HYDROTHERMAL PERFORMANCE OF Al_2O_3/WATER AND CUO/WATER NANOFLUIDS IN DIVERGENT-CONVERGENT MINICHANNEL HEATSINK WITH DIMPLES

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ABSTRACT

The recent trend in technological advancements in electronic devices offers high-performance compact systems. However, highly concentrated heat flux restricted their efficiency and reduced the Mean time before failure (MTBF). Many researchers exploit different passive heat transfer techniques like geometry modification to alleviate high heat flux. Despite the potential of divergent-convergent minichannel in mixing flow and a higher proportion of surface area to volume than conventional channels, research on it is inadequate. The study aims to develop and examine the influence of combined multi passive heat transfer techniques in an electronic device minichannel heatsink towards further augmenting heat transfer with minimal pressure loss and thermal resistance. This study combines corrugated geometry with innovative high thermal conductive nanofluid as hybrid passive techniques. The experimental validation concerning measured and predicted pressure drop and Heat Transfer Coefficient data indicated a maximum deviation of 19.1% and 13.8%, respectively. The numerical analysis employed a commercial CFD code based on the finite volume method. The investigation of forced convective heat transfer and nanofluids' flow achieved with single-phase and two-phase mixture models in a divergent-convergent minichannel heatsink (DCMH) having a hydraulic diameter of 1.42mm. The numerical investigation employed Al_2O_3/water and CuO/water nanofluids with 0 - 2.5 volume%, fluid velocity from 3 – 6 m/s (corresponding to Reynolds number (5000 – 10000), and the inlet temperature 303 K. The two-phase model exhibits better agreement with established correlation than the single-phase model. A numerical analysis of an enhanced geometry with dimples on the minichannel floor was developed to augment the hydrothermal performance. The results found that the effects of principal parameters on the chip heat flux demonstrated the heat transfer coefficient's growth with a rise in volume fractions and fluid velocity. Both nanofluids indicated better performance enhancement than water. Al_2O_3/water and CuO/water nanofluids augment over water by about 6.44% and 8.33% for 2.5 vol.%. Also, pressure loss rises when the velocity increases. The pressure loss relative to water at 2.5 vol.% and 5.5 m/s yields 15.14% and 18.56 % for Al_2O_3/water and CuO/water. The highest pumping power is 0.057 W for all the cases, which indicates the pumping demand is much lower than 1.0 W. The introduction of dimples on DCMH has considerably advanced hydrothermal performance with a PEC of 1.214 over the smooth model. The overall results established that the combined effects of DCMH and nanofluids have significantly improved the heat sink's hydrothermal performance and can provide the desired heat dissipation from the enclosed chips in compact electronic devices.

ABSTRAK

Aliran terkini dalam kemajuan teknologi dalam bidang peranti elektronik menawarkan sistem kompak berprestasi tinggi. Walau bagaimanapun, fluks haba yang sangat tinggi membataskan kecekapan dan mengurangkan Purata masa sebelum kegagalan (MTBF). Ramai penyelidik mengeksploitasi teknik pemindahan haba pasif yang berbeza seperti pengubahsuaian geometri untuk mengurangkan fluks haba yang tinggi. Terdapat penyelidikan bagi saluran mini bercapah-tumpu dalam pelbagai aliran dan nisbah bahagian luas permukaan kepada isipadu yang lebih tinggi daripada saluran konvensional, penyelidikan mengenainya masih sedikit. Matlamat penyelidikan adalah untuk membangunkan dan mengkaji kesan gabungan teknik pemindahan haba berbilang pasif dalam saluran mini sinki haba peranti elektronik ke arah penambahbaikan pemindahan haba dengan kehilangan tekanan dan rintangan terma yang minimum. Kajian ini menggabungkan geometri beralun dengan cecair nano konduktif terma tinggi yang inovatif sebagai teknik pasif hibrid. Pembuktian eksperimen mengenai kurangan tekanan diukur serta diramal dan data Pekali Pemindahan Haba menunjukkan sisihan maksimum 19.1% dan 13.8%. Analisis berangka menggunakan kod CFD komersial berdasarkan kaedah isipadu terhingga. Penyiasatan terhadap daya pemindahan haba perolakan dan aliran cecair nano tercapai dengan model campuran satu fasa dan dua fasa dalam sinki haba saluran kecil penumpuan mencapah (DCMH) yang mempunyai diameter hidraulik 1.42mm. Simulasi dijalankan dengan menggunakan cecair nano Al_2O_3/air dan CuO/air dengan isipadu 0 - 2.5 %, halaju bendalir 3-6 m/s (bersamaan dengan nombor Reynolds (5000 – 10000), dan suhu aliran masuk, 303 K. Dua fasa model menunjukkan keputusan yang lebih baik dengan korelasi yang telah ditetapkan berbanding model satu fasa. Analisa simulasi bagi geometri yang ditambahbaik dengan lekuk-lekuk pada permukaan saluran mini telah dibangunkan untuk menambah prestasi hidroterma. Keputusan mendapati bahawa kesan parameter utama pada fluks haba cip menunjukkan pertumbuhan pekali pemindahan haba dengan peningkatan pecahan isipadu dan halaju bendalir. Kedua-dua cecair nano menunjukkan peningkatan prestasi yang lebih baik berbanding air. Cecair nano Al_2O_3/air dan CuO/air lebih baik berbanding air sebanyak kira-kira 6.44% dan 8.33% untuk isipadu 2.5 %. Selain itu, kehilangan tekanan meningkat apabila halaju meningkat. Kehilangan tekanan relatif kepada air pada isipadu 2.5 % dan 5.5 m/s menghasilkan 15.14% dan 18.56 % bagi Al_2O_3/air dan CuO/air. Kuasa pengepaman tertinggi ialah 0.057 W untuk semua kes, yang menunjukkan keperluan pengepaman jauh lebih rendah daripada 1.0 W. Pengenalan lekuk-lekuk pada DCMH membawa kepada prestasi hidroterma yang maju dengan PEC sebanyak 1.214 berbanding model tanpa lekuk. Keseluruhan keputusan menunjukkan bahawa kesan gabungan DCMH dan cecair nano telah meningkatkan prestasi hidroterma sinki haba dengan ketara dan boleh memberikan pelesapan haba yang diperlukan daripada cip tertutup dalam peranti elektronik padat.

