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On the Application of Nanofluid in Minichannel for Heat Transfer and Fluid Flow Analysis

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Nura Mu'az Muhammad[1,2], Nor Azwadi Che Sidik[3,*], Dendy Adanta[4]

[1] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[2] Mechanical Engineering Department, Kano University of Science and Technology, Wudil, Nigeria
[3] Malaysia – Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[4] Department of mechanical engineering, faculty of engineering, Universitas Sriwijaya, South Sumatra, Indonesia

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ABSTRACT

Heat transfer and flow of fluids are processes that are prevalent in thermal engineering. They occur in many aspects of energy utilization and management. Rapid technological advances in electronic devices through reduction of sizes or simply miniaturization leads to the development of integrated circuits of ultra-large-scale magnitude (ULSIC) as new generation high-performance dense module, but with a consequence on increase power density and extremely intense heat flux which hampers on the long-term reliability and efficiency, as well as reduction of mean time between failure (MTBF) of electronic devices. 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. The Micro (MC) and minichannels (MiC) are the preferred state-of-the-art transport passage nowadays and are receiving much attention from researchers. They differ from conventional channels for having a 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 various recent experimental and numerical works on utilizing nanofluids in minichannels are reviewed and summarized with emphasis on heat transfer enhancement mechanisms and techniques employed, achievement of thermal improvement, and various thermal engineering applications.

Keywords:
Nanofluid, Minichannel heat sink, convective heat transfer, pressure drop, aspect ratio

1. Introduction

Nanofluid technology is regarded as one of the key emerging technologies that are presently attracting great research efforts in thermal engineering with the aim to provide improved working fluid for efficient thermal dissipation from high heat flux generating devices. Miniaturization which

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

involves reduction of sizes of components without compromise on the heat transfer capability is 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 a need for a dynamic, efficient and sustainable approaches toward heat transfer improvement through 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 the 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, 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 receive 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 influences 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 an extensive review of literature in relation to utilization of nanofluid in minichannel as a passive means of heat transfer enhancement [26-32]. It is the view of the authors of this work that, there are recent advances that need 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 provide a systematic review of the works conducted with emphasis on the state-of-art techniques used and novel approaches employed in carrying out experimental and numerical works on thermal and flow analysis using nanofluid and minichannel.

2. Status of Thermal and Flow Analysis using Minichannel and Nanofluids

A comprehensive review of related works and expression of researches conducted in this area was conducted to have a better understanding of the concepts involved 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, a combination of two or more nanofluids provides a hybrid nanofluid, which shows 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 produced either through a single step or two step methods. An extensive review was conducted on the synthesis and production of nanofluids [33].

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 [34] 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 a concentration of 1% and Reynolds number of 500, indicates a 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 [35] using concentrations of 0% - 5% and Re 250-1500. They highlighted that the use of a wavy channel with a 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.*, [36] conducted an experimental study through fabrication and characterization of spherical Silver NP of 25-29 nm to determine the relevance of base fluids (Deionised water, pure water, Ethylene Glycol and the mixture of water-EG) on thermophysical properties of the 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 [37] 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 aluminum 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 a sharp advantage over pure water in the liquid block's cooling. Hence, the hybrid nanofluid has good potential for cooling improvement in electronics. Azwadi and Adamu [38] 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 [39, 40] and Cu-H_2O [41, 42].

2.1.2 Non-Metallic nanofluid

The commonest used nanoparticles are Alumina (Al_2O_3), Titania (TiO_2) and Silica (SiO_2), 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 [43], while formulation of metal-oxide nanofluids and their thermo-physical properties, mechanisms, and heat transfer performance was reviewed by [44] 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 [45] investigated multi-objective optimization of energy efficiency of the 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 a 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. [46] 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*., [47] 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 [48] 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. The 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. [49] dispersed TiO_2 of 21 nm size in distilled water to analyzed 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%. [50] 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 [51] and multi-walled CNT [52]) and Graphene are receiving interest from researchers. Bahiraei *et al*., [53] 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*., [54] 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 enhance 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*., [55] show that heat transfer improved with an 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, micro-fin (#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 [56, 57] compiled extensive reviews on the application of nano and MEPCM in engineering applications. Ho *et al*., [58] 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, [59] observed that heat dissipation depends on heat flow rates and NP showed 57% enhancement under the highest flow rate, whereas MEPCM showed averaged HTC of 51% under low flow rate, and in a similar work [60] 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. [61-65].

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*., [66] 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 [67] 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 categorized 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.

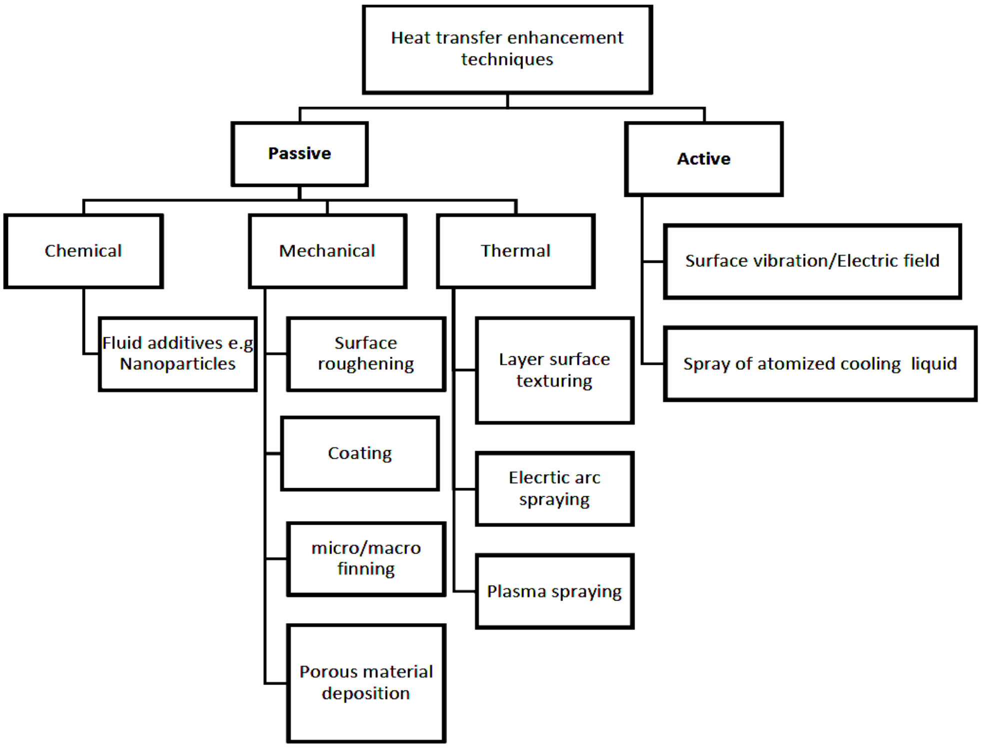


Fig. 1. Heat transfer enhancement techniques

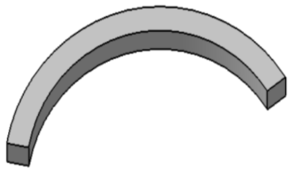
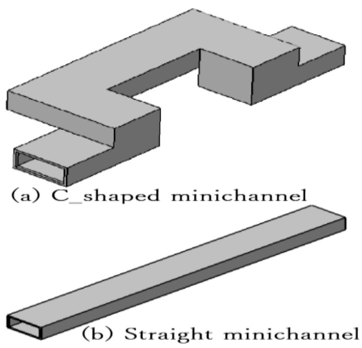
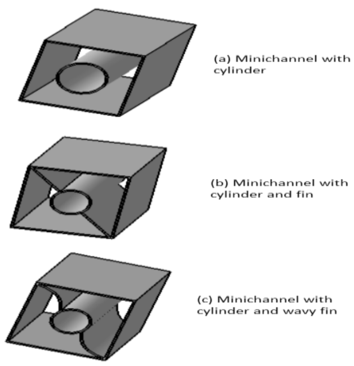
2.2.1 Active method

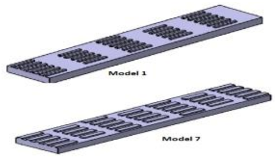
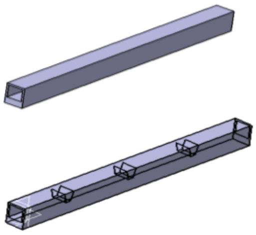
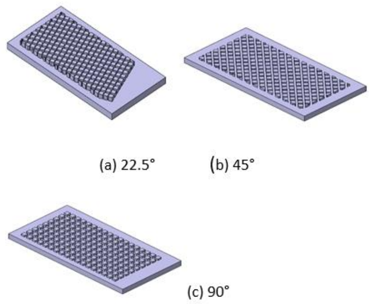
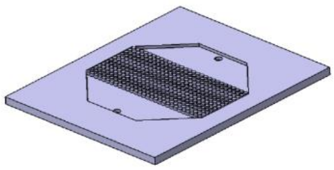
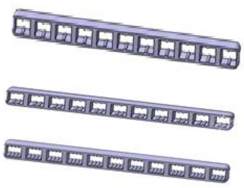
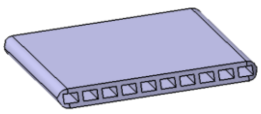
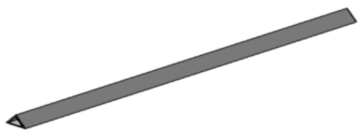
Few available types of research that employed active method include; Ozbey *et al*. [68] investigated the magnetic actuation of ferrofluid with dynamic magnetic fields in a small channel. Mohammadpourfard [69] investigated hydro-thermal behavior of magnetic nanofluid (ferrofluid) Fe_3O_4-kerosene and 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 [70] 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 a substantial impact on the fluid flow through the entire heat sink and temperature distribution. Thus, in the thermal cooling of the heat sink, observing temperature non-uniformity is vital. Other researchers that employed active methods include [71-73].

