhancement with a schematic representation of the minichannels used.

Table 1
Passive heat transfer enhancement technique using Nanofluid

Nanofluid system (NP/BF)	Passive technique	Principle remarks	Geometrical shape
Al_2O_3/H_2O [74]	Chaotic flow	• Amongst the different shapes of particles, nanofluid with nanoplatelets shows the largest convective heat transfer improvement and its followed by cylindrical, blade, spherical, and brick shaped NPs. Similar trend observed for pressure drop and convective HTC.	
CMC/TiO_2/ H_2O [75]	Chaotic flow	• When concentration and Reynolds number increased by 4% and 200 respectively, frictional entropy generation also increases, while thermal entropy generation decreases.	
Al_2O_3/H_2O [76]	Flow obstruction	• Thermal conductivity raises with concentration of nanoparticles and these aggregated effects enhances convective HTC at Re 1000 and 5vol.% by 26.47% compared to water. • Heat transfer enhancement of 84.4% and 199.6% for 1vol% and 5vol.% respectively, observed for nanofluid at Re=100.	
Al_2O_3-H_2O [77]	Flow obstruction	• Enhancement in heat transfer observed for the OSPMHSs at the least values of the studied design parameters, i.e. t = 1 mm, ℓ = 5 mm, pt = 1 mm, and pl = 5 mm.	
Al_2O_3-H_2O and MWCNT-H_2O [78]	Flow obstruction	• Al_2O_3-H_2O nanofluid with 1 vol.% shows the highest overall performance in the triangular pin fin miniature channel, though MWCNT-water nanofluid gives the highest and least overall performance in the trapezoidal pin fin of type (3) and triangular pin fin, respectively.	

Graphene nanoplatelets [79]	Flow obstruction	• Amongst the three configurations, 22.5° heat sink has shown better enhancement as compared to other heat sinks and the average enhancements observed by 22.5°, 45° and 90° heat sinks are 23.86%, 22.44% and 19.68%, respectively.	
MWCNT [80]	Flow obstruction	• MWCNT bundle device exhibited 2.3 more heat flux removal from a silicon base than the other set up. And fully covered MWCNT device indicated 1.6 times the heat flux required to maintain same silicon base temperature.	
TiO_2-H_2O [81]	Flow obstruction	• Increase in Nusselt number by up to 158% at about Re = 3600 and the maximum PEC value reached 2.0 at Re = 5150.	 MMFT (a) 1 fin (b) 2 fins (c) 4 fins
Al_2O_3, HEG and their hybrid [82]	Flow restriction	• Increase of Re from 200 to 1000 leads to the decrease of total entropy generation from 0.0361 W/K to 0.0184 W/K for the maximum applied heat flux of 25 kW/m^2.	
Al_2O_3/H_2O. [83]	Flow restriction	• HTC enhances averagely by 56% with increase in Re from 100 to 500 at 5%. Increasing the Reynolds number from 100 to 300 and from 300 to 500 decreases the thermal entropy generation rate by 29.7% and 18.9%, respectively.	
Al_2O_3-H2O [84]	Flow restriction	• Thermal performance factor of 1.24 was obtained at Re 490 for 1.5 vol%, and at same Re, 1.12 and 1.07 were obtained at 1 vol% and 0.5 vol% respectively	
Al_2O_3-H2O [85]	Flow restriction	• The increase of channel diameter reduces the pressure drop in the heat sink. • The minichannel heat sink with a hydraulic diameter of 4 mm has a much lower thermal resistance than of 6 mm and 8 mm.	

Al_2O_3-H_2O [86]	Flow restriction	• Using a CMCHS of 20 mm wave-length and 2 mm wave-amplitude, the lowest base temperature of 30.5°C at heater Power of 50 W. • average performance factor of 2.68 obtained for the simultaneous utilization of corrugated minichannels and Al_2O_3/H_2O nanofluid inside the MCHS.	
CuO/R600a-POE [87]	Flow restriction	• Condensing HTC increased averagely by 4.1%, 8.11%, and 13.7% with respect to the R600a-oil mixture for the respective concentrations of 0.5%,1% and 1.5%	
MWCNT/DI H_2O [88]	Flow restriction	• lowest base temperature of 49.7C obtained at a heater power of 255W. • The highest overall HTC recorded was 1498 W/m^2K at a volumetric flow rate of 1 LPM for 0.2 mm fin spacing heat sink with MWCNT nanofluid coolant. • Whereas, the lowest overall HTC was found as 1200 W/m^2K at 0.5 LPM for 1.5 mm fin spacing heat sink with DI water as a coolant.	
TMAH coated Fe3O4 and GA coated CNTs [89]	Flow restriction	• increasing the Reynolds number, minimum point of thermal entropy generation moves toward smaller magnetite concentrations. At low magnetite concentration, total entropy generation rate possesses a minimum (optimal) point with respect to CNT concentration while an ascending trend is observed at high magnetite concentrations.	
Ag/H_2O [33]	Straight channel	• Nanofluid's thermal conductivity improves with increase in concentration and consequently, convective HTC enhances by 15.2% with increasing concentration from 0 to 1% at Re = 1500.	
Al_2O_3/H_2O [73]	Straight channel	• Nusselt number attained 76% maximum in laminar region when Al2O3-H2O is used and 40% in turbulent region in divergent straight MiC	 (a) Straight MiC (b) Divergent Mic
Alumina and Titania [90]	Straight channel	• Alumina nanofluid indicated average HTC of 3.2% higher than that of water, while Titania has the same value with water. CFD simulation predicted a 5% HTC which is higher than that calculated from experimental readings.	

TiO_2-H_2O [91]	Straight channel	• Using TiO_2 nanofluid, the lowest wall temperature is measured to be 37.05°C which occurred at Reynolds number of 922 and corresponding heating power of 100 W. Maximum enhancement of 12.75% for distilled water at 100 W	
Al_2O_3-H2O [92]	Surface roughening	• Heat transfer and pressure drop were enhanced respectively by 3.73 times and 4.25 times as a function of (Xs/dp) and (Ys/dp) of 1.8.	

2.3 Method of heat transfer analysis:

Heat transfer analysis like in other science and engineering fields employ experiments, numerical simulations and theoretical methods as tools to support research and development. Experimental method is more reliable, but factors such as speed, cost, repeatability and safety, coupled with recent technological advancement and wide-spread access to computers makes simulation more preferred than experimental measurements or theoretical analysis. Some of the prospects and challenges of these methods were highlighted by [93, 94].

2.3.1 Experimental heat transfer analysis

Ho *et al*. [95] investigated the thermal performance of Al_2O_3/H_2O nanofluid with weight fraction of 0.1–1 %. They varied the wall temperature between 50 °C and 110 °C, and found that, the nanofluid can enhance the heat transfer performance of the natural circulation loop studied and the average heat transfer effectiveness at the heating and cooling sections were approximately 3.5–22% and 9.5–62% respectively. Dominic *et al*. [96] also employed Al_2O_3/H_2O of 35 – 45 nm at volume fractions of 0.1%, 0.5% and 0.8 % with Re 700 – 1900 to investigate heat transfer and pressure drop for laminar flow in thermally developing and hydrodynamically developed regions and reported a contradictory result where the performance factor (PF) of water in wavy minichannels over their straight counterparts was higher than the nanofluids.

Arshad and Ali [97] investigated thermal and hydrodynamic performance of Graphene Nanoplatelets (GNP) in comparison to distilled water on integral fin heat sink and observed that the GNPs nanofluids indicated the lowest base temperature and maximum convective heat transfer enhancement as 36.81 °C and 23.91% coincide to Re 972 for heat flux of 47.96 KW/m^2, respectively. Hussien *et al*. [98] combined GNPs with MWCNT in water at low Re and low volume fraction and reported that heat transfer enhancement increases with an increase in nanoparticle concentrations, but decreases with increase in Reynolds no. The maximum enhancement obtained at 0.25% MWCNTs/0.035% GNPs hybrid and Re of 200 was 43.4%. Summary of other experimental works conducted in heat transfer analysis are presented in table 2.