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LIST OF ABBREVIATIONS

CA	-	Chaotic advection
CFD	-	Computational Fluids Dynamics
CNT	-	Carbon Nanotube
CV	-	Control volume
CPU	-	Central Processing Unit
DCMH	-	Divergent-Convergent Minichannel Heatsink
DPM	-	Discrete-phase model
DV	-	Dean Vortices
EG	-	Ethylene glycol
FESEM	-	Field Electron Scanning Electron Microscope
GNP	-	Graphene Nanoplatelet
HP	-	Hydrothermal Performance
HTE	-	Heat Transfer Enhancement
MCHS	-	Minichannel Heatsink
MiC	-	Microchannel
MWCNT	-	Multi-walled CNT
NA	-	Not available
NP	-	Nanoparticle
PEC	-	Performance Evaluation Criteria
OQ	-	Orthogonal Quality
OS	-	Orthogonal Skew
PG	-	Propylene glycol
RNG	-	Renormalised Group
SWCNT	-	Single-walled CNT
TEM	-	Transmission Electron Microscope
UDF	-	User-Defined Function
UHF	-	Uniform Heat Flux
UWT	-	Uniform Wall Temperature

LIST OF SYMBOLS

Roman symbols

Cp	-	Fluid specific heat capacity
De	-	Dean number
Dh	-	Hydraulic diameter
d	-	Dimple diameter
f	-	Friction factor
h	-	Heat Transfer coefficient (HTC)
K	-	Boltzmann constant
K	-	Kelvin (temperature scale)
k or λ	-	Fluid thermal conductivity
k	-	Turbulent kinetic energy
Kn	-	Knudsen number
L	-	Length of the minichannel section
ṁ	-	Mass flow rate
Nu	-	Nusselt number
P	-	Static pressure
Pr	-	Prandtl number
Re	-	Reynolds number
S	-	Area of the lateral surface of the channel
ș	-	Pitch of dimples
T	-	Temperature
U	-	Fluid inlet velocity
u	-	Fluid inlet velocity on the x-axis
U/u	-	Nondimensional fluid velocity
V	-	Volume
Ṽ	-	Volume flow rate
vol.%	-	Volume concentration
wt.%	-	Weight concentration
x, y and z	-	Cartesian coordinates
ΔP	-	Measured/predicted pressure differential

Greek symbols

ξ	-	Frictional coefficient
ρ	-	Density
μ	-	Dynamic viscosity
μ	-	Fluid viscosity coefficient
Δ	-	Gradient
λ	-	Molecule mean free path
φ	-	Particle concentration
Γ	-	Response variable
τ	-	Shear stress
Ψ	-	Sphericity factor of nanoparticle
σ	-	Surface tension
ε	-	Turbulent dissipation rate
ϖ	-	Weight fraction

Subscripts

avg	-	Average value
bf	-	Base fluid
b	-	Bulk
w	-	Channel Wall
eff	-	Effective
f	-	Fluid
in	-	Inlet
mean	-	Mean value
m	-	Mixture
nf	-	Nanofluid
np	-	Nanoparticle
out	-	Outlet
p	-	Particle