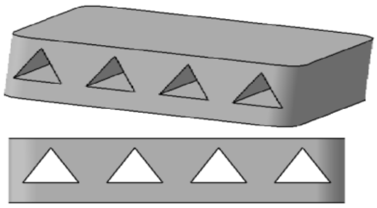
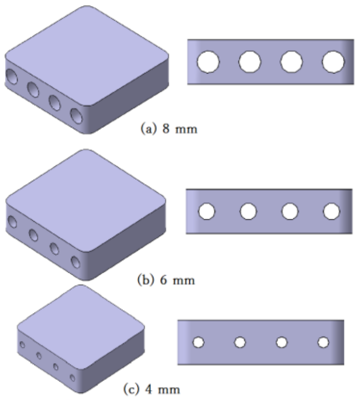
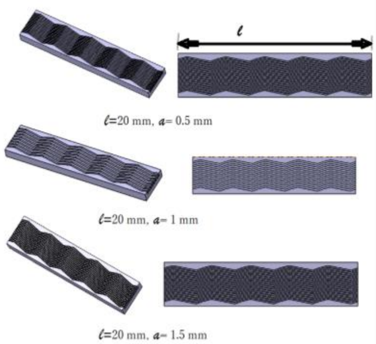
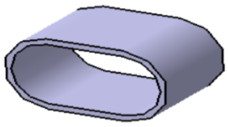
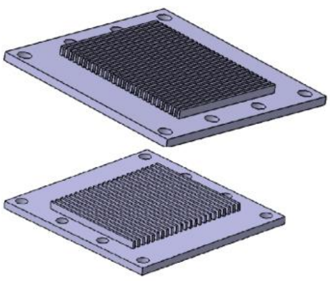
2.2.2 Passive method

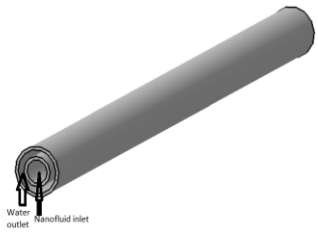
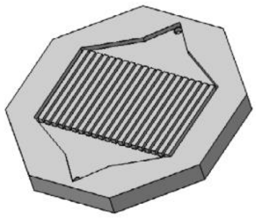
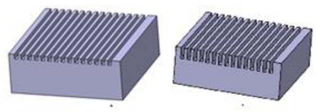
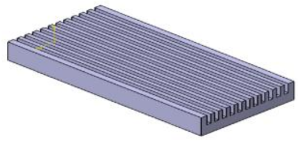
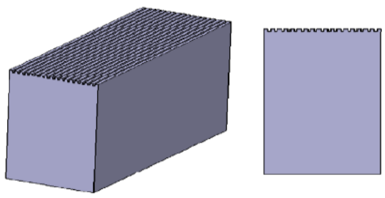
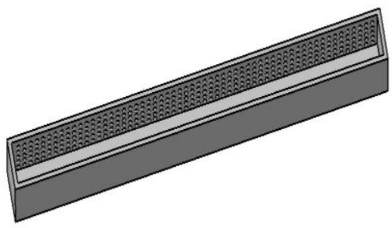
Dominic *et al.*, [74] observed that passive method for forced convective heat transfer enhancement can be achieved through a decrease in thickness of thermal boundary layer, increase in fluid interruption and an increase in velocity gradient near a heat transfer wall. In addition, investigators observed 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 illustrates some of the works that employed a 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	Principal remarks	Geometrical shape
Al_2O_3/H_2O [75]	Chaotic flow	• Amongst the different shapes of particles, nanofluid with nanoplatelets show the largest convective heat transfer improvement and its followed by cylindrical, blade, spherical, and brick shaped NPs. The similar trend observed for pressure drop and convective HTC.	
$CMC/TiO_2/H_2O$ [76]	Chaotic flow	• Increased concentration and Reynolds number by 4% and 200 respectively, lead to frictional entropy generation increase, while thermal entropy generation decreases.	
Al_2O_3/H_2O [77]	Flow obstruction	• Thermal conductivity raises with a concentration of nanoparticles and these aggregated effects enhance 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 [78]	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 [79]	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 [80]	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 [81]	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 the same silicon base temperature.	
TiO_2-H_2O [82]	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 [83]	Flow restriction	• The increase of Re from 200 to 1000 leads to a 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. [84]	Flow restriction	• HTC enhances averagely by 56% with an 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 [85]	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 [86]	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 6 mm and 8 mm.	
Al_2O_3-H_2O [87]	Flow restriction	• Using a CMCHS of 20 mm wavelength 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 [88]	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 [89]	Flow restriction	• the lowest base temperature of 49.7C obtained at a heater power of 255W. • The highest overall HTC recorded was 1498 W/m^{2}K 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^{2}K 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 [90]	Flow restriction	• increasing the Reynolds number, the 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 [34]	Straight channel	• Nanofluid's thermal conductivity improves with an 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 [74]	Straight channel	• Nusselt number attained 76% maximum in the laminar region when Al_2O_3-H_2O is used and 40% in the turbulent region in divergent straight MiC	 (a) Straight MiC (b) Divergent Mic
Alumina and Titania [91]	Straight channel	• Alumina nanofluid indicated average HTC of 3.2% higher than that of water, while Titania has the same value as water. CFD simulation predicted a 5% HTC which is higher than that calculated from experimental readings.	
TiO_2-H_2O [92]	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 [93]	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. The 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 make the simulation more preferred than experimental measurements or theoretical analysis. Some of the prospects and challenges of these methods were highlighted by [94, 95].

2.3.1 Experimental heat transfer analysis

Ho *et al*. [96] investigated the thermal performance of Al_2O_3/H_2O nanofluid with a 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*., [97] 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 [98] 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*., [99] 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 is presented in table 2.

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

Nanofluid system (NP/BF)	Particle morphology (nm)	Nanofluid Concentration (%)	Validity range	Max. Heat improvement (%)	Principal findings
Ag/H_2O (Silver-water) [100]	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, the heat transfer coefficient is found to increase from 30 to 35%.
Al_2O_3/H_2O [101]	40 - 50	0.1 and 0.2 vol.	Re 200-1000	40	• the COP of the thermoelectric module at 0.2 vol% shows 40% enhancement, but with reduction of 9.15% in the 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 [102]	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 [103]	33	10wt	Re 133 -1515	57	• the largest enhancement of around 57% in 10wt% obtained at the highest flow rate of 1515.
Al_2O_3/H_2O [104]	40	5vol	Re 600 - 4500	19	• Thus, nanofluids should be utilized 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 [105]	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 [106]	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 the addition of nanoparticles
Al_2O_3/H_2O & TiO_2/H_2O [107]	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 [108]	25	1, 3, 5 and 7vol.	Re 40 - 1000	40	• 40% heat transfer enhancement observed in the fully developed regime of the laminar flow.
Al_2O_3/H_2O & Al_2O_3-Polyalphaolefin (PAO) [109]	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 the thermal efficiency of nanofluid is adversely offset by dual effects of increased viscosity and lower specific heat.
Al_2O_3-Polyalphaolefin (PAO) [110]	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 [111]	-	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 [112]	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 [113]	70 (SiC) and 110 (Al_2O_3)	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 surpasses the Al2O3-water nanofluid, with the maximum increases of 85% and 52%, respectively.
SiC/H_2O [114]	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. • A smaller increase in resistance, along with the enhancement of heat transfer effect.
SiO_2, Al_2O_3, CuO/DI H_2O [115]	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 [116]	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 [117]	NA	0.05, 0.01, 0.1, 0.5, and 1 vol.	Re 97 - 6200	43	• The Nusselt number increases with increasing volume concentration, then depreciate, paving the way to an optimal volume concentration. When Re reaches 6200, the 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 [118]	10, 30 and 50	0.005, 0.01, 0.1, 0.5 and 1 vol.	Re 100 - 6100	61	• TiO_2 with the 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 [119]	24	0, 1, 2 and 4 wt.		29.7	• The highest heat enhancement of 44.6% in CHF and 29.7% in HTC have 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 a 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 [120]. Mostly researchers in thermo-hydraulic analyses employ Finite

Volume Method (FVM). It is based on the integral form of governing equations and solves for the represented variable value for the cell volume, with control volume, a volume of fluid (VOF) and the mixture as common models. Some researchers have reported the application of different solution methods such as Inverse Heat conduction (IHC), Function Specification Method (FSM), Singular Value Decomposition (SFS) and Conjugated Gradient Method (CGM) [121, 122].

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 the single-phase model to study heat transfer performances of NP with various thermophysical parameters. Classical theories [123-127] were employed for the study, however, mostly these classical theories failed to adequately solve thermo-hydraulic properties, hence some researchers proposed some correlations [128, 129].

Pati *et al*., [130] used the single-phase model to investigate the thermohydraulic performance of two different configurations of the 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 the lower wavelength is almost same for both the channels, whereas for raccoon channel is always more than that for the 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*., [131] 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 an accurate prediction of the models indicated by researchers [84, 132, 133]. Naphon and Nakharintr [134] 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. The 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 [135] 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 underpredicted values of convective HTC.

Arjun and Rakesh [136] 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*. [137] 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 [138], they used the Eulerian two-phase model to analyze 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)	Concentration (%)	working parameter	Significant findings
TiO_2/H_2O [139]	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 [140]	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 [141]	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. The figure of merit is always larger than 1.5 by using the chaotic channel instead of the simple channel.
CuO-H_2O [142]	NA	0.02 - 0.04 vol%	Re 1000	• Convective heat transfer increases with the increase of inclination angle from 0° to 75°, while total entropy generation decreases.