Table 2
Summary of experimental investigation on heat enhancement of Nanofluids in minichannels

Nanofluid system (NP/BF)	Particle morphology (nm)	Nanofluid Concentration (%)	Validity range	Max. Heat improvement (%)	Principle findings
Ag/H_2O (Silver-water) [99]	NA	0.25 to 0.5vol	Re 1000 - 100000	45.6	• increase in HTC with 0.5 vol% yielded 45.6% of the silver nanoparticles compared with that of the base fluid. • HTC increased approximately by 12% in the laminar regime and 20–25% in the transition regime in relation to that of the base fluid. • For higher Reynolds number above 10000 within the turbulent regime, heat transfer coefficient is found to increase from 30 to 35%.
Al_2O_3/H_2O [100]	40 - 50	0.1 and 0.2 vol.	Re 200-1000	40	• the COP of thermoelectric module at 0.2 vol% shows 40% enhancement, but with reduction of 9.15% in thermoelectric temperature difference between the hot and cold side. • Local Nusselt number improved by 23.92% also at 0.2 vol.% in contrast with that of water at a Reynolds number of 1000 and at 400 W power input.
Al_2O_3/H_2O [101]	20 & 80	0.41, 0.58, and 0.83	q= 285 - 1550 W/m^2	-	• Effectiveness of heat transfer is more in smaller particles for a fixed particle concentration, though increase in particle concentration results in some gains up to a certain threshold.
Al_2O_3/H_2O [102]	33	10wt	Re 133 -1515	57	• largest enhancement of around 57% in 10wt% obtained at the highest flow rate of 1515.
Al_2O_3/H_2O [103]	40	5vol	Re 600 - 4500	19	• Thus, nanofluids should be utilised in either the laminar flow or fully developed turbulent flow at adequately high Re to yield enhanced heat transfer performance.
Al_2O_3/H_2O [104]	142 (max cluster)	0.1-0.25	Re 395 -989	18	• HTC enhanced by 18% and the heat sink base temperature (about 2.7 °C) was lowered by the nanofluid, however, it exhibited thermal resistance of 15.72% less at 0.25 vol.% and higher Reynolds number compared to the distilled water.
Al_2O_3/H_2O [105]	NA	0.05 to 0.2vol.	Vf 0.5 - 1.25 l/min	11	• 11% reduction in entropy generation is recorded for the nanofluid compared with pure water. Density and frictional effects on the surface of the channel increases with addition of nanoparticles
Al_2O_3/H_2O & TiO_2/H_2O [106]	NA	0.8, 1.6, 2.4, 3.2 and 4 vol.	NA	17.32	• thermal conductivity enhanced by 11.98% and 9.97% at 4vol% for Al_2O_3 and TiO_2 dispersed in water respectively. Instead of water, Al_2O_3-H_2O improves cooling up to 17.32%, similarly TiO_2-H_2O achieved 1.88% to 16.53%.

Al_2O_3/H_2O [107]	25	1, 3, 5 and 7vol.	Re 40 - 1000	40	• 40% heat transfer enhancement observed in fully developed regime of the laminar flow.
Al_2O_3/H_2O & Al_2O_3-Polyalphaolefin (PAO) [108]	40	1, 2, 3.5 & 5 vol. (Al_2O_3/H_2O) & 0.65 and 1.3 vol. (Al2O3-PAO)	Re 500 - 2500	-	• observed that thermal effectiveness of nanofluid is adversely offset by dual effects of increased viscosity and lower specific heat.
Al_2O_3-Polyalphaolefin (PAO) [109]	60 (spherical) and 5 - 11 (nanorod)	0.65 and 1.3vol	Re 350 and 490	28.70	• the enhancement in heat transfer efficiency of 28.7% at 1.3vol% was obtained for NF2 near the entrance, but it decreases below 21% as it approaches the channel exit.
HEG/H_2O [110]	-	0.05, 0.07, 0.10, 0.20 and 0.25 wt	-	21.55	• Found optimal conditions of concentration and flow rate of nanofluid at 0.1wt% and 950mL/min, at which 11.29%, 21.55% and 3.5% were recorded respectively for the improved voltage, output power and conversion efficiency.
PCE [111]	290	10 and 20 wt.	Re 500 - 1000	-	• The heating power also affects the heat transfer performance of the PCE and the proposed correlation of heat transfer in laminar flow for the PCE shows a deviation within ±20.0% compared to the experimental results.
SiC & Al_2O_3 in H_2O [112]	70 (SiC) and 110 (Al2O3)	0.001, 0.005, 0.01, 0.1, and 1 vol.		85	• The friction factors at 1 vol.% increased by up to 39.2% and 51.6% for the SiC-water and Al_2O_3-water nanofluids, respectively. • the SiC-water nanofluid Nusselt no surpass the Al2O3-water nanofluid, with the maximum increases of 85% and 52%, respectively.
SiC/H_2O [113]	NA	0.001 to 0.1	Re 150 - 5200	80.85	• As the Reynolds number approaches 5200, the largest growth rate of Nusselt number runs up to 80.8% at a volume fraction of 0.01% compared with the results of base fluid. • Smaller increase in resistance, along with the enhancement of heat transfer effect.
SiO_2, Al_2O_3, CuO/DI H_2O [114]	18.1, 28.3 and 45.6	0.25, 0.5, 1.0 and 2.0 vol.	Re 7000	40	• Heat transfer coefficient at 1 vol% was 40% higher than that of water at all Re. Also, at a fixed Re, a concentration of 2% of the nanofluid gives twice increase in heat exchange than with water
SiO_2 & Al_2O_3 [115]	10-100	0.5 to 2 vol.		-	• Inlet temperature found to be significant on turbulent heat transfer performance of nanofluids. • Increase in nanoparticles concentration at fixed Reynolds number leads to the increase in local and average heat transfer coefficients.
TiO_2-H_2O, Cu-H_2O & SiO_2-H_2O [116]	NA	0.05, 0.01, 0.1, 0.5, and 1 vol.	Re 97 - 6200	43	• Nusselt number increases with increasing volume concentration, then depreciate, paving way to an optimal volume concentration. When Re reaches 6200, Nusselt number increases by up to 43% for 0.01% TiO_2-water nanofluid.

					• TiO_2-water nanofluids at 0.01% concentration displayed the superb performance.
TiO_2-H_2O [117]	10, 30 and 50	0.005, 0.01, 0.1, 0.5 and 1 vol.	Re 100 - 6100	61	• TiO_2 with size of 10 nm indicated an increase of 61% for the Nu at 0.01 vol.% and Re 0f 6100. while, maximum PEC obtained is 1.52 at the same parameters.
ZnO/Al_2O_3 [118]	24	0, 1, 2 and 4 wt.		29.7	• A highest heat enhancement of 44.6% in CHF and 29.7% in HTC were observed for the 4wt.% and mass flux of 88kg/m^2s of surfactant added to ZnO-Al_2O_3 composite coating. Thus, hydrophilicity increases with increase in doping level.

2.3.2 Numerical simulation

Solutions of governing equations in numerical methods known as discretization normally involves: Finite Volume Method (FVM), Finite Element Method (FEM) and Finite Difference Method (FDM). The FVM and FEM methods are applicable to both structured and unstructured grids, while FDM uses only structured grids. [119] Mostly researchers in thermo-hydraulic analyses employ Finite Volume Method (FVM). It is based on integral form of governing equations and solves for the represented variable value for the cell volume, with control volume, volume of fluid (VOF) and mixture as common models. Some researchers have reported application of different solution methods such as Inverse Heat conduction (IHC), Function Specification Method (FSM), Singular Value Decomposition (SFS) and Conjugated Gradient Method (CGM) [120, 121].
The governing equations used include that of mass, momentum and energy for steady state laminar incompressible fluid usually in non-dimensional form. The governing equations can be expressed either in polar or cartesian coordinates for cylindrical and channel geometries, respectively. The cartesian three dimensional governing equations were given in equations 2 to 5 under section 3.1.2.

2.3.2.1 Single-phase

Some researchers considered nanofluid as a homogenous mixture and they used single-phase model to study heat transfer performances of NP with various thermophysical parameters. Classical theories [122-126] were employed for the study, however, mostly these classical theories failed to adequately solve thermo-hydraulic properties, hence some researchers proposed some correlations [127, 128].

Pati *et al*. [129] used single-phase model to investigate the thermohydraulic performance of two different configurations of sinusoidal wavy-walled channel formed by changing phase shift angles between the bi-opposite heated walls. They observed that, heat transfer depends on the geometry of the wall and highly controlled by the wavelength of the wall waviness. for instance, the rate of heat transfer at lower wavelength is almost same for both the channels, whereas for raccoon channel is always more than that for serpentine channel for higher wavelength and the variation is more obvious for larger values of amplitude of wall waviness and Reynolds number. Moraveji *et al*. [130] modelled laminar forced convection on Al_2O_3 nanofluid with size particles of 33 nm and concentrations of 0.5, 1 and 6 wt.% within Re of 130 - 1600 in mini-channel heat sink performed in CFD by four individual approaches (single phase, VOF, mixture, Eulerian) of FVM.

2.3.2.1 Two-phase

Mostly, works on nanofluid for heat transfer enhancements were numerically solved using two-phase models with available approaches such as Eulerian, Lagrangian, mixture and volume of fluid (VOF), with accurate prediction of the models indicated by researchers [83, 131, 132]. Naphon and Nakharintr [133] studied laminar convective heat transfer of single and two-phase models in 3D using TiO-H_2O with PS 21 nm, VF 0.4 vol% and Re 80 – 200 in mini-rectangular fin heat sinks made of copper. Two-phase numerical model gave better enhancement than experimental single-phase results for all the Reynolds numbers. The maximum variations from the experimental data for the two-phase and single-phase models are 1.66% and 3.74%, respectively. Saeed and Kim [134] studied numerically the thermo-hydraulic performance of Al_2O_3-H_2O in mini-channel heat sinks with four different channel configurations using single phase and two-phase models, and observed that two-phase mixture model predicted results agreed closely with an experimental model while single phase numerical model has under predicted values of convective HTC.