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Research and development (R & D) of systems and devices are witnessing a new paradigm because of recent manufacturing technology advancements. The innovation results in highly efficient and compact devices and systems. However, high heat flux generation, which must be evacuated instantly and promptly to safeguard the devices and system from untimely failure, stands as the impediment towards their broader applications. Heat transfer and fluid flow are prevalent in thermal engineering in energy application and management aspects. The process encompasses diverse application areas such as cooling, heating, and mass transfer in power/energy generation. Convective heat transfer is among the heat transfer modes, classified as either free or forced convection based on the fluid flow type [1]. Convection is a prime factor in thermohydraulic applications. Robust engineering design and thermal system investigation demand the proper evaluation of thermophysical properties of a working fluid by experiment or accurate numerical prediction, in addition to the dynamic design of flow passages. The fluid's thermophysical properties comprise thermodynamic and transport properties. The latter include thermal conductivity and viscosity, which account for momentum and energy transfer in a system. The former relates to the state of equilibrium of a system. It includes properties like temperature, pressure, heat capacity and density, among others [2].

Rapid technological advances in electronic devices by size reduction or simply miniaturisation lead to the development of integrated circuits of ultra-large-scale magnitude (ULSIC) as future generation super-performance dense modules, but with a consequence of increasing power density and too intense heat flux [3]. The miniaturisation and customer ever-changing demands in terms of high-performance devices continuously push the boundaries of heat transfer enhancement. Consequently, it hampers the long-term reliability and efficiency and reduces the mean time between failure (MTBF) of electronic devices. Thermal management (TM) as a method of dissipating excess heat and controlling system temperature [4] requires dynamic, efficient, and sustainable approaches through continuous research and development.

Current developments in semiconductor devices require faster but smaller devices. The technology roadmap by iNEMI (International Electronics Manufacturing Initiative) projected by the year 2020 that the high-performance microprocessor chips, as depicted in Figure 1.1(a), would dissipate peak power and maximum high flux of around 360 W and 190 W/cm^2, respectively [5]. However, the high power density and high operating or junction temperature should not surpass 80–90 °C [6] tend to upset this development. Also, Atalla et al. [7] reported that the reliability of electronic devices' temperature and lifespan relate inversely to the device's components temperature.

Sohel and Castro [5] observed that high junction temperature causes low performance and failure to the devices. The electronic device's failure factor is the relative failure frequency ratio at all temperatures to failure rate at 75 °C. Figure 1.1(b) illustrates an exponential increase of f_t as the device temperature rises [5]. Thus, controlling the junction temperature could ensure performance reliability and the long life of the device.

Convective heat transfer refers to transferring heat away from heat-dissipating surfaces. The fluid in contact with the high-temperature gradient surface removes heat, declining the temperature gradient. Newton's law of cooling provides a governing equation for the heat convection rate as a heat transfer coefficient (h), the material's surface area (A_s), and the temperature difference (ΔT) amid the pipe/duct wall and the fluid. The temperature gradient intensification has an operational limit imposed by material properties and manufacturing specifications. On the other hand, the need for a compact system, i.e., miniaturisation, restrict surface area expansion.