3. Manufacturing Techniques

Advanced technologies are employed in producing microscale channels. The most commonly employed technologies include micro milling using Computer Numerical control (CNC) machine, Electric discharge machine (EDM), Coating of metal-oxide on a substrate (such as in Sol-gel synthesis, thermal spraying, sintering, spray-pyrolysis), and using adhesive. Sujith *et al*., [143] studied the effect of spray pyrolyzed Fe doped Al2O3-TiO2 on critical heat flux using 0, 1.8, 3.6 and 7.2 % weight concentration of Fe. They found an overall enhancement of 52.39% and 44.11% in the CHF and HTC respectively, for 7.2% Fe doped TiO2-Al2O3 for a mass flux of 88 kg/m^{2}s. EDM process involves removal of electrically conductive material without physical contact with the electrode through localized melting/evaporation caused by electrical discharging, thus, it allowed minichannels fabrication on hard, brittle and refractory materials. Naphon and Nakharintr [144] fabricated minichannel heat sink from the copper by the wire EDM with the length, width and a fin height of 110, 60 and 1 mm, respectively. The Schematic of EDM process is shown in Figure 2.

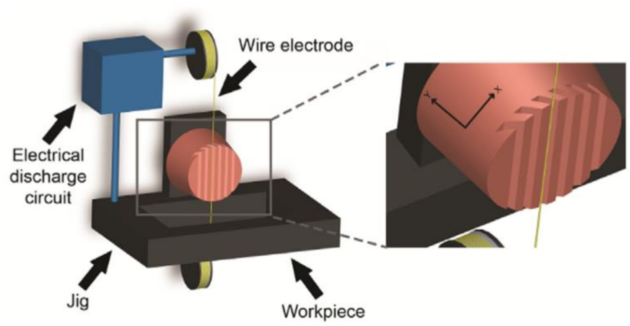


Fig. 2. Schematic process of fabrication of inclined minichannel using EDM [145]

Pool boiling and flow boiling are thermal phenomena and their enhancement using nanofluids were comprehensively reviewed by Liang [146] and Das [147] respectively. Techniques to enhance heat transfer surface for flow boiling in a minichannel and pool boiling studies were reported by vibration-assisted laser and electro-machining [148], and by using laser and spark erosion [149, 150]. Akbari *et al*., [151] studied the effect of inclined and re-entrant inclined minichannel on pool boiling enhancement through bubble dynamics of Ag-DZ-Nanocoolant shown in Figure 3. They observed that increasing nanoparticles concentration can increase the Critical Heat Flux (CHF) and Heat Transfer Coefficient (HTC) on the nano-coated surface by 120% and 100% higher than those of the plain surface. Gheitaghy *et al*., [145] carried out similar work but by varying inclination and spacing of MiCs. Heat dissipation improved with an increase in channel inclination and depth, but with a decrease in channel pitch. The highest HTC and CHF up to 170% and 65% respectively were obtained for the orthogonally intersected minichannels compared to the plain surface. This improvement may be linked to bubble dynamics, heat transfer area, bubble slide and scrape, and capillary flow. They confirmed that EDM provides a more practical method of fabrication of inclined minichannels.

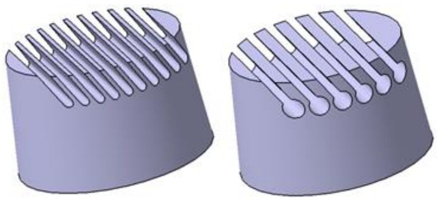


Fig. 3. Inclined and re-entrant minichannels configuration

4.0 Potential Engineering Applications of Nanofluids in Minichannels

4.1 Heat Exchanger

Heat exchangers are going through a transformation and the recent desire is to have lightweight, compact and more efficient heat exchangers for thermal management. Some researchers [2, 26, 152] have extensively reviewed the prospect of using minichannel in heat exchangers for fluid flow and heat transfer. Zewede *et al*., [153] investigated the convective heat transfer of Ethanol/Polyalphaolefin(PAO) nanoemulsion flowing through a heat exchanger made of 12 circular MiC and reported 75% enhancement, while Trinh and Xu [154] used the same nanofluid reported increase in average Nusselt no of 24% and 11 % for 8 wt% and 4 wt%, respectively for nanoemulsion fluid compared to that of pure PAO at the same Reynolds number of 3400.

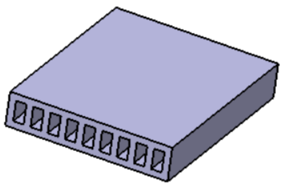
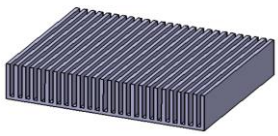
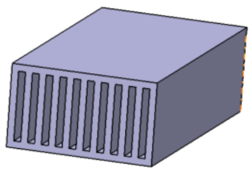
Sarafraz and Hormozi [155] observed heat transfer, pressure drop and fouling studies of multi-walled carbon nanotube nano-fluids inside a plate heat exchanger using inlet temperature between 50-70°C and Re 2500, and reported that increase in concentration and flow rate of nanofluid can enhance HTC. Under the same condition, the pressure drop increased. A non-linear prolong fouling behavior for nanofluid also observed. Ray et al. [156] compare the performance of three different nanofluids (Al_2O_3, CuO_2, SiO_2-ETG-H_2O) in the compact heat exchanger and reported that among the nanofluid, aluminum oxide nanofluid of 0.5 vol% indicated enhanced convective and overall HTC of 11% and 4.85%, respectively.

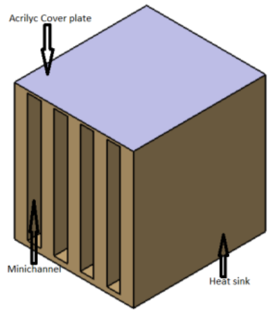
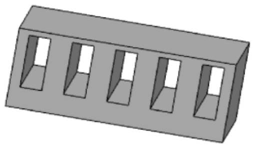
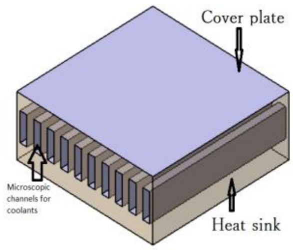
4.2 Electronic Cooling

Heat sinks are regarded as a type of heat exchangers employed in electronic devices cooling, due to the simplicity of fabrication, low cost, and reliability of heat dissipation. They have extended surfaces which are either flat-plate fins or pins fins shapes [157]. Mostly investigators prefer using a liquid block with variable aspect ratio and number channels for electronic thermal management. Ma *et al*., [158] studied flow and heat transfer of a closed-loop cooling system for electronic thermal management using minichannel through power input of 0 - 240W with an increment of 20W each step. They reported that the system has a cooling capability of 240W (corresponding to a heat flux of 30 W/cm^2) at the base temperature under 80°C. For efficient cooling of the heat sink in electronic devices, increasing surface area by an increase of aspect ratio can reduce the thermal resistance, hence, optimal design of the microscale channel is vital for reliable and practical performance.

Though, most of the investigators used single layer heat sink, however Karunanithi *et al*., [159] used a stacked multilayer of porous media, where the porosity varies from one layer to the next layer (porosity scaling) along with the heat transfer direction and indicated advantages over traditional single-layered channels in terms of both pressure drop and thermal resistance, but its inconvenient in terms of miniaturization and fluid volume. Summary of other work in cooling electronic devices using nanofluid and minichannel are presented in table 4.

Table 4
Liquid cooling blocks for Electronic devices heat sinks

Researcher	**Nanofluid**	**Working Temperature (°C)**	**Power density (W/cm^2)**	**Principal findings**	**Geometry**
Kumar and Sarkar. [160]	Al2O3-H2O and Al2O3-MWCNT	27	8.3	Maximum HTC enhancement at 0.01vol% of hybrid nanofluids and minichannel depth of 0.5mm found as 15.6%, with insignificant pressure drop increment.	
Moraveji [161]	TiO2 and SiC /H2O	NA	-	Increase in nanoparticles concentration and Reynolds number leads to higher heat transfer coefficient.	
Ijam et al. [162]	SiC/H2O and TiO2/H2O	35	12.44	thermal conductivity at 4 vol% of nanoparticles SiC/H_2O and TiO_2/H_2O enhanced by 12.44% and 9.99% respectively. The nanofluids indicated thermal	

				efficiency of 7.25%-12.43%, and 7.73%-12.77% for SiC/H_2O and TiO_2/H_2O respectively.	
Khaleduzzaman et al. [163]	Al2O3/H2O (13 nm spherical)	NA	NA	Overall energy efficiency of 94.68%. indicated by Al2O3 nanofluid with 0.25vol.% the highest improvement of outlet exergy of 60.86% of the heat sink at the same concentration compared to water at the flow rate of 1.0l/min.	
Bergman. [164]	Al2O3/H2O (36 nm spherical)	35	NA	Found minimal enhancement and suggested limited usefulness of nanofluid in a heat sink cooling application.	
Tuckerman & Pierse	Conventional fluid	71	790	maximum thermal resistances at downstream was around 0.l°C/W.cm^2, and tested up to 790 W/cm^2.	

4.3 Solar

Mahian *et al*., [165] evaluated the turbulent flow effect on the performance of minichannel-based solar collector using variety nanofluid (Cu/water, Al_2O_3/water, TiO_2/water, and SiO_2/water) having same size of 25 nm at 4vol% and indicated that amongst the nanofluids, Al_2O_3-H_2O and Si_2O_3-H_2O have the highest and lowest HTC respectively, whereas Cu-H_2O has the lowest entropy generation. They further proposed a model to compute thermal conductivity based on consideration of aggregation and Brownian motion effect in the nanoparticles, it is expressed in equation (1)

$$\frac{K_{nf}}{K_f} = \frac{K_p+2K_f-2\phi(K_f-K_p)}{K_p+2K_f+\phi(K_f-K_p)} + \frac{\phi\rho C_{Pf}}{2K_f}\sqrt{\frac{2K_bT_{ave}}{3\pi d_p\mu_f}} \quad (1)$$

where, bf and np refer to base fluid and nanofluid, respectively. for nanofluid and hybrid nanofluid, np is 1 and 2, respectively.