Arjun and Rakesh [135] studied forced convective heat transfer in porous pin fins in rectangular silicon minichannels using MWCNT, Al_2O_3/ H_2O, CuO/H_2O NFs. Porous pin fins show better overall heat transfer performances than in traditional solid pin fins. Increase in nanofluid volume concentration, raises pressure drops, while heat fluxes in porous pin fin channels increase and maximal overall heat transfer attained at 0.01% concentration. Nu improve by 6% with regards to porosity and 88 % with respect to 0.01% Al_2O_3/H_2O. Ghasemi et al. [136] studied the influence of heat sink with two variants cross-sectional shapes on the flow and heat transfer characteristics using CuO-H_2O of 29 nm and observed that rectangular channel has lower thermal resistance compared to circular channel at the same Reynolds number 490 and cross section area. In their other work [137], they used Eulerian two-phase model to analyse laminar forced convection heat transfer of nanofluid using TiO_2/H_2O at Re 200 -500 and concluded that, heat transfer enhancement increases with an increase in Re with the optimum performance evaluation criterion occurred in Re 490 and 0.75vol% was around 1.23. Summary of other numerical works in heat transfer analysis are presented in table 3.

Table 3
Summary *of numerical works on nanofluids in minichannel using single-phase models*

Nanofluid system NP/BF	particle size (nm)	Concen tration (%)	working paramete r	Significant findings
TiO_2/H_2O [138]	20, 40, 60 & 80	1, 2, 3 & 4 vol.	Re 500-2000, q 10kW/m^2	• The Bejan number higher than 0.8 at all concentrations, which signifies that heat transfer is responsible for more than 80% of the generated entropy.
Al_2O_3/H_2O [139]	10, 50, and 90	1,3 and 5	Re 200, 1000 & 2000	• The rate of aggregate entropy generation diminishes by adding the nanoparticles to the water, which is advantageous in terms of energy utilization.
Graphene-Pl [140]	NA	0, 0.02, 0.06 & 0.1 vol%	Re 331.7, 663.3, 995.0, 1326.7 and 1658.3.	• Higher heat transfer and pressure drop observed for the chaotic channel than the simple one. Significant improvement in heat transfer and minimal pressure drop noticed due to the superior qualities of Graphene. Figure of merit is always larger than 1.5 by using the chaotic channel instead of the simple channel.

CuO-H_2O [141]	NA	0.02 - 0.04 vol%	Re 1000	• Convective heat transfer increases with increase of inclination angle from 0° to 75°, while total entropy generation decreases.

3. Methodology

3.1 Problem statement and Mathematical modelling

The main scope of the current simulation is to illustrate the performance of the diverging-converging minichannel in term of heat transfer and flow characteristics by studying the effect of nanofluid types, concentration and thermophysical properties. To achieve this, proper modelling of the minichannel was conducted. Also, appropriate models were employed to evaluate the thermophysical properties of the nanofluids, since, the classical "effective medium theory" proposed by Einstein [124] failed to accurately predict the behaviour of the nanoparticles especially at concentration above 0.2%.

3.1.1 Model geometry

The physical model considered in the numerical study as depicted in fig. 2 shows the schematic design of the divergent-convergent minichannel heat sink (DCMCHS) with dimensions of $L\times W\times H_b$=30mm×30 mm×2.25 mm having 10 parallel channels each of width and height of 1mm and 1.25mm, respectively. The bottom of computational domain is heated at a constant heat transfer rate of 40.5 W, which implies that, the heat flux at the base of DCMCHS is 45 kW/m^2 while the top has an adiabatic cover plates. The nanofluid passes through the channels of heat sink made of up aluminium and remove heat by convection from a heat dissipating component (chip) that is attached to the bottom of the heat sink. Since the minichannels are made-up to be identical in terms of both heat transfer and hydrodynamics, thus, only one of the channels is used as computational domain as shown in figure 2(b).

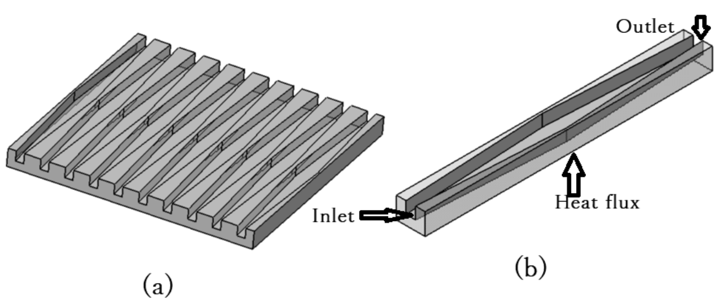


Fig. 2. (a) 3D Schematic design of DCMCHS and (b) Computational domain

The geometry is characterised with certain restrictions such as, equal angle of divergence and convergence (6°), length of 30 mm, while hydraulic diameter is determined from the trapezoidal section at the midplane of either the divergent or convergent section [142]. Thus: the hydraulic diameter can be obtained as:

$$D_h = \frac{4A}{P} = \frac{2(\acute{W}\cdot\dot{H})}{\acute{W}\cdot\dot{H}} \quad (1)$$

Where: $\dot{H}$, W_t and W_b represent the slant height, widths at top and bottom sections of the fluid domain. Table 1 illustrated the geometrical values used in the study.

3.1.2 Governing equations

The steady state conservation equations for mass, momentum and energy in fluid are respectively presented in non-dimensional form as follows:
Continuity equation given by:

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}+\frac{\partial u}{\partial z}=0 \tag{2}$$

whereas momentum equations in x, y and z components, respectively are given as:

$$\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{3a}$$

$$\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3b}$$

$$\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{3c}$$

where u, v and w are the velocity components in x, y and z directions, respectively. In addition, the pressure drop, weight density and dynamic viscosity of the fluid are represented with p, ρ and μ, respectively.
Energy equation for the fluid:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{k_f}{\rho Cp}+\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{4}$$

Energy equation for the solid:

$$k_s\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=0 \tag{5}$$

where T, k_f and k_s are temperature, and thermal conductivities of fluid and solid materials, respectively.

3.1.3 Boundary conditions

Three boundary conditions are applied to close the above mathematical equations. At the inlet boundary, temperature and pressure of the nanofluid are specified as 30℃ (303K) and 1 bar respectively, while "Pressure outlet" is imposed at the outlet with 0 Pa (gauge pressure). A constant heat flux of 45 kW/m^2 is applied on the bottom wall while, for all other walls, no slip condition (viscous flow) is experienced, thus velocity gradient forms in fluid and exerts flow resistance as pressure drop. All variables are initiated from the inlet boundary condition.

3.1.4 Thermophysical properties of fluid

The working fluids used in this simulation are Alumina (Al_2O_3), Silica (SiO_2) and Copper (Cu) nanofluids dispersed in deionized water with volume fractions of 0.001, 0.005 and 0.008. It is assumed that the nanofluid is in thermal equilibrium with zero relative velocity. The properties of nanofluid and the base fluid (water) considered in the present study are the ones used by Abdelrazek et al. [143] and presented in Table 2.

Table 4
Thermophysical properties of water and nanoparticles at Temperature of 27°C [143]

Materials	Density (kg/m^3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)	Viscosity (kg/ms)	Particle size (nm)
Water (H_2O)	995.8	4178.4	0.615	8.03E-04	-
Alumina (Al_2O_3)	3970	765	36	-	<50
Copper (Cu)	8933	385	401	-	
SiO_2	2220	745	1.38	-	

The thermo-physical properties of nanofluid are calculated using the relations below:

The density of nanofluids was determined using model developed by Pak et al. [144] as shown in equation (6):

$$\rho = (1-\phi)\rho_{bf} + \phi\rho_p \tag{6}$$

The specific heat of the nanofluids, equation (7) was calculated using Xuan and Roetzel. [145]:

$$Cp_{nf} = \frac{\phi(\rho Cp)_p + (1-\phi)(\rho Cp)_{bf}}{\rho_{nf}} \tag{7}$$

The thermal conductivity of the nanofluid (k_{nf}) was calculated using the Maxwell model [146] for nanofluids with volume fraction less than unity and considering Brownian motion where n=3 for spherical Al_2O_3, and is given by equation (8) as follows:

$$k_{nf} = \frac{k_p + (n-1)k_{bf} - \phi(n-1)(k_{bf}-k_p)}{k_p + (n-1)k_{bf} + \phi(k_{bf}-k_p)} k_{bf} \tag{8}$$

The viscosity of the nanofluids, equation (9) was calculated using the viscosity correlation proposed by Maiga et al. [147] as follows:

$$\mu_{nf} = \mu_w(1 + 7.3\phi + 123\phi^2) \tag{9}$$

where, φ, Cp, k and ρ are the concentration of the nanoparticle, heat capacity, thermal conductivity, viscosity and density respectively. While subscripts bf, p and nf denotes the base fluid, the nanoparticle and nanofluid respectively.

3.2 Numerical approach

The three-dimensional forced convection flow and heat transfer were modelled using commercial CFD solver, ANSYS FLUENT 17 with the assumptions that: the working fluid is considered three-dimensional, incompressible, and Newtonian. It is flowing in steady state laminar condition. The thermophysical properties of heat sink and fluid are constant, while the effect of radiation heat transfer for fluid flow and the influence of gravity and other body forces are neglected. The finite volume method approach was employed in the simulation, where velocity and pressure fields where coupled using SIMPLE algorithm. A second-order upwind interpolation scheme is used for discretization of the convective and diffusive terms. The convergence criteria were set when the normalised residual values are below 10^{-6} for all the variables.

3.2.1 Grid independency

A hexahedral mapped mesh was used for all the simulations. Various grids of sizes from 600,000 to 1.228 million elements were used in checking the mesh independency of the solution to ensure that, the results obtained does not rely on the size and the number of generated cells. The variation in the Nusselt numbers between the solutions on the grids with 0.90 million and 1.2 million elements is found to be below 0.5%, hence, to save computing time and memory, grid sizes of around 0.90

million elements were used for all the simulations in this study. The mesh of the fluid domain is illustrated in fig. 3.