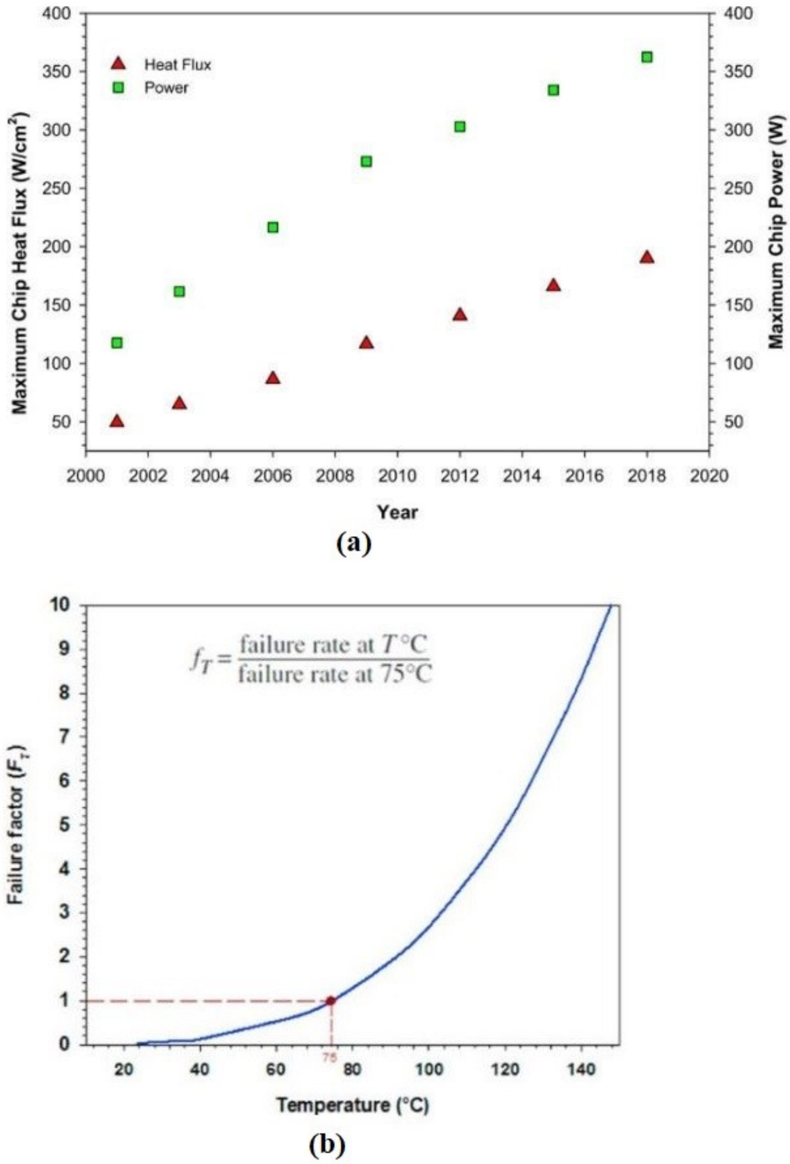

Figure 1.1 (a) iNEMI predictions of maximum rates of heat flux and power of a microchip, (b) Failure rate of electronic devices based on temperature [5]

Accordingly, the heat transfer coefficient can be enhanced using high thermal conductivity fluid, the variation of flow regime, and surface area variation. Some researchers employ air [8, 9] or liquid cooling [10, 11] to convey heat dissipation from space-constrained electronic devices. However, the conventional fluids failed to provide adequate rapid high heat dissipation with the highly concentrated heat flux due to their low thermal conductivity. Figure 1.2 summarised the different categories of convective heat transfer. A forced convection heat transfer in an electronic chip set (EC) by internal flow formed the basis of this study.

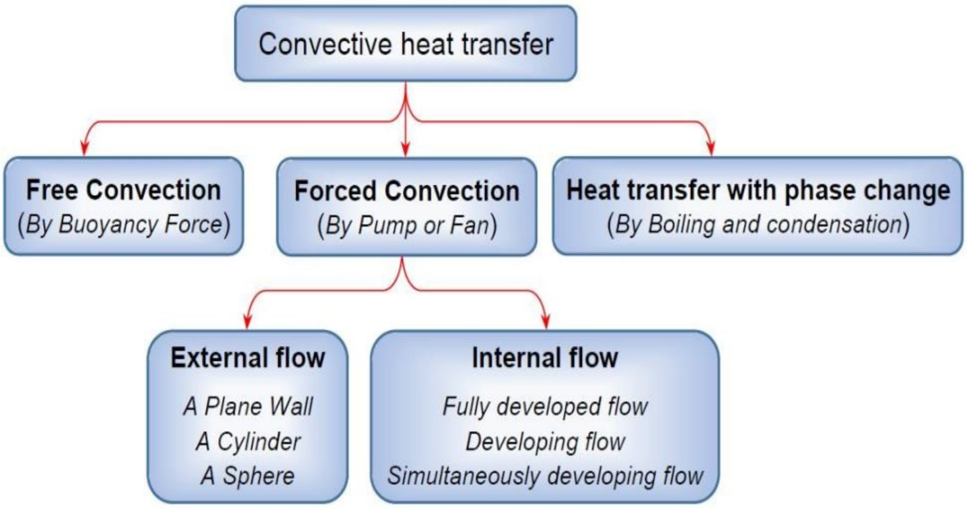

Figure 1.2 Flowchart for convective heat transfer classifications [12]

The cylindrical pipe is the most employed conduit for fluid transport in the industry. Most of the earlier studies used it in their analysis [13-15]. Three distinct flow regimes exist for fluid flow in a pipe/channel. These include laminar, transition and turbulent regimes. A variation of these regimes occurs at a specific location known as a boundary layer. Reynolds number (*Re*) is the main characteristic dimensionless parameter differentiating these regimes. It correlates between forces of inertia and viscous in a flowing fluid. For example, the laminar flow has smooth streamlines with well-ordered motion.