While in another work [166], they examined the effects of nanoparticle shape and tube materials using First and second laws in a minichannel-based solar collector using boehmite alumina nanofluids. The heat exchanger is made up of copper and steel tubes. The result shows that steel tubes at a mass flow rate of 0.5 kg/s show an average entropy generation rate of 11% higher than copper tubes, while it reaches 18% for a mass flow rate of 0.75 kg/s. Sharaf and Orhan [167] used Al_2O_3/H_2O (low to moderate temperatures) and Al_2O_3/synthetic oil (moderate to high temperatures) to analyze and optimize through Genetic Algorithm, densely packed receiver assembly components in high-concentration CPVT solar collectors. Suganthi et al. [168] investigated the heat transfer performance of the ZnO of 25 and 45 nm sizes and Propylene Glycol (PG), respectively in water for solar energy collection & discharging of thermal energy storage. The nanofluids show a 16.5% rise in heat transfer rate for 2 vol% nanofluids at constant heat flux conditions. At the same concentration, the HTC on the coolant side increased by 29% for heat removal from a constant temperature source.

Three different aqueous nanofluids; Al_2O_3, CuO, and SiC were exploited in cooling of photovoltaic (PV) thermal units to enhance its efficiency due to increases in cell temperature obtained during conversion of a small part of the absorbed solar radiation into electricity with the remaining part been lost as heat. SiC shows the best stability and the highest thermal conductivity (4.8% at 4% concentration) compared to the other two nano-substances, while, CuO gave higher thermal conductivity than Al_2O_3 but with lower stability, though it was observed that this material reliably stable compared to in other studies [169]. In overall, the nanofluid reduced the indoor PV/T system temperature and improved power generated.

4.4 Refrigeration and other Specialized Cooling

Zhou *et al*., [170] studied the impact of NP concentration on flow boiling heat transfer coefficients of nano-refrigerant in a micro heat exchanger by direct metal laser sintering. The particle size of the Al_2O_3 was 96 nm. They concluded that the HTCs increased comparatively with the pure refrigerant R141b by 55.0%, 72.0%, 53.0%, 42.3% and 39.9% for 0.05, 0.1, 0.2, 0.3 and 0.4 weight% of Al_2O_3/R141b+Span-80 nano-refrigerant, respectively. Hemmat *et al*., [171] predicted and optimized the thermal and rheological characteristics of Al_2O_3/antifreeze using response surface methodology. Good agreement between the predicted and experimental values was observed. Thus, >99% of variations in viscosity and thermal conductivity of the nanofluid could be predicted by the models. Carbon nanofiber in ethylene and PVP were used as Nanocoolant at 0.1%- 1wt% and the presence of nanoparticles enhanced the forced convective heat transfer performance of the CNF-based nanofluid in a laminar flow as against the base fluid only, and the highest thermal conductivity of 0.642 W/m.K was obtained at volume concentration of 0.5 wt% and temperature of 40°C. [172, 173] also exploit the advantages of nanofluid in refrigeration systems.

Zakaria *et al*., [174] analyzed thermal improvement for a single Proton Exchange Membrane Fuel Cell (PEMFC) cooling plate by a numerical method using low concentration Al_2O_3-H_2O-EG. The thermal performance improved by 7.3% and 4.6% for 0.5 and 0.1 vol % of Al_2O_3 consecutively as compared to the base fluid of 50:50 (water: EG). Better heat transfer enhancement observed at a higher volume fraction of Al_2O_3, but with a penalty of higher pumping power required as much as 0.04W due to raising in pressure drop. Huang [175] viewed the use of effective cooling techniques as vital in high heat flux applications, such as aircraft combustion chambers. Regenerative cooling system, where coolant (e.g., engine fuel) flows through the cooling tubes along the chamber wall to dispel heat by forced convection and thermal cracking. Al_2O_3-kerosene nanofluids were discharged through a vertical upward mini tube at supercritical pressures. As the concentration of NPs increases, the HTC decreases due to the modification of the inner wall surface by the NPs.

4.5 Biomedical systems

Sesen *et al*., [176] uses Fe_2O_3 with particle diameter of 32-100 nm to investigate microflows through electromagnetically actuation device and found that the magnetically actuated pump can achieve flow rates as high as ~30 µl/min with consumed power of 20 Watts and the flow rate can be controlled precisely down to ~5µL/min with the micropump device, hence, this precise flow control device can be very useful in drug delivery systems. However, safety and production cost hamper the commercialization of this innovation.

5. Conclusion

This study reviewed and concisely summarized the recent researches on the application of nanofluid in minichannel for heat transfer augmentation with emphasis on experimental and numerical works conducted with the following inferences made from the review:

- Nanofluid due to its higher surface to volume ratio can significantly improve heat transfer than the base fluid, and hybrid nanofluid formed from a combination of more than one nanofluids has better enhancement than the individual nanofluids.
- Thermal conductivity depends on size, material, and concentration of nanoparticles. Similarly, viscosity also depends on nanoparticles concentration. Addition of surfactant can reduce agglomeration of nanoparticles, but it can increase the viscosity of the nanofluid, hence it might affect the heat transfer enhancement.
- Thermophysical properties such as thermal conductivity, viscosity, material density, and specific heat capacity can be solved using classical theories, like Einstein, Maxwell, etc., however, these theories failed to describe thermal conductivity and viscosity of nanofluids, because those models considered only macro-sized particles.
- Two-phase models predict better results for convective heat transfer due to consideration of slip mechanism between nanoparticles and the base fluid, which is mostly neglected in single-phase approach, though contradictory results reduced the certainty of the results obtained using these approaches.
- Most of the researchers affirmed that use of nanofluid as an alternative to the conventional fluid can enhance the heat efficiency in heat exchangers and electronic devices in most cases by up to 50% thereby ensuring the system reliability.
- reduction of hydraulic diameter can effectively remove excess heat and improves the 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; creating secondary flow, cavity, constriction along the passage and roughness of the surface.

Thus, its recommended that, future works should be expected to dwell on modification of classical theories or new correlations needed to incorporate micro and nano-sized particles for determination of thermophysical properties, and determination of heat transfer mechanism of nanofluid in minichannel with emphasis on optimum enhancement of its thermophysical properties, as well as design of different shapes of minichannel heat sinks that are practicable and economically feasible.

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References

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

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

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

[4] Pryazhnikov, M. I., A. V. Minakov, V. Ya Rudyak, and D. V. Guzei. "Thermal conductivity measurements of nanofluids." *International Journal of Heat and Mass Transfer* 104 (2017): 1275-1282.
[5] Philip, John, and P. D. Shima. "Thermal properties of nanofluids." *Advances in colloid and interface science* 183 (2012): 30-45.
[6] Ambreen, Tehmina, and Man-Hoe Kim. "Heat transfer and pressure drop correlations of nanofluids: a state of art review." *Renewable and Sustainable Energy Reviews* 91 (2018): 564-583.
[7] Maciejewska, B., K. Strąk, and M. Piasecka. "The solution of a two-dimensional inverse heat transfer problem using the Trefftz method." *Procedia Engineering* 157 (2016): 82-88.
[8] Nikkam, Nader, Mohsin Saleemi, Ehsan B. Haghighi, Morteza Ghanbarpour, Rahmatollah Khodabandeh, Mamoun Muhammed, Björn Palm, and Muhammet S. Toprak. "Fabrication, characterization and thermophysical property evaluation of SiC nanofluids for heat transfer applications." *Nano-Micro Letters* 6, no. 2 (2014): 178-189.
[9] Rudyak, V. Ya, A. V. Minakov, and M. I. Pryazhnikov. "Thermal properties of nanofluids and their similarity criteria." *Technical Physics Letters* 43, no. 1 (2017): 23-26.
[10] Xie, Shangzhen, Mehrdad Shahmohammadi Beni, Jiejin Cai, and Jiyun Zhao. "Review of critical-heat-flux enhancement methods." *International Journal of Heat and Mass Transfer* 122 (2018): 275-289.
[11] Ceotto, D., and V. Ya Rudyak. "Phenomenological formula for thermal conductivity coefficient of water-based nanofluids." *Colloid Journal* 78, no. 4 (2016): 509-514.
[12] Fard, M. Haghshenas, M. Nasr Esfahany, and M. R. Talaie. "Numerical study of convective heat transfer of nanofluids in a circular tube two-phase model versus single-phase model." *International Communications in Heat and Mass Transfer* 37, no. 1 (2010): 91-97.
[13] Ny, G., N. Barom, S. Noraziman, and S. Yeow. "Numerical study on turbulent-forced convective heat transfer of Ag/Heg water nanofluid in pipe." *J. Adv. Res. Mater. Sci* 22, no. 1 (2016): 11-27.
[14] Sheikholeslami, M., M. Gorji-Bandpy, and Soheil Soleimani. "Two phase simulation of nanofluid flow and heat transfer using heatline analysis." *International Communications in Heat and Mass Transfer* 47 (2013): 73-81.
[15] Rudyak, V. Ya, and S. L. Krasnolutskii. "Simulation of the thermal conductivity of a nanofluid with small particles by molecular dynamics methods." *Technical Physics* 62, no. 10 (2017): 1456-1465.
[16] Buschmann, M. H., R. Azizian, T. Kempe, J. E. Juliá, Raúl Martínez-Cuenca, B. Sundén, Z. Wu, A. Seppälä, and Tapio Ala-Nissila. "Correct interpretation of nanofluid convective heat transfer." *International Journal of Thermal Sciences* 129 (2018): 504-531.
[17] Fotowat, Shahram, Serena Askar, and Amir Fartaj. "Experimental transient response of a minichannel heat exchanger with step flow variation." *Experimental Thermal and Fluid Science* 89 (2017): 128-139.
[18] Ismail, Mohammed, Shahram Fotowat, and Amir Fartaj. "Simulation of Al2O3-ATF Nanofluid in a Compact Heat Exchanger." In *Proceedings of the 2nd International Conference on Fluid Flow, Heat and Mass Transfer*, pp. 149_1-8. 2015.
[19] Tullius, J. F., and Y. Bayazitoglu. "Effect of Al2O3/H2O nanofluid on MWNT circular fin structures in a minichannel." *International Journal of Heat and Mass Transfer* 60 (2013): 523-530.
[20] Huminic, Gabriela, Angel Huminic, Claudiu Fleaca, Florian Dumitrache, and Ion Morjan. "Thermo-physical properties of water based SiC nanofluids for heat transfer applications." *International Communications in Heat and Mass Transfer* 84 (2017): 94-101.
[21] Hendricks, Terry J., Bryan Mcenerney, Fivos Drymiotis, Ben Furst, and Abhibit Shevade. "Design and Testing of High-Performance Mini-Channel Graphite Heat Exchangers in Thermoelectric Energy Recovery Systems." In *ASME 2017 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers Digital Collection, 2017.
[22] Murshed, SM Sohel, and CA Nieto De Castro. "A critical review of traditional and emerging techniques and fluids for electronics cooling." *Renewable and Sustainable Energy Reviews* 78 (2017): 821-833.
[23] Elsheikh, A. H., S. W. Sharshir, Mohamed E. Mostafa, F. A. Essa, and Mohamed Kamal Ahmed Ali. "Applications of nanofluids in solar energy: a review of recent advances." *Renewable and Sustainable Energy Reviews* 82 (2018): 3483-3502.
[24] Hassan, Abdelrahman Hussein, Santiago Martinez-Ballester, and José Gonzálvez-Maciá. "A new moving boundary model for evaluating the performance of wet fins: Application to minichannel evaporators." *Applied Thermal Engineering* 127 (2017): 566-579.
[25] Vinodhan, V. Leela, K. S. Suganthi, and K. S. Rajan. "Convective heat transfer performance of CuO–water nanofluids in U-shaped minitube: potential for improved energy recovery." *Energy Conversion and Management* 118 (2016): 415-425.
[26] Khattak, M.A., Mukhtar, A. and Afaq, S.K., 2016. Application of nano-fluids as coolant in heat exchangers: a review. *J. Adv. Rev. Sci. Res*, *22*(1), pp.1-11.