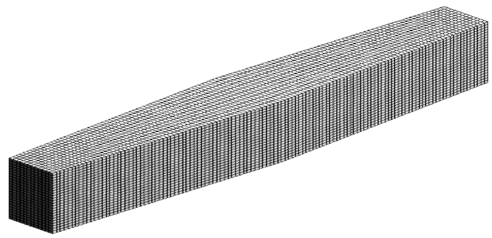
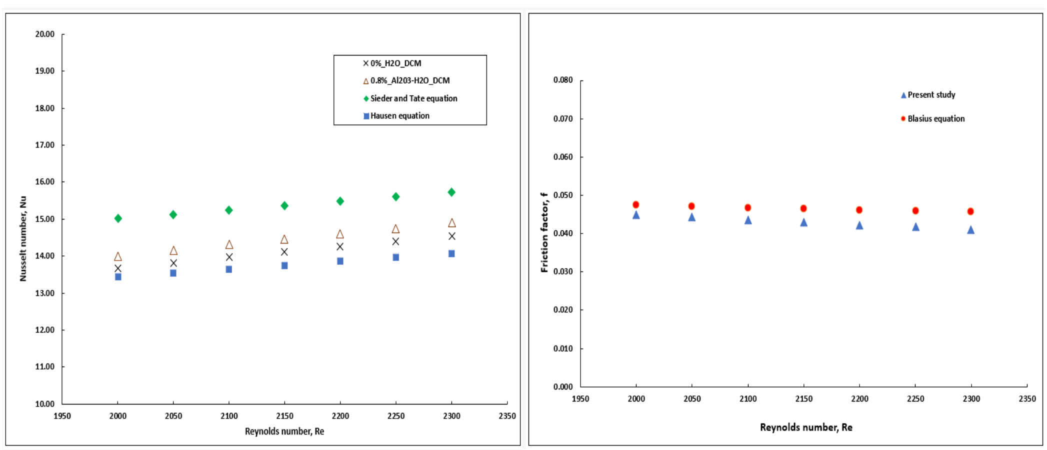


Fig. 3 3D Mesh of the fluid domain

3.2 Validation

The precision and validity of the numerical results were validated through comparison with existing correlations in the literature due to non-availability of experimental results in diverging-converging minichannels. Sieder and Tate, and Hausen correlations [103] for fully developed laminar region were employed for Nusselt number enhancement, while Blasius relation [148] were used for frictional resistance; to substantiate the ability of the solver to accurately and reliably predict the results. The comparisons were performed with the friction factor and average Nusselt number for the range of Reynolds numbers in all the values of nanofluid concentrations and base fluid, as presented in Fig. 4.



(a) (b)

Fig. 4 Validation of results of (a) Nusselt number and (b) friction factor as functions of Reynolds number

It can be observed from fig. 4 (a) that, Sieder and Tate correlation over predict the average Nusselt number at Re 2300 by about 5.2% for 0.8% concentration of the nanofluid and 7.4% higher for the base fluid. However, Hausen correlation under predict the average Nusselt number at the same Reynolds number by 6% and 3.5% for 0.8% concentration of the nanofluid and base fluid, respectively. Since the deviations of the average Nusselt numbers from the two correlations used is within ±10%, it can be considered that, the numerical results were appreciably well predicted by the method employed. For the friction factor, fig. 4 (b) indicates that, the numerical friction factor of the DCMCHS in the fluid shows appreciable agreement with the correlated results of Blasius, however, the deviation of the numerical friction factor from the theoretical values of nanofluid is around 5% and 10% lower at 2000 and 2300 Reynolds numbers, respectively. Perhaps, this could be due to the increase of pressure drops as the flow velocity increases at the entrance of the channel, and to the assumptions made in mathematical formulation of the simulation.

3.3 Data processing

The following equations (10-15) would be used to estimate the different important thermal and flow parameters of the minichannel heat sink.
The average heat transfer coefficient (h) and Nusselt number (Nu) were respectively obtained by:

$$h = \frac{q}{(T_w - T_b)} \tag{10}$$

$$Nu = \frac{hD_h}{k} \tag{11}$$

The base fluid velocity is estimated by using the relation of Reynolds number as follows:

$$Re = \frac{\rho u D_h}{\mu} \tag{12}$$

However, to take the influence of base fluid in the nanofluid formed, the nanofluid velocity is determined using the following expression:

$$u_{nf} = \frac{\rho_{bf}}{\rho_{nf}} \frac{\mu_{nf}}{\mu_{bf}} u_{bf} \tag{13}$$

While, pressure drop was determined from Darcy-Weisbach relation which relates the drops in pressure to frictional resistance in the flow as:

$$\Delta P = \frac{f \rho u^2}{2} \left(\frac{L}{D_h} \right) \tag{14}$$

The performance of flow in the minichannel is evaluated using pumping power which can be determine as function of the differential pressure drop, frictional resistance and velocity of the flow. It's given as:

$$PP = \Delta P \cdot f \cdot u \tag{15a}$$

However, some other expression of pumping power existed in the literature, such as:

$$PP = \Delta P \cdot \dot{V} \tag{15b}$$

$$PP = \Delta P \cdot \left(\frac{\dot{m}}{\rho} \right) \tag{15c}$$

where q, D_h, L, u, k, T_w and T_b are the heat flux, hydraulic diameter, channel length, fluid velocity, thermal conductivity of the fluid, average temperatures on the wall and bulk fluid respectively. Darcy friction factor (f) can be obtained from equation (14).

4. Conclusions

Numerical analysis of heat transfer and fluid flow characteristics of divergent-convergent minichannel heat sink (DCMCHS) has been proposed using water-based nanofluids, and the following conclusions were made based on the expected results:

- There would be a significant influence of Reynolds number on heat transfer enhancement on both the base fluid and the nanofluid. Deceleration and acceleration of the flow at the middle of the channel causes recirculation and vortices creation which enhances flow mixing.
- There would be slight increase in friction factor which may be linked to non-uniformity of channel passage due to divergence and convergence nature, and perhaps, decreases with increase in Reynolds number. The trend would be similar across all the volume fractions.

- Heat transfer coefficient would be enhanced by certain magnitude, say 15% due to influence of nanofluid in DCMCHS and increase in thermal conductivity of the nanofluid over water.
- The Performance factor which is a factor to indicate the augmentation in heat transfer of nanofluid over base fluid would be expected to be above unity.
- Better enhancement in heat transfer and hydrodynamic influence could be achieved and well predicted if the numerical analysis could be extended to turbulent regime and moderately higher volume concentration, say up to 4 %.

References

[1] Tuckerman, D. B. and Pease, R. F. W., "High-performance heat sinking for VLSI," *IEEE Electron Device Letters,* vol. 2, no. 5, (1981): 126-129.

[2] Dixit, T. and Ghosh, I., "Review of micro- and mini-channel heat sinks and heat exchangers for single phase fluids," *Renewable and Sustainable Energy Reviews,* Review vol. 41, (2015): 1298-1311.

[3] Leela Vinodhan, V., Suganthi, K. S., and Rajan, K. S., "Convective heat transfer performance of CuO–water nanofluids in U-shaped minitube: Potential for improved energy recovery," *Energy Conversion and Management,* vol. 118, (2016): 415-425.

[4] Pryazhnikov, M. I., Minakov, A. V., Rudyak, V. Y., and Guzei, D. V., "Thermal conductivity measurements of nanofluids," *International Journal of Heat and Mass Transfer,* Article vol. 104, (2017): 1275-1282.

[5] Rudyak, V. Y. and Minakov, A. V., "Thermophysical properties of nanofluids," *European Physical Journal E,* Article vol. 41, no. 1, (2018): Art. no. 15.

[6] Ambreen, T. and Kim, M. H., "Heat transfer and pressure drop correlations of nanofluids: A state of art review," *Renewable and Sustainable Energy Reviews,* Review vol. 91, (2018): 564-583.

[7] Maciejewska, B., Strąk, K., and Piasecka, M., "The Solution of a Two-dimensional Inverse Heat Transfer Problem Using the Trefftz Method," *Procedia Engineering,* vol. 157, (2016): 82-88.

[8] Nikkam, N., Saleemi, M., Haghighi, E. B., Ghanbarpour, M., Khodabandeh, R., Muhammed, M., Palm, B., and Toprak, M. S., "Fabrication, Characterization and Thermophysical Property Evaluation of SiC Nanofluids for Heat Transfer Applications," *Nano-Micro Letters,* Article vol. 6, no. 2, (2014): 178-189.

[9] Rudyak, V. Y., Minakov, A. V., and Pryazhnikov, M. I., "Thermal properties of nanofluids and their similarity criteria," *Technical Physics Letters,* Article vol. 43, no. 1, (2017): 23-26.

[10] Xie, S., Shahmohammadi Beni, M., Cai, J., and Zhao, J., "Review of critical-heat-flux enhancement methods," *International Journal of Heat and Mass Transfer,* Review vol. 122, (2018): 275-289.

[11] Ceotto, D. and Rudyak, V. Y., "Phenomenological formula for thermal conductivity coefficient of water-based nanofluids," *Colloid Journal,* Article vol. 78, no. 4, (2016): 509-514.