In contrast, turbulent flow exhibits velocity fluctuations (eddies) with highly random motion. For an internal flow, the highest threshold for a laminar flow is up to $Re = 2100$ because of the dominance of inertial forces over the viscous forces. The transition occurs beyond these values. It is an uncertain region since the flow alternates between the laminar and turbulent cases. The onset of turbulence appears from $Re \geq 4000$ [16].

1.1.1 Flow and heat entrance regions and lengths

Determination of flow features is crucial for adequately evaluating enhancement parameters for flow and heat transmission in micro and minichannels.

For example, for fluid entering a channel under constant velocity, the fluid particles in the layer attached to the channel surface reach a standstill due to the no-slip condition. Besides, it steadily slows down the motion of fluid particles within the adjacent layers due to the friction effect. Thus, to mitigate the velocity reduction, the fluid velocity at the channel's midsection must increase to maintain the mass flow rate uniformity inside the channel. This leads to the development of the velocity gradient in the channel.

The velocity boundary layer is the flow area where significant viscous shear forces and velocity variations. The boundary layer thickness evolved along the flow direction. It advanced towards the channel core, where it occupies the whole channel. The flow features due to hydrodynamic and thermal entrance effect include hydrodynamically and thermally developing, simultaneously developing flow and hydrodynamically and thermally fully developed, as depicted in Figure 1.3.

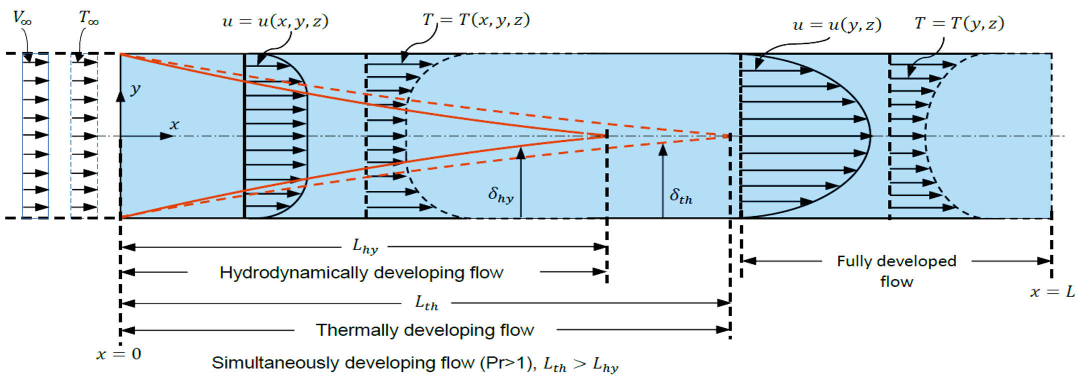

Figure 1.3 Schematic of a pipe with different hydrodynamic and thermal entrance conditions [12]

The hydrodynamic entrance region is the domain from the pipe/channel inlet to where the hydrodynamic boundary layer converges to the centreline. The region's length referred to as hydrodynamic entrance length (L_h). Similarly, thermal entrance length (L_{th}) is the length from the channel inlet to the location where the thermal boundary layer converges to the centreline [12]. Hydrodynamically developing flow occurs at the entrance due to the velocity profile development there. The profiles of velocity and temperature are growing in the simultaneous developing flow. The HTC and friction factor changes along the flow path. The hydrodynamically and thermally fully developed zone begins after the entrance zone, where the velocity and temperature profiles are constant and fully developed. The least HTC and friction coefficient values are obtained in this region and remain uniform along the channel length. The laminar regime exhibits a parabolic velocity profile in the fully developed area. It is slightly flat in turbulent regimes due to radially intense mixing and eddy movement [16].

However, hot fluid resides typically on the channel's wall in a pipe and straight channel. Low-temperature liquid occupies the channel's centre because of the steady thermal boundary layer growth. These situations lead to deplorable heat transfer [3]. Later, researchers developed other geometries to overcome this geometrical deficiency and are related to circular shape by the hydraulic diameter for ease of comparison.

Tuckerman and Pease [17] in 1981 initiated the application of forced liquid cooling on a planar Very-large-scale circuit (VLSI) in the silicon microchannel heat sink with thermal flux as far as 790 W/cm^2 to achieve high performance. They observed that a silicon temperature intensifies by 71℃ over the inlet water temperature. However, they noticed that the coefficient of heat transfer (HTC) amid the silicon layer and the water hinders the low thermal resistance achievement. Therefore, researchers employed various heat transfer enhancement techniques towards efficient high heat flux removal to overcome high thermal resistance and pressure drop.