[27] Koca, Halil Dogacan, Serkan Doganay, Alpaslan Turgut, Ismail Hakki Tavman, R. Saidur, and Islam Mohammed Mahbubul. "Effect of particle size on the viscosity of nanofluids: A review." *Renewable and Sustainable Energy Reviews* 82 (2018): 1664-1674.

[28] Sidik, Nor Azwadi Che, Muhammad Noor Afiq Witri Mohd Yazid, and Rizalman Mamat. "Recent advancement of nanofluids in engine cooling system." *Renewable and Sustainable Energy Reviews* 75 (2017): 137-144.

[29] Sarkar, Jahar. "A critical review on convective heat transfer correlations of nanofluids." *Renewable and sustainable energy reviews* 15, no. 6 (2011): 3271-3277.

[30] Wu, Zan, and Bengt Sunden. "On further enhancement of single-phase and flow boiling heat transfer in micro/minichannels." *Renewable and Sustainable Energy Reviews* 40 (2014): 11-27.

[31] Hemmati-Sarapardeh, Abdolhossein, Amir Varamesh, Maen M. Husein, and Kunal Karan. "On the evaluation of the viscosity of nanofluid systems: Modeling and data assessment." *Renewable and Sustainable Energy Reviews* 81 (2018): 313-329.

[32] Muhammad, Nura Mu'az, and Nor Azwadi Che Sidik. "Applications of Nanofluids and Various Minichannel Configurations for Heat Transfer Improvement: A Review of Numerical Study." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 46: 49-61.

[33] Sidik, Nor Azwadi Che, Muhammad Mahmud Jamil, Wan Mohd Arif Aziz Japar, and Isa Muhammad Adamu. "A review on preparation methods, stability and applications of hybrid nanofluids." *Renewable and Sustainable Energy Reviews* 80 (2017): 1112-1122.

[34] Bahiraei, Mehdi, and Saeed Heshmatian. "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* 149 (2017): 155-167.

[35] Gupta, Akshay, Suripeddi Srinivas, and Ashish Kandoi. "MODELLING AND SIMULATION OF Au-WATER NANOFLUID FLOW IN WAVY CHANNELS." *Frontiers in Heat and Mass Transfer (FHMT)* 5, no. 1 (2014).

[36] Nikkam, Nader, and Muhammet S. Toprak. "Fabrication and thermo-physical characterization of silver nanofluids: An experimental investigation on the effect of base liquid." *International Communications in Heat and Mass Transfer* 91 (2018): 196-200.

[37] Bahiraei, Mehdi, and Saeed Heshmatian. "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* 127 (2017): 1233-1245.

[38] Azwadi, CS Nor, and I. M. Adamu. "Turbulent force convective heat transfer of hybrid nano fluid in a circular channel with constant heat flux." *J. Adv. Res. Fluid Mech. Therm. Sci* 19, no. 1 (2016): 1-9.

[39] Sinz, C., H. Woei, M. Khalis, and S. A. Abbas. "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* 24, no. 1 (2016): 1-11.

[40] Zainal, S., C. Tan, C. J. Sian, and T. J. Siang. "ANSYS simulation for Ag/HEG hybrid nanofluid in turbulent circular pipe." *Journal of Advanced Research in Applied Mechanics* 23 (2016): 20-35.

[41] Hosseinirad, Elham, and Faramarz Hormozi. "Influence of shape, number, and position of horizontal minifins on thermal-hydraulic performance of minichannel heat sink using nanofluid." *Heat Transfer Engineering* 38, no. 9 (2017): 892-903.

[42] Sivasubramanian, M., T. Theivasanthi, and R. Manimaran. "Experimental investigation on heat transfer enhancement in a minichannel using CuO-water nanofluid." *International Journal of Ambient Energy* 40, no. 8 (2019): 847-853.

[43] Ilyas, Suhaib Umer, Rajashekhar Pendyala, Marneni Narahari, and Lim Susin. "Stability, rheology and thermal analysis of functionalized alumina-thermal oil-based nanofluids for advanced cooling systems." *Energy conversion and management* 142 (2017): 215-229.

[44] Suganthi, K. S., and K. S. Rajan. "Metal oxide nanofluids: Review of formulation, thermo-physical properties, mechanisms, and heat transfer performance." *Renewable and Sustainable Energy Reviews* 76 (2017): 226-255.

[45] Bahiraei, Mehdi, and Saeed Heshmatian. "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* 154 (2017): 180-190.

[46] Dominic, A., J. Sarangan, S. Suresh, and V. S. Devahdhanush. "An experimental study of heat transfer and pressure drop characteristics of divergent wavy minichannels using nanofluids." *Heat and Mass Transfer* 53, no. 3 (2017): 959-971.

[47] Zhou, Jianyang, Xiaoping Luo, Zhenfei Feng, Jian Xiao, Jinxin Zhang, Feng Guo, and Haiyan Li. "Saturated flow boiling heat transfer investigation for nanofluid in minichannel." *Experimental Thermal and Fluid Science* 85 (2017): 189-200.