[12] Ghasemi, S. E., Ranjbar, A. A., and Hosseini, M. J., "Numerical study of convective heat transfer of nanofluid: A review," *Numerical Heat Transfer; Part A: Applications,* Article vol. 72, no. 2, (2017): 185-196.

[13] Ny, G, Barom, N, Noraziman, S, and Yeow, S, "Numerical study on turbulent-forced convective heat transfer of Ag/Heg water nanofluid in pipe," *J. Adv. Res. Mater. Sci.,* vol. 22, no. 1, (2016): 11-27.

[14] Sheikholeslami, M., Gorji-Bandpy, M., and Soleimani, S., "Two phase simulation of nanofluid flow and heat transfer using heatline analysis," *International Communications in Heat and Mass Transfer,* Article vol. 47, (2013): 73-81.

[15] Rudyak, V. Y. and Krasnolutskii, S. L., "Simulation of the thermal conductivity of a nanofluid with small particles by molecular dynamics methods," *Technical Physics,* Article vol. 62, no. 10, (2017): 1456-1465.

[16] Buschmann, M. H. Azizian, R. Kempe, T. Juliá, J. E. Martínez-Cuenca, R. Sundén, B. Wu, Z. Seppälä, A. and Ala-Nissila, T., "Correct interpretation of nanofluid convective heat transfer," *International Journal of Thermal Sciences,* vol. 129, (2018): 504-531.

[17] Fotowat, Shahram, Askar, Serena, and Fartaj, Amir, "Experimental transient response of a minichannel heat exchanger with step flow variation," *Experimental Thermal and Fluid Science,* vol. 89, (2017): 128-139.

[18] Ismail, Mohammed, Fotowat, Shahram, and Fartaj, Amir, "Simulation of Al2O3-ATF Nanofluid in a Compact Heat Exchanger," in *Proceedings of the 2nd International Conference on Fluid Flow, Heat and Mass Transfer*, Ottawa, Ontario, Canada,, 2015, no. Paper No. 149, pp. 149_1-8, 2015.
[19] Tullius, J. F. and Bayazitoglu, Y., "Effect of Al2O3/H2O nanofluid on MWNT circular fin structures in a minichannel," *International Journal of Heat and Mass Transfer,* Article vol. 60, no. 1, (2013): 523-530.
[20] Huminic, G., Huminic, A., Fleaca, C., Dumitrache, F., and Morjan, I., "Thermo-physical properties of water based SiC nanofluids for heat transfer applications," *International Communications in Heat and Mass Transfer,* Article vol. 84, (2017): 94-101.
[21] Hendricks, T. J., McEnerney, B., Drymiotis, F., Furst, B., and Shevade, A., "Design and testing of high-performance mini-channel graphite heat exchangers in thermoelectric energy recovery systems," 2017, vol. 6.
[22] Sohel Murshed, S. M. and Nieto de Castro, C. A., "A critical review of traditional and emerging techniques and fluids for electronics cooling," *Renewable and Sustainable Energy Reviews,* Review vol. 78, (2017): 821-833.
[23] Elsheikh, A. H., Sharshir, S. W., Mostafa, M. E., Essa, F. A., and Ahmed Ali, M. K., "Applications of nanofluids in solar energy: A review of recent advances," *Renewable and Sustainable Energy Reviews,* Review vol. 82, (2018): 3483-3502.
[24] Hassan, A. H., Martínez-Ballester, S., and Gonzálvez-Maciá, J., "A new moving boundary model for evaluating the performance of wet fins: Application to minichannel evaporators," *Applied Thermal Engineering,* Article vol. 127, (2017): 566-579.
[25] Leela Vinodhan, V., Suganthi, K. S., and Rajan, K. S., "Convective heat transfer performance of CuO-water nanofluids in U-shaped minitube: Potential for improved energy recovery," *Energy Conversion and Management,* Article vol. 118, (2016): 415-425.
[26] Khattak, MA, Mukhtar, A, and Afaq, S Kamran, "Application of nano-fluids as coolant in heat exchangers: a review," *J. Adv. Rev. Sci. Res.,* vol. 22, no. 1, (2016): 1-11.
[27] Koca, H. D., Doganay, S., Turgut, A., Tavman, I. H., Saidur, R., and Mahbubul, I. M., "Effect of particle size on the viscosity of nanofluids: A review," *Renewable and Sustainable Energy Reviews,* Review vol. 82, (2018): 1664-1674.
[28] Sidik, Nor Azwadi Che, Yazid, Muhammad Noor Afiq Witri Mohd, and Mamat, Rizalman, "Recent advancement of nanofluids in engine cooling system," *Renewable and Sustainable Energy Reviews,* vol. 75, (2017): 137-144.
[29] Sarkar, J., "A critical review on convective heat transfer correlations of nanofluids," *Renewable and Sustainable Energy Reviews,* Review vol. 15, no. 6, (2011): 3271-3277.
[30] Wu, Z. and Sundén, B., "On further enhancement of single-phase and flow boiling heat transfer in micro/minichannels," *Renewable and Sustainable Energy Reviews,* Article vol. 40, (2014): 11-27.
[31] Hemmati-Sarapardeh, A., Varamesh, A., Husein, M. M., and Karan, K., "On the evaluation of the viscosity of nanofluid systems: Modeling and data assessment," *Renewable and Sustainable Energy Reviews,* Review vol. 81, (2018): 313-329.
[32] Che Sidik, N. A., Mahmud Jamil, M., Aziz Japar, W. M. A., and Muhammad Adamu, I., "A review on preparation methods, stability and applications of hybrid nanofluids," *Renewable and Sustainable Energy Reviews,* Review vol. 80, (2017): 1112-1122.
[33] Bahiraei, M. and Heshmatian, S., "Application of a novel biological nanofluid in a liquid block heat sink for cooling of an electronic processor: Thermal performance and irreversibility considerations," *Energy Conversion and Management,* Article vol. 149, (2017): 155-167.
[34] Srinivas, S., Gupta, A., and Kandoi, A. K., "Modelling and simulation of au-water nanofluid flow in wavy channels," *Frontiers in Heat and Mass Transfer,* Article vol. 5, no. 1, (2014).
[35] Nikkam, N. and Toprak, M. S., "Fabrication and thermo-physical characterization of silver nanofluids: An experimental investigation on the effect of base liquid," *International Communications in Heat and Mass Transfer,* Article vol. 91, (2018): 196-200.

[36] Bahiraei, M. and Heshmatian, S., "Efficacy of a novel liquid block working with a nanofluid containing graphene nanoplatelets decorated with silver nanoparticles compared with conventional CPU coolers," *Applied Thermal Engineering,* Article vol. 127, (2017): 1233-1245.
[37] Azwadi, CS Nor and Adamu, IM, "Turbulent force convective heat transfer of hybrid nano fluid in a circular channel with constant heat flux," *J. Adv. Res. Fluid Mech. Therm. Sci.,* vol. 19, no. 1, (2016): 1-9.
[38] Sinz, C, Woei, H, Khalis, M, and Abbas, SA, "Numerical study on turbulent force convective heat transfer of hybrid nanofluid, Ag/HEG in a circular channel with constant heat flux," *J. Adv. Res. Fluid Mech. Therm. Sci.,* vol. 24, no. 1, (2016): 1-11.
[39] Zainal, S, Tan, C, Sian, C, and Siang, T, "ANSYS simulation for Ag/HEG hybrid nanofluid in turbulent circular pipe," *J. Adv. Res. Appl. Mech.,* vol. 23, no. 1, (2016): 20-35.
[40] Hosseinirad, E. and Hormozi, F., "Influence of Shape, Number, and Position of Horizontal Minifins on Thermal-Hydraulic Performance of Minichannel Heat Sink Using Nanofluid," *Heat Transfer Engineering,* Article vol. 38, no. 9, (2017): 892-903.
[41] Sivasubramanian, M., Theivasanthi, T., and Manimaran, R., "Experimental investigation on heat transfer enhancement in a minichannel using CuO-water nanofluid," *International Journal of Ambient Energy,* Article in Press (2018): 1-7.
[42] Ilyas, S. U., Pendyala, R., Narahari, M., and Susin, L., "Stability, rheology and thermal analysis of functionalized alumina- thermal oil-based nanofluids for advanced cooling systems," *Energy Conversion and Management,* Article vol. 142, (2017): 215-229.
[43] Suganthi, K. S. and Rajan, K. S., "Metal oxide nanofluids: Review of formulation, thermo-physical properties, mechanisms, and heat transfer performance," *Renewable and Sustainable Energy Reviews,* Review vol. 76, (2017): 226-255.
[44] Bahiraei, M. and Heshmatian, S., "Optimizing energy efficiency of a specific liquid block operated with nanofluids for utilization in electronics cooling: A decision-making based approach," *Energy Conversion and Management,* Article vol. 154, (2017): 180-190.
[45] Dominic, A., Sarangan, J., Suresh, S., and Devahdhanush, V. S., "An experimental study of heat transfer and pressure drop characteristics of divergent wavy minichannels using nanofluids," *Heat and Mass Transfer/Waerme- und Stoffuebertragung,* Article vol. 53, no. 3, (2017): 959-971.
[46] Zhou, J., Luo, X., Feng, Z., Xiao, J., Zhang, J., Guo, F., and Li, H., "Saturated flow boiling heat transfer investigation for nanofluid in minichannel," *Experimental Thermal and Fluid Science,* Article vol. 85, (2017): 189-200.
[47] Ali, H. M. and Arshad, W., "Thermal performance investigation of staggered and inline pin fin heat sinks using water based rutile and anatase TiO2 nanofluids," *Energy Conversion and Management,* Article vol. 106, (2015): 793-803.
[48] Naphon, P. and Nakharintr, L., "Heat transfer of nanofluids in the mini-rectangular fin heat sinks," *International Communications in Heat and Mass Transfer,* Article vol. 40, no. 1, (2013): 25-31.
[49] Murshed, S. M. S., Leong, K. C., Yang, C., and Nguyen, N. T., "Convective heat transfer characteristics of aqueous TiO2 nanofluid under laminar flow conditions," *International Journal of Nanoscience,* Article vol. 7, no. 6, (2008): 325-331.
[50] Hemmat Esfe, M., Abbasian Arani, A. A., and Firouzi, M., "Empirical study and model development of thermal conductivity improvement and assessment of cost and sensitivity of EG-water based SWCNT-ZnO (30%:70%) hybrid nanofluid," *Journal of Molecular Liquids,* Article vol. 244, (2017): 252-261.
[51] Shahzad, Muhammad Imran, Giorcelli, Mauro, Ventola, Luigi, Perrone, Denis, Shahzad, Nadia, Chiavazzo, Eliodoro, Asinari, Pietro, Cocuzza, Matteo, and Tagliaferro, Alberto, "Convective heat transfer enhancement for electronic device applications using patterned MWCNTs structures," *Heat Transfer Engineering,* vol. 37, no. 9, (2016): 783-790.
[52] Bahiraei, M., Godini, A., and Shahsavar, A., "Thermal and hydraulic characteristics of a minichannel heat exchanger operated with a non-Newtonian hybrid nanofluid," *Journal of the Taiwan Institute of Chemical Engineers,* Article in Press (2018).