1.1.2 Techniques for heat transfer augmentation

Heat transfer enhancement classification consists of either active or passive techniques. However, a simultaneous application within either of the categories leads to combined techniques [18]. An active approach achieved heat transfer enhancement by applying external power sources like magnetic/electric fields, mechanical aids, surface vibrations, among others. Conversely, a passive technique operates without external power sources [19]. For instance, geometrical variations such as surface roughening and additives in fluids. In their critical review paper, Steinke and Kandlikar

[20] recommended testing heat transfer performance and a decline in pressure through experimental and numerical approaches. Figure 1.4 highlights some passive heat transmission techniques applied in micro/minichannel analysis.

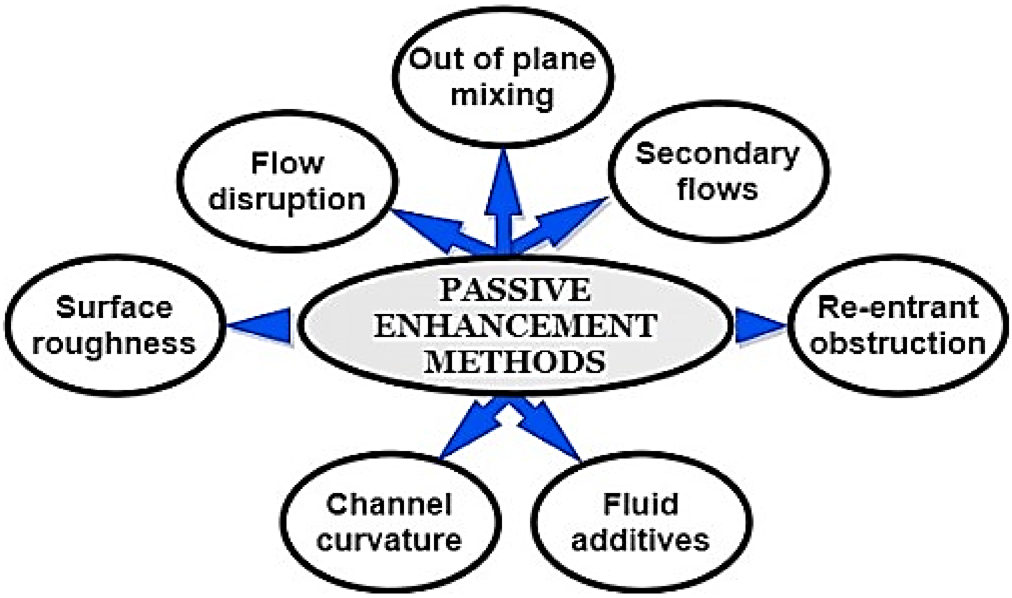

Figure 1.4 Passive heat transfer enhancement techniques [18]

A nanofluid is a dispersion of nanoparticles (NPs), usually in sizes of $10 – 10^2$ nm in a host fluid. It can advance the heat transfer rate considerably because of a higher surface area - volume proportion than a base fluid [21-23]. Consequently, it enhanced the heat transfer coefficient (HTC) by convection. However, with a setback on pressure loss, which subsequently requires more pumping power for the fluid flow. The agglomeration of particles from the nanoscale to the macroscale impedes a nanofluid application. It may block and erode the minichannel surface [24]. Also, improper determination of nanofluid thermophysical properties may not give the desired high performing thermal conductive liquid.

Evolution and progress in nanofluid utilisation abound in literature, as highlighted in notable comprehensive reviews [25-28]. Also, the medium of its transportation is receiving attention from researchers. Micro (MiC) and minichannels (MC) are the preferred passages for nanofluids transportation. Other advantages of micro/mini channels include less consumption of materials during fabrication, less inventory of working fluid since minimum quantity can satisfy the cooling requirement and a higher proportion of surface area to fluid volume. On the other hand, Sujith et al. [29] found a heat transfer rate increment in minichannels because of higher surface area to volume proportion and nonappearance of stratified flow. Nevertheless, with a disadvantage of increments in pressure drop, channel's fouling and flow instability.

Analysis of thermal systems may involve either experimental or numerical approaches. Though experimental investigation remains the veritable approach, being cost-intensive impedes its broader application for a detailed study [30]. On the other hand, numerical analysis of thermal and hydraulic processes is essential for fundamental and feasible research. Thus, fluid properties and channel geometry modifications lead to an effective passive heat transfer improvement technique.

Microchannel offers higher heat transfer augmentation than minichannel. However, its smaller hydraulic diameter leads to high pumping power and pressure drop, as well as cost-intensive and more sophisticated manufacturing techniques than minichannel [31]. Thus, minichannel still receive interest for utilisation in heat sinks, as well as in semiconductor devices. Moreover, experimental works exhibited divergence in heat transfer improvement between micro and mini channels, necessitating further research in the area [7].