[48] Ali, Hafiz Muhammad, and Waqas Arshad. "Thermal performance investigation of staggered and inline pin fin heat sinks using water based rutile and anatase TiO2 nanofluids." *Energy conversion and management* 106 (2015): 793-803.
[49] Naphon, Paisarn, and Lursukd Nakharintr. "Heat transfer of nanofluids in the mini-rectangular fin heat sinks." *International Communications in Heat and Mass Transfer* 40 (2013): 25-31.
[50] Murshed, SM Sohel, Kai Choong Leong, Chun Yang, and Nam-Trung Nguyen. "Convective heat transfer characteristics of aqueous TiO 2 nanofluid under laminar flow conditions." *International Journal of Nanoscience* 7, no. 06 (2008): 325-331.
[51] Esfe, Mohammad Hemmat, Ali Akbar Abbasian Arani, and Masoumeh Firouzi. "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* 244 (2017): 252-261.
[52] Shahzad, Muhammad Imran, Mauro Giorcelli, Luigi Ventola, Denis Perrone, Nadia Shahzad, Eliodoro Chiavazzo, Pietro Asinari, Matteo Cocuzza, and Alberto Tagliaferro. "Convective heat transfer enhancement for electronic device applications using patterned MWCNTs structures." *Heat Transfer Engineering* 37, no. 9 (2016): 783-790.
[53] Bahiraei, Mehdi, Ali Godini, and Amin Shahsavar. "Thermal and hydraulic characteristics of a minichannel heat exchanger operated with a non-Newtonian hybrid nanofluid." *Journal of the Taiwan Institute of Chemical Engineers* 84 (2018): 149-161.
[54] Shahsavar, Amin, Mehdi Moradi, and Mehdi Bahiraei. "Heat transfer and entropy generation optimization for flow of a non-Newtonian hybrid nanofluid containing coated CNT/Fe3O4 nanoparticles in a concentric annulus." *Journal of the Taiwan Institute of Chemical Engineers* 84 (2018): 28-40.
[55] Diao, Y. H., C. Z. Li, J. Zhang, Y. H. Zhao, and Y. M. Kang. "Experimental investigation of MWCNT–water nanofluids flow and convective heat transfer characteristics in multiport minichannels with smooth/micro-fin surface." *Powder Technology* 305 (2017): 206-216.
[56] Chai, Lei, Rabia Shaukat, Liang Wang, and Hua Sheng Wang. "A review on heat transfer and hydrodynamic characteristics of nano/microencapsulated phase change slurry (N/MPCS) in mini/microchannel heat sinks." *Applied Thermal Engineering* 135 (2018): 334-349.
[57] Kaviarasu, C., and D. Prakash. "Review on Phase Change Materials with Nanoparticle in Engineering Applications." *Journal of Engineering Science & Technology Review* 9, no. 4 (2016).
[58] Ho, Ching-Jenq, Wei-Chen Chen, Wei-Mon Yan, and Pouria Amani. "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* 122 (2018): 651-659.
[59] Ho, Ching-Jenq, Wei-Chen Chen, Wei-Mon Yan, and Mohammad Amani. "Cooling performance of MEPCM suspensions for heat dissipation intensification in a minichannel heat sink." *International Journal of Heat and Mass Transfer* 115 (2017): 43-49.
[60] Ho, Ching-Jenq, Wei-Chen Chen, and Wei-Mon Yan. "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* 69 (2014): 293-299.
[61] Ismail, Mohammed, Shahram Fotowat, and Amir Fartaj. *Transient Response of Minichannel Heat Exchanger Using Al 2 O 3-EG/W Nanofluid*. No. 2016-01-0229. SAE Technical Paper, 2016.
[62] Hassan, Mohammadreza, Rad Sadri, Goodarz Ahmadi, Mahidzal Dahari, Salim Kazi, Mohammad Safaei, and Emad Sadeghinezhad. "Numerical study of entropy generation in a flowing nanofluid used in micro-and minichannels." *Entropy* 15, no. 1 (2013): 144-155.
[63] Afifah, A. N., S. Syahrullail, and NA Che Sidik. "Natural convection of alumina-distilled water nanofluid in cylindrical enclosure: an experimental study." *J. Adv. Res. Fluid Mech. Therm. Sci* 12, no. 1 (2015): 1-10.
[64] Yu, Leyuan, Aritra Sur, and Dong Liu. "Flow boiling heat transfer and two-phase flow instability of nanofluids in a minichannel." *Journal of Heat Transfer* 137, no. 5 (2015): 051502.
[65] Ghasemi, Seyed Ebrahim, A. A. Ranjbar, and M. J. Hosseini. "Experimental evaluation of cooling performance of circular heat sinks for heat dissipation from electronic chips using nanofluid." *Mechanics Research Communications* 84 (2017): 85-89.
[66] Sohel, M. R., Saidur Rahman, Mohd Sabri, Mohd Faizul, M. M. Elias, and S. S. Khaleduzzaman. "Investigation of heat transfer performances of nanofluids flow through a circular minichannel heat sink for cooling of electronics." In *Advanced Materials Research*, vol. 832, pp. 166-171. Trans Tech Publications, 2014.
[67] Sohel, M. R., R. Saidur, N. H. Hassan, M. M. Elias, S. S. Khaleduzzaman, and I. M. Mahbubul. "Analysis of entropy generation using nanofluid flow through the circular microchannel and minichannel heat sink." *International Communications in Heat and Mass Transfer* 46 (2013): 85-91.

[68] Özbey, Arzu, Mehrdad Karimzadehkhouei, Sinan Eren Yalçın, Devrim Gozuacik, and Ali Koşar. "Modeling of ferrofluid magnetic actuation with dynamic magnetic fields in small channels." *Microfluidics and Nanofluidics* 18, no. 3 (2015): 447-460.
[69] 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* 41, no. 4 (2012): 302-317.
[70] Naphon, Paisarn, and Setha Klangchart. "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* 38, no. 10 (2011): 1400-1405.
[71] Abdulwahab, Mohammed Raad. "A numerical investigation of turbulent magnetic nanofluid flow inside square straight channel." *J. Adv. Res. Fluid Mech. Therm. Sci* 1, no. 1 (2014): 44-52.
[72] Beriache, M., A. Bettahar, L. Loukarfi, L. Mokhtar Saïdia, and H. Naji. "Numerical study on hydraulic and thermal characteristics of a minichannel heat sink with impinging air flow." *Mechanics* 17, no. 2 (2011): 156-161.
[73] Jehad, D. G., and G. A. Hashim. "Numerical prediction of forced convective heat transfer and friction factor of turbulent nanofluid flow through straight channels." *J. Adv. Res. Fluid Mech. Therm. Sci* 8, no. 1 (2015): 1-10.
[74] Dominic, A., J. Sarangan, S. Suresh, and V. S. Devah Dhanush. "An experimental study of forced convective fluid flow in divergent minichannels using nanofluids." In *Applied Mechanics and Materials*, vol. 592, pp. 1418-1422. Trans Tech Publications, 2014.
[75] Liu, Fang, Yang Cai, Liqiu Wang, and Jun Zhao. "Effects of nanoparticle shapes on laminar forced convective heat transfer in curved ducts using two-phase model." *International Journal of Heat and Mass Transfer* 116 (2018): 292-305.
[76] Bahiraei, Mehdi, Khashayar Gharagozloo, Masoud Alighardashi, and Nima Mazaheri. "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* 144 (2017): 374-387.
[77] Ahmadi, Ali Akbar, Erfan Khodabandeh, Hesam Moghadasi, Navid Malekian, Omid Ali Akbari, and Mehdi Bahiraei. "Numerical study of flow and heat transfer of water-Al 2 O 3 nanofluid inside a channel with an inner cylinder using Eulerian–Lagrangian approach." *Journal of Thermal Analysis and Calorimetry* 132, no. 1 (2018): 651-665.
[78] Khoshvaght-Aliabadi, M., O. Sartipzadeh, S. Pazdar, and M. Sahamiyan. "Experimental and parametric studies on a miniature heat sink with offset-strip pins and Al2O3/water nanofluids." *Applied Thermal Engineering* 111 (2017): 1342-1352.
[79] Hosseinirad, Elham, and Faramarz Hormozi. "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* 118 (2017): 199-213.
[80] Ali, Hafiz Muhammad, and Waqas Arshad. "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* 106 (2017): 465-472.
[81] Shenoy, S., J. F. Tullius, and Y. Bayazitoglu. "Minichannels with carbon nanotube structured surfaces for cooling applications." *International Journal of Heat and Mass Transfer* 54, no. 25-26 (2011): 5379-5385.
[82] Zhang, Ji, Yanhua Diao, Yaohua Zhao, and Yanni Zhang. "An experimental investigation of heat transfer enhancement in minichannel: combination of nanofluid and micro fin structure techniques." *Experimental Thermal and Fluid Science* 81 (2017): 21-32.
[83] Ahammed, Nizar, Lazarus Godson Asirvatham, and Somchai Wongwises. "Entropy generation analysis of graphene–alumina hybrid nanofluid in multiport minichannel heat exchanger coupled with thermoelectric cooler." *International Journal of Heat and Mass Transfer* 103 (2016): 1084-1097.
[84] Bahiraei, Mehdi, and Shakiba Mohammadi Majd. "Prediction of entropy generation for nanofluid flow through a triangular minichannel using neural network." *Advanced Powder Technology* 27, no. 2 (2016): 673-683.
[85] Ghasemi, Seyed Ebrahim, A. A. Ranjbar, and M. J. Hosseini. "Thermal and hydrodynamic characteristics of water-based suspensions of Al2O3 nanoparticles in a novel minichannel heat sink." *Journal of Molecular Liquids* 230 (2017): 550-556.
[86] Ghasemi, Seyed Ebrahim, A. A. Ranjbar, and M. J. Hosseini. "Experimental and numerical investigation of circular minichannel heat sinks with various hydraulic diameter for electronic cooling application." *Microelectronics Reliability* 73 (2017): 97-105.
[87] Khoshvaght-Aliabadi, Morteza, and Mohammad Sahamiyan. "Performance of nanofluid flow in corrugated minichannels heat sink (CMCHS)." *Energy conversion and management* 108 (2016): 297-308.
[88] Ghorbani, Babak, M. A. Akhavan-Behabadi, Sasan Ebrahimi, and Krishna Vijayaraghavan. "Experimental investigation of condensation heat transfer of R600a/POE/CuO nano-refrigerant in flattened tubes." *International Communications in Heat and Mass Transfer* 88 (2017): 236-244.

[89] Jajja, Saad Ayub, Wajahat Ali, and Hafiz Muhammad Ali. "Multiwalled carbon nanotube nanofluid for thermal management of high heat generating computer processor." *Heat Transfer—Asian Research* 43, no. 7 (2014): 653-666.

[90] BBahiraei, Mehdi, Mohamad Berahmand, and Amin Shahsavar. "Irreversibility analysis for flow of a non-Newtonian hybrid nanofluid containing coated CNT/Fe3O4 nanoparticles in a minichannel heat exchanger." *Applied Thermal Engineering* 125 (2017): 1083-1093.

[91] Utomo, Adi T., Ashkan IT Zavareh, Heiko Poth, Mohd Wahab, Mohammad Boonie, Phillip T. Robbins, and Andrzej W. Pacek. "Heat transfer coefficient of nanofluids in minichannel heat sink." In *AIP Conference Proceedings*, vol. 1479, no. 1, pp. 66-69. AIP, 2012.

[92] Arshad, Waqas, and Hafiz Muhammad Ali. "Experimental investigation of heat transfer and pressure drop in a straight minichannel heat sink using TiO2 nanofluid." *International Journal of Heat and Mass Transfer* 110 (2017): 248-256.