[53] Shahsavar, Amin, Moradi, Mehdi, and Bahiraei, Mehdi, "Heat transfer and entropy generation optimization for flow of a non-Newtonian hybrid nanofluid containing coated CNT/Fe 3 O 4 nanoparticles in a concentric annulus," *Journal of the Taiwan Institute of Chemical Engineers,* (2018).
[54] Diao, Y. H., Li, C. Z., Zhang, J., Zhao, Y. H., and Kang, Y. M., "Experimental investigation of MWCNT–water nanofluids flow and convective heat transfer characteristics in multiport minichannels with smooth/micro-fin surface," *Powder Technology,* Article vol. 305, (2017): 206-216.
[55] Chai, L., Shaukat, R., Wang, L., and Wang, H. S., "A review on heat transfer and hydrodynamic characteristics of nano/microencapsulated phase change slurry (N/MPCS) in mini/microchannel heat sinks," *Applied Thermal Engineering,* Review vol. 135, (2018): 334-349.
[56] Kaviarasu, C. and Prakash, D., "Review on phase change materials with nanoparticle in engineering applications," *Journal of Engineering Science and Technology Review,* Review vol. 9, no. 4, (2016): 26-386.
[57] Ho, C. J., Chen, W. C., Yan, W. M., and Amani, P., "Contribution of hybrid Al2O3-water nanofluid and PCM suspension to augment thermal performance of coolant in a minichannel heat sink," *International Journal of Heat and Mass Transfer,* Article vol. 122, (2018): 651-659.
[58] Ho, C. J., Chen, W. C., Yan, W. M., and Amani, M., "Cooling performance of MEPCM suspensions for heat dissipation intensification in a minichannel heat sink," *International Journal of Heat and Mass Transfer,* Article vol. 115, (2017): 43-49.
[59] Ho, C. J., Chen, W. C., and Yan, W. M., "Correlations of heat transfer effectiveness in a minichannel heat sink with water-based suspensions of Al2O3 nanoparticles and/or MEPCM particles," *International Journal of Heat and Mass Transfer,* Article vol. 69, (2014): 293-299.
[60] Ismail, M., Fotowat, S., and Fartaj, A., "Transient Response of Minichannel Heat Exchanger Using Al2O3-EG/W Nanofluid," Conference Paper vol. 2016-April, no. April, (2016).
[61] Hassan, M., Sadri, R., Ahmadi, G., Dahari, M. B., Kazi, S. N., Safaei, M. R., and Sadeghinezhad, E., "Numerical study of entropy generation in a flowing nanofluid used in micro- and minichannels," *Entropy,* Article vol. 15, no. 1, (2013): 144-155.
[62] Afifah, AN, Syahrullail, S, and Sidik, NA Che, "Natural convection of alumina-distilled water nanofluid in cylindrical enclosure: an experimental study," *J. Adv. Res. Fluid Mech. Therm. Sci.,* vol. 12, no. 1, (2015): 1-10.
[63] Yu, L., Sur, A., and Liu, D., "Flow boiling heat transfer and two-phase flow instability of nanofluids in a minichannel," *Journal of Heat Transfer,* Article vol. 137, no. 5, (2015): Art. no. 051502.
[64] Ghasemi, S. E., Ranjbar, A. A., and Hosseini, M. J., "Experimental evaluation of cooling performance of circular heat sinks for heat dissipation from electronic chips using nanofluid," *Mechanics Research Communications,* Article vol. 84, (2017): 85-89.
[65] Sohel, M. R., Saidur, R., Sabri, M. F. M., Elias, M. M., and Khaleduzzaman, S. S., "Investigation of heat transfer performances of nanofluids flow through a circular minichannel heat sink for cooling of electronics," in *Advanced Materials Research* vol. 832, ed. Switzerland: Trans Tech Publications, 2014, pp. 166-171.
[66] Sohel, M. R., Saidur, R., Hassan, N. H., Elias, M. M., Khaleduzzaman, S. S., and Mahbubul, I. M., "Analysis of entropy generation using nanofluid flow through the circular microchannel and minichannel heat sink," *International Communications in Heat and Mass Transfer,* Article vol. 46, (2013): 85-91.
[67] Özbey, A., Karimzadehkhouei, M., Yalçın, S. E., Gozuacik, D., and Koşar, A., "Modeling of ferrofluid magnetic actuation with dynamic magnetic fields in small channels," *Microfluidics and Nanofluidics,* Article vol. 18, no. 3, (2015): 447-460.
[68] Mohammadpourfard, M., "Numerical study of ferrofluid flow and heat transfer in the presence of a non-uniform magnetic field in rectangular microchannels," *Heat Transfer - Asian Research,* Article vol. 41, no. 4, (2012): 302-317.
[69] Naphon, Paisarn and Klangchart, Setha, "Effects of outlet port positions on the jet impingement heat transfer characteristics in the mini-fin heat sink," *International Communications in Heat and Mass Transfer,* vol. 38, no. 10, (2011): 1400-1405.

[70] Abdulwahab, Mohammed Raad, "A numerical investigation of turbulent magnetic nanofluid flow inside square straight channel," *J. Adv. Res. Fluid Mech. Therm. Sci.,* vol. 1, no. 1, (2014): 44-52.

[71] Beriache, M., Bettahar, A., Loukarfi, L., Mokhtar Saïdia, L., and Naji, H., "Numerical study on hydraulic and thermal characteristics of a minichannel heat sink with impinging air flow," (2011).

[72] Jehad, DG and Hashim, GA, "Numerical prediction of forced convective heat transfer and friction factor of turbulent nanofluid flow through straight channels," *J. Adv. Res. Fluid Mech. Therm. Sci.,* vol. 8, no. 1, (2015): 1-10.

[73] Dominic, A., Sarangan, J., Suresh, S., and Devah Dhanush, V. S., "An experimental study of forced convective fluid flow in divergent minichannels using nanofluids," vol. 592-594, ed, 2014, pp. 1418-1422.

[74] Liu, F., Cai, Y., Wang, L., and Zhao, J., "Effects of nanoparticle shapes on laminar forced convective heat transfer in curved ducts using two-phase model," *International Journal of Heat and Mass Transfer,* Article vol. 116, (2018): 292-305.

[75] Bahiraei, M. Gharagozloo, K. Alighardashi, M. and Mazaheri, N., "CFD simulation of irreversibilities for laminar flow of a power-law nanofluid within a minichannel with chaotic perturbations: An innovative energy-efficient approach," *Energy Conversion and Management,* Article vol. 144, (2017): 374-387.

[76] Ahmadi, A. A. Khodabandeh, E. Moghadasi, H. Malekian, N. Akbari, O. A. and Bahiraei, M., "Numerical study of flow and heat transfer of water-Al2O3 nanofluid inside a channel with an inner cylinder using Eulerian–Lagrangian approach," *Journal of Thermal Analysis and Calorimetry,* Article vol. 132, no. 1, (2018): 651-665.

[77] Khoshvaght-Aliabadi, M., Sartipzadeh, O., Pazdar, S., and Sahamiyan, M., "Experimental and parametric studies on a miniature heat sink with offset-strip pins and Al2O3/water nanofluids," *Applied Thermal Engineering,* Article vol. 111, (2017): 1342-1352.

[78] Hosseinirad, E. and Hormozi, F., "New correlations to predict the thermal and hydraulic performance of different longitudinal pin fins as vortex generator in miniature channel: Utilizing MWCNT-water and Al2O3 - water nanofluids," *Applied Thermal Engineering,* Article vol. 118, (2017): 199-213.