Micro and minichannel heatsinks are applicable in single-phase and multiphase (e.g. two-phase) conditions. The heatsink achieved high heat transfer enhancement in both situations due to the favourable small hydraulic diameter. Some studies compared different models for heat transfer enhancement. The two-phase numerical model gave better enhancement than single-phase results at all Reynolds numbers when aqueous TiO_2 nanofluid was analysed for hydrothermal analysis [32]. Saeed and Kim [33] corroborated this finding when they employed Al_2O_3-H_2O. However, Albojamal and Vafai [34] proposed a Single-phase. They compared it with two multiphase models: the discrete phase model (DPM) and the mixture model (MM). The DPM overrated the heat transfer coefficient values. Accordingly, the MM demonstrated an improbable rise in HTC at a large volume fraction. The single-phase approach proposed has an excellent correlation with the experimental values. The anomaly in reporting similar research with contradicting results suggested further research in the area.

The primary motive of the new heatsink design is to sustain within the allowable limit the junction temperature of a high-performance compact electronic device due to excessive heat flux. It requires minimal pumping power of the coolant and low substrate thermal resistance. However, the combined passive corrugated minichannel heatsink with highly conductive nanofluid can provide adequate liquid cooling in an electronic system, with a penalty on pressure loss.

1.2 Problems Statement

Nowadays, there is an increasing demand for high-performance electronic devices, laser equipment, high beam solar panels, etc. The consequence is high heat flux, which is worsened by the space constraint in the devices on the coolants' cooling mechanism and poor thermal performance. Nava-Arriaga [35] noticed the thermal cooling challenges faced by the electronic chip (EC), and they developed thermal solutions using multiple minichannel distributors. However, the substantial pressure differential reduced the efficiency of the novel method.

Some researchers observed that a minichannel hydraulic diameter reduction and nanofluid application could enhance the heat transfer coefficient. The synergetic ability of nanoparticles could significantly influence the heat transfer capability of traditional fluids like water and glycols. While some researchers observed enhancement due to nanoparticles thermal conductivity, others reported higher enhancement in low thermal conductivity nanoparticles over those with higher thermal conductance values [36]. Also, researchers found the heat transfer coefficient augmentation in nanofluid decline below that of water at a high nanoparticles volume fraction; for instance, in the study of Pak and Cho [37], nanofluid HTC reduced by twelve per cent at 3.0 % Al_2O_3 concentration relative to water. These contradictions sometimes may be linked to heat transfer mechanisms and geometry changes.

A sketchy detail in modelling nanofluids in the turbulent region based on two-phase analysis leads to inadequate hydrothermal performance evaluation. Most previous studies preferred single-phase for hydrothermal performance (HP) numerical analysis [38] due to its simplicity and less demand for computational resources. The model assumed a nanofluid as a homogenous mixture and ignored the slip mechanism. Conversely, a two-phase model regarded the individual components separately with a slip mechanism and involved other particle-particle and particle-liquid interactions. Thus, the model may provide better performance with good accords with the experimental result.

The challenges of developing a transport medium at the micro and mini-scale level without severe penalties on pressure loss and thermal resistance reduce the applicability of thermal systems' methods. However, nanofluid may be an adequate coolant, a rise in viscosity in nanofluid results in a drastic pressure drop. Moreover, it may deteriorate thermal advancement and increase thermal resistance in small hydraulic diameter channels like minichannel. Thus, a combination of a minichannel having a geometrically modified surface like dimples with high thermal conductive nanofluid may offer a passive system with minimal thermal resistance at moderate pumping power.

1.3 Research Objectives

The research involved numerical Computational Fluid Dynamics (CFD) and experimental tests on the convection heat transfer and fluid flow augmentation. The aim is to develop and examine the influence of combined multi passive heat transfer techniques in a minichannel heatsink towards further augmenting heat transfer with minimal pressure loss and thermal resistance.

The objectives of this research are enumerated as follows:

1. To investigate the synergetic ability of nanofluid thermophysical properties on the hydrothermal performance of an electronic device minichannel heatsink.
2. To evaluate the hydrothermal performance of aqueous nanofluids using a two-phase numerical model in a minichannel heatsink.

3. To numerically examine the effect of dimples on diverging-converging minichannel as surface roughness passive method for advanced thermal system application.

1.4 Scope of the research

The research study deals with thermal system management in electronic devices using a divergent-convergent minichannel heatsink. The research involves domains of numerical analysis and experimental validation and defines the following scope to achieve the set objectives:

1. The nanofluids used in this study are composed of nanoparticles (constant average particle size (APS) between 20- 40nm) of Aluminium-oxide (Al_2O_3) and Copper-oxide (CuO) with distilled water (H_2O) as a carrier fluid. The size and morphology are considered based on the supplier specification (Skyspring Nanomaterials Inc. USA). The thermophysical properties of the fluids are temperature-dependent. The nanofluids preparation used a Two-step method with the particles volume fraction of 0.00-0.025.