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

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

[95] Hussien, Ahmed A., Mohd Z. Abdullah, and Al-Nimr Moh'd A. "Single-phase heat transfer enhancement in micro/minichannels using nanofluids: theory and applications." *Applied energy* 164 (2016): 733-755.

[96] Ho, Ching-Jenq, Y. N. Chung, and Chi-Ming Lai. "Thermal performance of Al2O3/water nanofluid in a natural circulation loop with a mini-channel heat sink and heat source." *Energy conversion and management* 87 (2014): 848-858.

[97] 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.

[98] Arshad, Waqas, and Hafiz Muhammad Ali. "Graphene nanoplatelets nanofluids thermal and hydrodynamic performance on integral fin heat sink." *International Journal of Heat and Mass Transfer* 107 (2017): 995-1001.

[99] Hussien, Ahmed A., Mohd Z. Abdullah, Nadiahnor Md Yusop, Al-Nimr Moh'd A, Muataz A. Atieh, and Mohammad Mehrali. "Experiment on forced convective heat transfer enhancement using MWCNTs/GNPs hybrid nanofluid and mini-tube." *International Journal of Heat and Mass Transfer* 115 (2017): 1121-1131.

[100] Raja Bose, Jefferson, Lazarus Godson Asirvatham, N. Kumar, T. Michael, and Somchai Wongwises. "Numerical study on convective heat transfer characteristics of silver/water nanofluid in minichannel." *Current Nanoscience* 13, no. 4 (2017): 426-434.

[101] Ahammed, Nizar, Lazarus Godson Asirvatham, and Somchai Wongwises. "Thermoelectric cooling of electronic devices with nanofluid in a multiport minichannel heat exchanger." *Experimental Thermal and Fluid Science* 74 (2016): 81-90.

[102] Ghaziani, Navid O., and Fatemeh Hassanipour. "Convective heat transfer of al2o3 nanofluids in porous media." *Journal of Heat Transfer* 139, no. 3 (2017): 032601.

[103] Ho, Ching-Jenq, and W. C. Chen. "An experimental study on thermal performance of Al2O3/water nanofluid in a minichannel heat sink." *Applied Thermal Engineering* 50, no. 1 (2013): 516-522.

[104] Liu, Dong, and Leyuan Yu. "Single-phase thermal transport of nanofluids in a minichannel." *Journal of Heat Transfer* 133, no. 3 (2011): 031009.

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

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

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

[108] Vafaei, Saeid, and Dongsheng Wen. "Convective heat transfer of aqueous alumina nanosuspensions in a horizontal mini-channel." *Heat and Mass Transfer* 48, no. 2 (2012): 349-357.

[109] Yu, Leyuan, and Dong Liu. "Study of the thermal effectiveness of laminar forced convection of nanofluids for liquid cooling applications." *IEEE Transactions on Components, Packaging and Manufacturing Technology* 3, no. 10 (2013): 1693-1704.

[110] Yu, Leyuan, Dong Liu, and Frank Botz. "Laminar convective heat transfer of alumina-polyalphaolefin nanofluids containing spherical and non-spherical nanoparticles." *Experimental thermal and fluid science* 37 (2012): 72-83.

[111] Li, YiHuai, ZiHua Wu, HuaQing Xie, JiaoJiao Xing, JianHui Mao, YuanYuan Wang, and Zhen Li. "Study on the performance of TEG with heat transfer enhancement using graphene-water nanofluid for a TEG cooling system." *Science China Technological Sciences* 60, no. 8 (2017): 1168-1174.
[112] Ma, F., J. Chen, and P. Zhang. "Experimental study of the hydraulic and thermal performances of nano-sized phase change emulsion in horizontal mini-tubes." *Energy* 149 (2018): 944-953.
[113] Zhang, Ji, Yanhua Diao, Yaohua Zhao, and Yanni Zhang. "Thermal-hydraulic performance of SiC-water and Al2O3-water nanofluids in the minichannel." *Journal of Heat Transfer* 138, no. 2 (2016): 021705.
[114] Ijam, Ali, Rahman Saidur, and P. Ganesan. "Cooling of minichannel heat sink using nanofluids." *International Communications in Heat and Mass Transfer* 39, no. 8 (2012): 1188-1194.
[115] Rudyak, V. Ya, A. V. Minakov, and S. L. Krasnolutskii. "Physics and mechanics of heat exchange processes in nanofluid flows." *Physical Mesomechanics* 19, no. 3 (2016): 298-306.
[116] Minakov, A. V., D. V. Guzei, M. I. Pryazhnikov, V. A. Zhigarev, and V. Ya Rudyak. "Study of turbulent heat transfer of the nanofluids in a cylindrical channel." *International Journal of Heat and Mass Transfer* 102 (2016): 745-755.
[117] ZHANG, Ji, Yan-Hua DIAO, Yao-Hua ZHAO, Yan-Ni ZHANG, and Qin SUN. "An Experimental Study on Flow and Heat Transfer Characteristics of Nanofluids in Multiport Minichannel Flat Tube." *Journal of Engineering Thermophysics* 5 (2015): 31.
[118] Zhang, Ji, Yanhua Diao, Yaohua Zhao, and Yanni Zhang. "Experimental study of TiO2–water nanofluid flow and heat transfer characteristics in a multiport minichannel flat tube." *International Journal of Heat and Mass Transfer* 79 (2014): 628-638.
[119] S Kumar, CS Sujith, S. Suresh, A. S. Praveen, MC Santhosh Kumar, and Vishakh Gopi. "Effect of surfactant addition on hydrophilicity of ZnO–Al2O3 composite and enhancement of flow boiling heat transfer." *Experimental Thermal and Fluid Science* 70 (2016): 325-334.
[120] Grinstein, Fernando F., Len G. Margolin, and William J. Rider, eds. *Implicit large eddy simulation: computing turbulent fluid dynamics*. Cambridge university press, 2007.
[121] Farahani, S. D., and F. Kowsary. "Estimation local convective boiling heat transfer coefficient in mini channel." *International Communications in Heat and Mass Transfer* 39, no. 2 (2012): 304-310.
[122] Farahani, S. D., F. Kowsary, and J. Jamali. "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* 55 (2014): 1-7.
[123] Batchelor, G. K. "The effect of Brownian motion on the bulk stress in a suspension of spherical particles." *Journal of fluid mechanics* 83, no. 1 (1977): 97-117.
[124] Brinkman, H. C. "The viscosity of concentrated suspensions and solutions." *The Journal of Chemical Physics* 20, no. 4 (1952): 571-571.
[125] Einstein, Albert. *Investigations on the Theory of the Brownian Movement*. Courier Corporation, 1956.
[126] Yu, W., and S. U. S. Choi. "The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Hamilton–Crosser model." *Journal of Nanoparticle Research* 6, no. 4 (2004): 355-361.
[127] Buongiorno, Jacopo. "Convective transport in nanofluids." *Journal of heat transfer* 128, no. 3 (2006): 240-250.
[128] Karimipour, Arash, Samad Ghasemi, Mohammad Hossein Karimi Darvanjooghi, and Ali Abdollahi. "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* 92 (2018): 90-99.
[129] Kamali, R., and A. R. Binesh. "Effects of nanoparticle size on nanofluids heat transfer characteristics in minichannels." *Journal of Computational and Theoretical Nanoscience* 10, no. 4 (2013): 1027-1032.
[130] Pati, Sukumar, Sumit Kumar Mehta, and Abhijit Borah. "Numerical investigation of thermo-hydraulic transport characteristics in wavy channels: comparison between raccoon and serpentine channels." *International Communications in Heat and Mass Transfer* 88 (2017): 171-176.
[131] Moraveji, Mostafa Keshavarz, and Reza Mohammadi Ardehali. "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* 44 (2013): 157-164.
[132] Hosseinirad, Elham, and Faramarz Hormozi. "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* 124 (2018): 83-96.
[133] Akbari, M., N. Galanis, and A. Behzadmehr. "Comparative analysis of single and two-phase models for CFD studies of nanofluid heat transfer." *International Journal of Thermal Sciences* 50, no. 8 (2011): 1343-1354.
[134] Naphon, Paisarn, and Lursukd Nakharintr. "Numerical investigation of laminar heat transfer of nanofluid-cooled mini-rectangular fin heat sinks." *Journal of Engineering Physics and Thermophysics* 88, no. 3 (2015): 666-675.
[135] Saeed, Muhammad, and Man-Hoe Kim. "Heat transfer enhancement using nanofluids (Al2O3-H2O) in mini-channel heatsinks." *International Journal of Heat and Mass Transfer* 120 (2018): 671-682.