[79] Ali, H. M. and Arshad, W., "Effect of channel angle of pin-fin heat sink on heat transfer performance using water based graphene nanoplatelets nanofluids," *International Journal of Heat and Mass Transfer,* Article vol. 106, (2017): 465-472.

[80] Shenoy, S., Tullius, J. F., and Bayazitoglu, Y., "Minichannels with carbon nanotube structured surfaces for cooling applications," *International Journal of Heat and Mass Transfer,* Article vol. 54, no. 25-26, (2011): 5379-5385.

[81] Zhang, J., Diao, Y., Zhao, Y., and Zhang, Y., "An experimental investigation of heat transfer enhancement in minichannel: Combination of nanofluid and micro fin structure techniques," *Experimental Thermal and Fluid Science,* Article vol. 81, (2017): 21-32.

[82] Ahammed, N., Asirvatham, L. G., and Wongwises, S., "Entropy generation analysis of graphene–alumina hybrid nanofluid in multiport minichannel heat exchanger coupled with thermoelectric cooler," *International Journal of Heat and Mass Transfer,* Article vol. 103, (2016): 1084-1097.

[83] Bahiraei, M. and Majd, S. M., "Prediction of entropy generation for nanofluid flow through a triangular minichannel using neural network," *Advanced Powder Technology,* Article vol. 27, no. 2, (2016): 673-683.

[84] Ghasemi, S. E., Ranjbar, A. A., and Hosseini, M. J., "Thermal and hydrodynamic characteristics of water-based suspensions of Al2O3 nanoparticles in a novel minichannel heat sink," *Journal of Molecular Liquids,* Article vol. 230, (2017): 550-556.

[85] Ghasemi, S. E., Ranjbar, A. A., and Hosseini, M. J., "Experimental and numerical investigation of circular minichannel heat sinks with various hydraulic diameter for electronic cooling application," *Microelectronics Reliability,* Article vol. 73, (2017): 97-105.

[86] Khoshvaght-Aliabadi, M. and Sahamiyan, M., "Performance of nanofluid flow in corrugated minichannels heat sink (CMCHS)," *Energy Conversion and Management,* Article vol. 108, (2016): 297-308.

[87] Ghorbani, B., Akhavan-Behabadi, M. A., Ebrahimi, S., and Vijayaraghavan, K., "Experimental investigation of condensation heat transfer of R600a/POE/CuO nano-refrigerant in flattened tubes," *International Communications in Heat and Mass Transfer,* Article vol. 88, (2017): 236-244.

[88] Jajja, S. A., Ali, W., and Ali, H. M., "Multiwalled carbon nanotube nanofluid for thermal management of high heat generating computer processor," *Heat Transfer - Asian Research,* Article vol. 43, no. 7, (2014): 653-666.

[89] Bahiraei, M., Berahmand, M., and Shahsavar, A., "Irreversibility analysis for flow of a non-Newtonian hybrid nanofluid containing coated CNT/Fe3O4 nanoparticles in a minichannel heat exchanger," *Applied Thermal Engineering,* Article vol. 125, (2017): 1083-1093.

[90] Utomo, A. T., Zavareh, A. I. T., Poth, H., Wahab, M., Boonie, M., Robbins, P. T., and Pacek, A. W., "Heat transfer coefficient of nanofluids in minichannel heat sink," in *Numerical Analysis and Applied Mathematics ICNAAM 2012*, 2012, vol. 1479, pp. 66-69: American Institute of Physics.

[91] Arshad, W. and Ali, H. M., "Experimental investigation of heat transfer and pressure drop in a straight minichannel heat sink using TiO2 nanofluid," *International Journal of Heat and Mass Transfer,* Article vol. 110, (2017): 248-256.

[92] Kumar, Sunil, Kothiyal, Alok Darshan, Bisht, Mangal Singh, and Kumar, Anil, "Numerical analysis of thermal hydraulic performance of Al2O3–H2O nanofluid flowing through a protrusion obstacles square mini channel," *Case Studies in Thermal Engineering,* vol. 9, (2017): 108-121.

[93] Vanaki, Sh M, Ganesan, P, and Mohammed, HA, "Numerical study of convective heat transfer of nanofluids: a review," *Renewable and Sustainable Energy Reviews,* vol. 54, (2016): 1212-1239.

[94] Hussien, A. A., Abdullah, M. Z., and Al-Nimr, M. A., "Single-phase heat transfer enhancement in micro/minichannels using nanofluids: Theory and applications," *Applied Energy,* Review vol. 164, (2016): 733-755.

[95] Ho, CJ, Chung, YN, and Lai, Chi-Ming, "Thermal performance of Al2O3/water nanofluid in a natural circulation loop with a mini-channel heat sink and heat source," *Energy Conversion and Management,* vol. 87, (2014): 848-858.

[96] Dominic, A., Sarangan, J., Suresh, S., and Devah Dhanush, V. S., "An Experimental Investigation of Wavy and Straight Minichannel Heat Sinks Using Water and Nanofluids," *Journal of Thermal Science and Engineering Applications,* Article vol. 7, no. 3, (2015): Art. no. 031012.

[97] Arshad, W. and Ali, H. M., "Graphene nanoplatelets nanofluids thermal and hydrodynamic performance on integral fin heat sink," *International Journal of Heat and Mass Transfer,* Article vol. 107, (2017): 995-1001.

[98] Hussien, A. A., Abdullah, M. Z., Yusop, N. M., Al-Nimr, M. A., Atieh, M. A., and Mehrali, M., "Experiment on forced convective heat transfer enhancement using MWCNTs/GNPs hybrid nanofluid and mini-tube," *International Journal of Heat and Mass Transfer,* Article vol. 115, (2017): 1121-1131.

[99] Bose, J. R. Asirvatham, L. G. Kumar, T. M. N. and Wongwises, S., "Numerical study on convective heat transfer characteristics of silver/water nanofluid in minichannel," *Current Nanoscience,* Article vol. 13, no. 4, (2017): 426-434.

[100] Ahammed, N., Asirvatham, L. G., and Wongwises, S., "Thermoelectric cooling of electronic devices with nanofluid in a multiport minichannel heat exchanger," *Experimental Thermal and Fluid Science,* Article vol. 74, (2016): 81-90.

[101] Ghaziani, N. O. and Hassanipour, F., "Convective Heat Transfer of Al2O3 Nanofluids in Porous Media," (2017).

[102] Ho, C. J. and Chen, W. C., "An experimental study on thermal performance of Al2O 3/water nanofluid in a minichannel heat sink," *Applied Thermal Engineering,* Conference Paper vol. 50, no. 1, (2013): 516-522.

[103] Liu, D. and Yu, L., "Single-phase thermal transport of nanofluids in a minichannel," *Journal of Heat Transfer,* Article vol. 133, no. 3, (2011): Art. no. 031009.

[104] Sohel, M. R. Khaleduzzaman, S. S. Saidur, R. Hepbasli, A. Sabri, M. F. M. Mahbubul, I. M., "An experimental investigation of heat transfer enhancement of a minichannel heat sink using Al2O3-H2O nanofluid," *International Journal of Heat and Mass Transfer,* Article vol. 74, (2014): 164-172.

[105] Sohel, M. R., Saidur, R., Khaleduzzaman, S. S., and Ibrahim, T. A., "Cooling performance investigation of electronics cooling system using Al2O3-H2O nanofluid," *International Communications in Heat and Mass Transfer,* Article vol. 65, (2015): 89-93.

[106] Ijam, A., Saidur, R., and Ganesan, P., "Cooling of minichannel heat sink using nanofluids," *International Communications in Heat and Mass Transfer,* Article vol. 39, no. 8, (2012): 1188-1194.

[107] Vafaei, S. and Wen, D., "Convective heat transfer of aqueous alumina nanosuspensions in a horizontal mini-channel," *Heat and Mass Transfer/Waerme- und Stoffuebertragung,* Article vol. 48, no. 2, (2012): 349-357.

[108] Yu, L. and Liu, D., "Study of the thermal effectiveness of laminar forced convection of nanofluids for liquid cooling applications," *IEEE Transactions on Components, Packaging and Manufacturing Technology,* Article vol. 3, no. 10, (2013): 1693-1704, Art. no. 5503870.

[109] Yu, L., Liu, D., and Botz, F., "Laminar convective heat transfer of alumina-polyalphaolefin nanofluids containing spherical and non-spherical nanoparticles," *Experimental Thermal and Fluid Science,* Article vol. 37, (2012): 72-83.

[110] Li, Y. H., Wu, Z. H., Xie, H. Q., Xing, J. J., Mao, J. H., Wang, Y. Y., and Li, Z., "Study on the performance of TEG with heat transfer enhancement using graphene-water nanofluid for a TEG cooling system," *Science China Technological Sciences,* Article vol. 60, no. 8, (2017): 1168-1174.

[111] Ma, F., Chen, J., and Zhang, P., "Experimental study of the hydraulic and thermal performances of nano-sized phase change emulsion in horizontal mini-tubes," *Energy,* Article vol. 149, (2018): 944-953.