2. The two-phase numerical analysis applied the Mixture model in the Eulerian-Eulerian method. The modelling parameters include uniform inlet velocity of 3 to 6 m/s corresponding to Reynolds number (*Re*) range of 5000-10000. The operating temperature, 25°C to 30°C, typically corresponds to Malaysia's ambient temperatures and the heat flux between 500 to 850 kW/m^2.

3. The developed heatsink with corrugated channel features has seven parallel minichannels with a dimension of 30 x 1.0 x 1.25 mm cut on the Aluminium block of 30 x 21 x 2.25 mm. The surface modification technique involves spherical dimples etched laterally on the minichannel floor. The characteristics of the dimples are diameter ($\frac{1}{4}W_c \leq d$ (mm) $\leq 1W_c$) and spanwise length ($L_c/12 \leq d$ (mm) $\leq L_c/6$).

1.5 Significance of the research

Moore’s law is the scientific finding that electronic devices' component density and integrated circuit efficiency can double every two years. [39]. The law relies on observation and projection of diachronic trends rather than established Physics law [40]. The contemporary design is aimed at smaller and faster components. However, the consequences are large power densities, large operating temperatures, and a high tendency to fail. Thus, efficient heat flux removal is necessary to safeguard the devices. The research developed and tested heatsink in minichannel scale having a divergent-convergent geometry. It can boost nanofluid flow mixing and disturb the boundary layer, eventually increasing the heat transfer coefficient. The minichannel efficiently remove high heat flux up to 85 W/cm^2 and within a turbulent continuum with fair pressure loss and low thermal resistance. Thermal conductivity and viscosity are not always the determinants of the thermohydraulic performance of nanofluids. Density sometimes may play a vital role even for a nanofluid with a lower thermal conductivity value. The nanofluid prediction is better in two-phase than the single-phase due to slip-mechanism. The study found that nanofluids may perform differently in the two approaches depending on their thermophysical properties and other physical considerations like slip mechanisms. The researcher noted that CuO /water performed better in single-phase. However, it is inferior to Al_2O_3/water in the two-phase method. This innovative design ensures that devices operate efficiently and use energy sustainably to meet the global desire, as highlighted in Sustainable Development Goal (SDG) number 7. The study provides an insight on the optimum design of Divergent-Convergent Minichannel Heatsink-d considering dimple diameter and pitch as determinant variables on integrated hybrid Divergent-Convergent minichannel heatsink with nanofluids for hydrothermal performance. Thus, the methodology employed and the result obtained in this study would advance knowledge and proffer cost-effective and efficient thermal management solutions in modern electronic devices.

1.6 Chapter summary and thesis outline.

This chapter identified the contemporary challenges affecting thermal management of systems due to downscaling modern electronic devices and introduces the techniques applied by the thermal Scientist and Engineers to overcome such challenges generally and specifically to the minichannel heatsink. It highlighted the objectives to solve the problems within the research scope and the research outcome contribution to the thermal science and engineering analysis.

The thesis is composed of five chapters with four appendices. In addition to this chapter, the other chapters summarise as follows:

Chapter two - Literature review contains a comprehensive review of relevant previous literature and is subdivided into sections for easy understanding. It begins with the convective heat transfer studies, then the application of nanofluids as thermal fluid. Besides, it presents heat transfer enhancement techniques used by the investigators. Also, the chapter presents methods of heat transfer analysis involving both the experimental and numerical approaches. Finally, it rounds up with the research gap observed from the review to serve as the basis for conducting this research.

Chapter three - Research methodology: This chapter presented the methods used to achieve the research's desired objectives. The chapter described the experimental data measurement methods by appropriate instrumentation and facilities for the forced convection heat transfer and fluid flow in the DCMH. Also, it includes characterisation of nanoparticles using an analytical state-of-the-art analytical instrument, then nanofluids preparation and measurement of their thermophysical properties. Moreover, It contained a concise overview of the Computational Fluid Dynamic (CFD) approach and the numerical modelling of Divergent-Convergent Minichannel Heatsink.

Chapter four - Results and discussion: this chapter is subdivided into two sections. The first section presented the experimental results to validate the numerical results with pure water. Then modelled and measured thermophysical properties of water-based Aluminium-oxide and Copper-oxide nanofluids. The second section presents the numerical works for nanofluids for the two geometrical models of the Divergent-convergent minichannel heatsink

Chapter five – Conclusion and recommendations for future works: this section concisely concluded the entire research outcomes. It highlighted the specific achievements and novelty of the research. Moreover, it proffered recommendations for future work based on practical limitations and scopes.

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