[136] Arjun, K. S., and K. Rakesh. "Heat Transfer by Porous Pin Fins and Nanofluid in Rectangular Minichannels." *Mechanika* 24, no. 1 (2018).
[137] Ghasemi, Seyed Ebrahim, A. A. Ranjbar, and M. J. Hosseini. "Numerical study on effect of CuO-water nanofluid on cooling performance of two different cross-sectional heat sinks." *Advanced Powder Technology* 28, no. 6 (2017): 1495-1504.
[138] Ghasemi, Seyed Ebrahim, A. A. Ranjbar, and M. J. Hosseini. "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* 72, no. 2 (2017): 185-196.
[139] Bahiraei, Mehdi, and Farshad Abdi. "Development of a model for entropy generation of water-TiO2 nanofluid flow considering nanoparticle migration within a minichannel." *Chemometrics and Intelligent Laboratory Systems* 157 (2016): 16-28.
[140] Bahiraei, Mehdi, and Navid Cheraghi Kazerooni. "Second law analysis of nanofluid flow within a circular minichannel considering nanoparticle migration." *Entropy* 18, no. 10 (2016): 378.
[141] Bahiraei, Mehdi, and Nima Mazaheri. "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* 138 (2018): 337-349.
[142] Bahiraei, Mehdi, Arash Rezaei Gorjaei, and Azadeh Shahidian. "Investigating heat transfer and entropy generation for mixed convection of CuO–water nanofluid in an inclined annulus." *Journal of Molecular Liquids* 248 (2017): 36-47.
[143] Kumar, Sujith, S. Suresh, C. R. Aneesh, Santhosh Kumar, A. S. Praveen, and K. Raji. "Flow boiling heat transfer enhancement on copper surface using Fe doped Al2O3–TiO2 composite coatings." *Applied Surface Science* 334 (2015): 102-109.
[144] Naphon, Paisarn, and Lursukd Nakharintr. "Turbulent two phase approach model for the nanofluids heat transfer analysis flowing through the minichannel heat sinks." *International Journal of Heat and Mass Transfer* 82 (2015): 388-395.
[145] Gheitaghy, Amir Mirza, Alireza Samimi, and Hamid Saffari. "Surface structuring with inclined minichannels for pool boiling improvement." *Applied Thermal Engineering* 126 (2017): 892-902.
[146] Liang, Gangtao, and Issam Mudawar. "Review of pool boiling enhancement with additives and nanofluids." *International Journal of Heat and Mass Transfer* 124 (2018): 423-453.
[147] Das, P., S. Chakraborty, and S. Bhaduri. "Critical heat flux during flow boiling in mini and microchannel-a state of the art review." *Frontiers in Heat and Mass Transfer (FHMT)* 3, no. 1 (2012).
[148] Piasecka, M., K. Strąk, and B. Grabas. "Vibration-assisted laser surface texturing and electromachining for the intensification of boiling heat transfer in a minichannel." *Archives of Metallurgy and Materials* 62, no. 4 (2017): 1983-1990.
[149] Piasecka, Magdalena. "Laser texturing, spark erosion and sanding of the surfaces and their practical applications in heat exchange devices." In *Advanced Materials Research*, vol. 874, pp. 95-100. Trans Tech Publications, 2014.
[150] Piasecka, Magdalena. "Heat transfer research on enhanced heating surfaces in flow boiling in a minichannel and pool boiling." *Annals of Nuclear Energy* 73 (2014): 282-293.
[151] Akbari, Ebrahim, Amir Mirza Gheitaghy, Hamid Saffari, and Seyed Mostafa Hosseinalipour. "Effect of silver nanoparticle deposition in re-entrant inclined minichannel on bubble dynamics for pool boiling enhancement." *Experimental Thermal and Fluid Science* 82 (2017): 390-401.
[152] Bahiraei, Mehdi, Reza Rahmani, Ali Yaghoobi, Erfan Khodabandeh, Ramin Mashayekhi, and Mohammad Amani. "Recent research contributions concerning use of nanofluids in heat exchangers: a critical review." *Applied Thermal Engineering* 133 (2018): 137-159.
[153] Zewede, Fana, Henok Argaw, Thanh Tran, and Jiajun Xu. "Convective Heat Transfer of Ethanol/Polyalphaolefin Nanoemulsion Inside Circular Minichannel Heat Exchanger." In *ASME 2017 Heat Transfer Summer Conference*. American Society of Mechanical Engineers Digital Collection, 2017.
[154] Trinh, Vu, and Jiajun Xu. "An experimental study on flow and heat transfer characteristics of ethanol/polyalphaolefin nanoemulsion flowing through circular minichannels." *Nanoscale research letters* 12, no. 1 (2017): 216.
[155] Sarafraz, M. M., and F. Hormozi. "Heat transfer, pressure drop and fouling studies of multi-walled carbon nanotube nano-fluids inside a plate heat exchanger." *Experimental Thermal and Fluid Science* 72 (2016): 1-11.
[156] Ray, Dustin R., Debendra K. Das, and Ravikanth S. Vajjha. "Experimental and numerical investigations of nanofluids performance in a compact minichannel plate heat exchanger." *International Journal of Heat and Mass Transfer* 71 (2014): 732-746.
[157] Ahmed, Hamdi E., B. H. Salman, A. Sh Kherbeet, and M. I. Ahmed. "Optimization of thermal design of heat sinks: A review." *International Journal of Heat and Mass Transfer* 118 (2018): 129-153.

[158] Ma, Lei, Xuxin Zhao, Hongyuan Sun, Qixing Wu, and Wei Liu. "Experimental study of single phase flow in a closed-loop cooling system with integrated mini-channel heat sink." *Entropy* 18, no. 6 (2016): 128.
[159] Karunanithi, A. and Hassanipour, F., "Heat sink with multilayer of porous media." *Journal of Porous Media* 19, no. 8 (2016): 659-667.
[160] Kumar, Vivek, and Jahar Sarkar. "Two-phase numerical simulation of hybrid nanofluid heat transfer in minichannel heat sink and experimental validation." *International Communications in Heat and Mass Transfer* 91 (2018): 239-247.
[161] Moraveji, Mostafa Keshavarz, Reza Mohammadi Ardehali, and Ali Ijam. "CFD investigation of nanofluid effects (cooling performance and pressure drop) in mini-channel heat sink." *International Communications in Heat and Mass Transfer* 40 (2013): 58-66.
[162] Ijam, Ali, and Rahman Saidur. "Nanofluid as a coolant for electronic devices (cooling of electronic devices)." *Applied Thermal Engineering* 32 (2012): 76-82.
[163] Khaleduzzaman, S. S., M. R. Sohel, R. Saidur, I. M. Mahbubul, I. M. Shahrul, B. A. Akash, and J. Selvaraj. "Energy and exergy analysis of alumina–water nanofluid for an electronic liquid cooling system." *International Communications in Heat and Mass Transfer* 57 (2014): 118-127.
[164] Bergman, T. L. "Analysis of heat transfer enhancement in minichannel heat sinks with turbulent flow using H2O–Al2O3 nanofluids." *Journal of Electronic Packaging* 131, no. 2 (2009): 021008.
[165] Mahian, Omid, Ali Kianifar, Ahmet Z. Sahin, and Somchai Wongwises. "Performance analysis of a minichannel-based solar collector using different nanofluids." *Energy conversion and management* 88 (2014): 129-138.
[166] Mahian, Omid, Ali Kianifar, Saeed Zeinali Heris, and Somchai Wongwises. "First and second laws analysis of a minichannel-based solar collector using boehmite alumina nanofluids: effects of nanoparticle shape and tube materials." *International Journal of Heat and Mass Transfer* 78 (2014): 1166-1176.
[167] Sharaf, Omar Z., and Mehmet F. Orhan. "Thermodynamic analysis and optimization of densely-packed receiver assembly components in high-concentration CPVT solar collectors." *Energy Conversion and Management* 121 (2016): 113-144.
[168] Suganthi, K. S., and K. S. Rajan. "ZnO propylene glycol water nanofluids with improved properties for potential applications in renewable energy and thermal management." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 506 (2016): 63-73.
[169] Al-Waeli, Ali HA, Miqdam T. Chaichan, Hussein A. Kazem, and Kamaruzzaman Sopian. "Comparative study to use nano-(Al2O3, CuO, and SiC) with water to enhance photovoltaic thermal PV/T collectors." *Energy Conversion and Management* 148 (2017): 963-973.
[170] Zhou, Jianyang, Xiaoping Luo, Cong Deng, Mingyu Xie, Lin Zhang, Di Wu, and Feng Guo. "Influence of nanoparticle concentrations on flow boiling heat transfer coefficients of Al2O3/R141b in micro heat exchanger by direct metal laser sintering." *Chinese journal of chemical engineering* 25, no. 12 (2017): 1714-1726.
[171] Esfe, Mohammad Hemmat, Masoumeh Firouzi, Hossein Rostamian, and Masoud Afrand. "Prediction and optimization of thermophysical properties of stabilized Al2O3/antifreeze nanofluids using response surface methodology." *Journal of Molecular Liquids* 261 (2018): 14-20.
[172] Zainal Abidin, Syazwani, Imran Syakir Mohamad, Ahmad Yusairi Bani Hashim, Norli Abdullah, Md Isa, Mohamed Hafiz, Nor Azmmi Masripan, and Amirah Abdullah. "Investigation of thermal characteristics of CNF-based nanofluids for electronic cooling applications." *Journal of Mechanical Engineering and Sciences (JMES)* (2016): 2336-2349.
[173] Vasiliev, Leonard L., Alexander S. Zhuravlyov, and Alexander Shapovalov. "Heat transfer enhancement in mini channels with micro/nano particles deposited on a heat-loaded wall." *Journal of Enhanced Heat Transfer* 19, no. 1 (2012).
[174] Zakaria, Irnie, W. A. N. W. Mohamed, AMI Bin Mamat, R. Saidur, W. H. Azmi, Rizalman Mamat, K. I. Sainan, and H. Ismail. "Thermal Analysis of Heat Transfer Enhancement and Fluid Flow for Low Concentration of Al2O3 Water-Ethylene Glycol Mixture Nanofluid in a Single PEMFC Cooling Plate." *Energy Procedia* 79 (2015): 259-264.
[175] Huang, Dan, Xiao-yu Wu, Zan Wu, Wei Li, Hai-tao Zhu, and Bengt Sunden. "Experimental study on heat transfer of nanofluids in a vertical tube at supercritical pressures." *International Communications in Heat and Mass Transfer* 63 (2015): 54-61.
[176] Sesen, Muhsincan, Beste Bahceci, Ali Kosar, Soner Ulun, Caglar Huseyin Su, and H. Yagci Acar. "Magnetic actuation of nanofluids with ferromagnetic particles." In *ASME 2010 8th International Conference on Nanochannels, Microchannels, and Minichannels collocated with 3rd Joint US-European Fluids Engineering Summer Meeting*, pp. 1377-1381. American Society of Mechanical Engineers Digital Collection, 2010.