[112] Zhang, J., Diao, Y., Zhao, Y., and Zhang, Y., "Thermal-hydraulic performance of SiC-Water and Al2O3-water nanofluids in the minichannel," *Journal of Heat Transfer,* Article vol. 138, no. 2, (2016): Art. no. 021705.

[113] Zhao, Y. H., Zhang, Y. N., Diao, Y. H., and Zhang, J., "Flow and heat transfer characteristics of water-based SiC nanofluids inside minichannel," *Beijing Gongye Daxue Xuebao/Journal of Beijing University of Technology,* Article vol. 41, no. 7, (2015): 1085-1092.

[114] Rudyak, V. Y., Minakov, A. V., and Krasnolutskii, S. L., "Physics and mechanics of heat exchange processes in nanofluid flows," *Physical Mesomechanics,* Article vol. 19, no. 3, (2016): 298-306.

[115] Minakov, A. V., Guzei, D. V., Pryazhnikov, M. I., Zhigarev, V. A., and Rudyak, V. Y., "Study of turbulent heat transfer of the nanofluids in a cylindrical channel," *International Journal of Heat and Mass Transfer,* Article vol. 102, (2016): 745-755.

[116] Zhang, J., Diao, Y. H., Zhao, Y. H., Zhang, Y. N., and Sun, Q., "An experimental study on flow and heat transfer characteristics of nanofluids in multiport minichannel flat tube," *Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics,* Article vol. 36, no. 5, (2015): 1071-1076.

[117] Zhang, J., Diao, Y., Zhao, Y., and Zhang, Y., "Experimental study of TiO2-water nanofluid flow and heat transfer characteristics in a multiport minichannel flat tube," *International Journal of Heat and Mass Transfer,* Article vol. 79, (2014): 628-638.

[118] Sujith Kumar, C. S., Suresh, S., Praveen, A. S., Santhosh Kumar, M. C., and Gopi, V., "Effect of surfactant addition on hydrophilicity of ZnO-Al2O3 composite and enhancement of flow boiling heat transfer," *Experimental Thermal and Fluid Science,* Article vol. 70, (2016): 325-334.

[119] Kajishima, Takeo and Taira, Kunihiko, *Computational fluid dynamics: incompressible turbulent flows*. Springer, 2016.

[120] Farahani, S. D. and Kowsary, F., "Estimation local convective boiling heat transfer coefficient in mini channel," *International Communications in Heat and Mass Transfer,* Article vol. 39, no. 2, (2012): 304-310.

[121] Farahani, S. D., Kowsary, F., and Jamali, J., "Direct estimation of local convective boiling heat transfer coefficient in mini-channel by using conjugated gradient method with adjoint equation," *International Communications in Heat and Mass Transfer,* Article vol. 55, (2014): 1-7.

[122] Batchelor, G. K., "The effect of Brownian motion on the bulk stress in a suspension of spherical particles," *Journal of Fluid Mechanics,* Article vol. 83, no. 1, (1977): 97-117.

[123] Brinkman, H. C., "The viscosity of concentrated suspensions and solutions," *The Journal of Chemical Physics,* Article vol. 20, no. 4, (1952): 571.

[124] Einstein, A., "Investigations on the Theory of the Brownian Movement," *Dover Publications,* Article (1956).

[125] Yu, W. and Choi, S. U. S., "The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated Hamilton-Crosser model," *Journal of Nanoparticle Research,* Article vol. 6, no. 4, (2004): 355-361.

[126] Buongiorno, J., "Convective transport in nanofluids," *Journal of Heat Transfer,* Article vol. 128, no. 3, (2006): 240-250.

[127] Karimipour, Arash, Ghasemi, Samad, Darvanjooghi, Mohammad Hossein Karimi, and Abdollahi, Ali, "A new correlation for estimating the thermal conductivity and dynamic viscosity of CuO/liquid paraffin nanofluid using neural network method," *International Communications in Heat and Mass Transfer,* vol. 92, (2018): 90-99.

[128] Kamali, R. and Binesh, A. R., "Effects of nanoparticle size on nanofluids heat transfer characteristics in minichannels," *Journal of Computational and Theoretical Nanoscience,* Article vol. 10, no. 4, (2013): 1027-1032.

[129] Pati, S., Mehta, S. K., and Borah, A., "Numerical investigation of thermo-hydraulic transport characteristics in wavy channels: Comparison between raccoon and serpentine channels," *International Communications in Heat and Mass Transfer,* Article vol. 88, (2017): 171-176.

[130] Moraveji, Mostafa Keshavarz and Ardehali, Reza Mohammadi, "CFD modeling (comparing single and two-phase approaches) on thermal performance of Al2o3/water nanofluid in mini-channel heat sink," *International Communications in Heat and Mass Transfer,* vol. 44, (2013): 157-164.

[131] Hosseinirad, Elham and Hormozi, Faramarz, "Performance intensification of miniature channel using wavy vortex generator and optimization by response surface methodology: MWCNT-H2O and Al2O3-H2O nanofluids as coolant fluids," *Chemical Engineering and Processing - Process Intensification,* vol. 124, (2018): 83-96.

[132] Akbari, M., Galanis, N., and Behzadmehr, A., "Comparative analysis of single and two-phase models for CFD studies of nanofluid heat transfer," *International Journal of Thermal Sciences,* vol. 50, no. 8, (2011): 1343-1354.

[133] Naphon, P. and Nakharintr, L., "Numerical investigation of laminar heat transfer of nanofluid-cooled mini-rectangular fin heat sinks," *Journal of Engineering Physics and Thermophysics,* Article vol. 88, no. 3, (2015): 666-675.

[134] Saeed, M. and Kim, M. H., "Heat transfer enhancement using nanofluids (Al2O3-H2O) in mini-channel heatsinks," *International Journal of Heat and Mass Transfer,* Article vol. 120, (2018): 671-682.

[135] Arjun, K. S. and Rakesh, K., "Heat transfer by porous pin fins and nanofluid in rectangular minichannels," *Mechanika,* Article vol. 24, no. 1, (2017): 50-55.

[136] Ghasemi, Seyed Ebrahim, Ranjbar, AA, and Hosseini, MJ, "Numerical study on effect of CuO-water nanofluid on cooling performance of two different cross-sectional heat sinks," *Advanced Powder Technology,* vol. 28, no. 6, (2017): 1495-1504.

[137] Ghasemi, Seyed Ebrahim, Ranjbar, AA, and Hosseini, MJ, "Numerical study on the convective heat transfer of nanofluid in a triangular minichannel heat sink using the Eulerian–Eulerian two-phase model," *Numerical Heat Transfer, Part A: Applications,* vol. 72, no. 2, (2017): 185-196.

[138] Bahiraei, M. and Abdi, F., "Development of a model for entropy generation of water-TiO2 nanofluid flow considering nanoparticle migration within a minichannel," *Chemometrics and Intelligent Laboratory Systems,* Article vol. 157, (2016): 16-28.

[139] Bahiraei, M. and Kazerooni, N. C., "Second law analysis of nanofluid flow within a circular minichannel considering nanoparticle migration," *Entropy,* Article vol. 18, no. 10, (2016): Art. no. 378.

[140] Bahiraei, M. and Mazaheri, N., "Application of a novel hybrid nanofluid containing graphene–platinum nanoparticles in a chaotic twisted geometry for utilization in miniature devices: Thermal and energy efficiency considerations," *International Journal of Mechanical Sciences,* Article vol. 138-139, (2018): 337-349.

[141] Bahiraei, M., Gorjaei, A. R., and Shahidian, A., "Investigating heat transfer and entropy generation for mixed convection of CuO–water nanofluid in an inclined annulus," *Journal of Molecular Liquids,* Article vol. 248, (2017): 36-47.

[142] Duryodhan, V S, Singh, S G, and Agrawal, A, "Liquid flow through converging microchannels and a comparison with diverging microchannels," *Journal of Micromechanics and Microengineering,* vol. 24, no. 12, (2014): 125002.

[143] Abdelrazek, Ali H., Alawi, Omer A., Kazi, S. N., Yusoff, Nukman, Chowdhury, Zaira, and Sarhan, Ahmed A. D., "A new approach to evaluate the impact of thermophysical properties of nanofluids on heat transfer and pressure drop," *International Communications in Heat and Mass Transfer,* vol. 95, (2018): 161-170.

[144] Pak, Bock Choon and Cho, Young I, "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles," *Experimental Heat Transfer an International Journal,* vol. 11, no. 2, (1998): 151-170.

[145] Xuan, Yimin and Roetzel, Wilfried, "Conceptions for heat transfer correlation of nanofluids," *International Journal of heat and Mass transfer,* vol. 43, no. 19, (2000): 3701-3707.

[146] Yu, W. and Choi, S. U. S., "The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated Maxwell model," *Journal of Nanoparticle Research,* Article vol. 5, no. 1-2, (2003): 167-171.

[147] Maiga, Sidi El Becaye, Palm, Samy Joseph, Nguyen, Cong Tam, Roy, Gilles, and Galanis, Nicolas, "Heat transfer enhancement by using nanofluids in forced convection flows," *International journal of heat and fluid flow,* vol. 26, no. 4, (2005): 530-546.

[148] Abdolbaqi, M. K., Mamat, R., Sidik, N. A. C., Azmi, W. H., and Selvakumar, P., "Experimental investigation and development of new correlations for heat transfer enhancement and friction factor of BioGlycol/water based TiO2 nanofluids in flat tubes," (2017).