THERMAL ANALYSIS OF MICROCHANNEL HEAT SINK

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ABSTRACT

Microchannel heat sink is now one of the most effective cooling techniques. As micropump works under pulsation regime and influenced by the possibility of heat transfer enhancement through pulsation, the goal has been to study the effect of pulsation to thermal behavior of microchannel heat sink. A computational model for studying pulsatile flow in microchannel had been developed using FLUENT. The meshes generated had been tested for grid independency and the results numerically iterated by FLUENT had been validated and compared to various published data. The pulsating flow pressure amplitudes were 50%, 70% and 90% of mean pressure and the flow regime is laminar. Pulsation tested was with frequencies in the range 500 Hz to 1.5 kHz. The results of pulsating flow simulations had been analysed and compared with the steady flow simulations. The values of the augmentation factor of heat flux along the flow direction were found to be less than unity. The values of the augmentation factor of heat transfer coefficient along the flow direction were less than unity at the entrance region and increased above unity further downstream. Pulsation had resulted in a lower wall temperature distribution compared to steady flow. The pulsation amplitude and frequency investigated has no significant effect on wall temperature. Heat flux ratio and heat transfer coefficient ratio however varies at frequencies and amplitudes investigated.

ABSTRAK

Pembebasan haba melalui saluran bersaiz mikro telah dibuktikan sebagai salah satu teknik penyejukan yang efektif. Kajian literature menunjukkan pam bersaiz mikro bekerja secara denyutan. Kemungkinan penyerlahan pemindahan haba dan aliran melalui aliran denyutan di dalam saluran telah memperkuatkan keinginan terhadap pemyelidikan ini. Model komputer bagi mengkaji kesan aliran dedenyut di dalam saluran bersaiz mikro telah dibina menggunakan FLUENT. Grid yang digunakan telah diuji untuk ketidak bergantungan dan data yang diperolehi dari penyelesaian berangaka menggunakan FLUENT diuji kesahan dan dibandingkan dengan jurnal yang kukuh. Aliran dedenyut dihasilkan pada amplitude 50%, 70% dan 90% daripada tekanan purata dengan frekuensi dalam julat 500 Hz hingga 1.5 kHz. Aliran dianggap laminar. Keputusan untuk aliran dedenyut dibandingkan dengan aliran tenang melalui nisbah pemindahan haba dan nisbah pekali pemindahan haba. Nisbah pemindahan haba adalah kurang dari 1 manakala nisbah pekali pemindahan haba didapati kurang dari satu pada keadaan masukan dan meningkat melebihi satu pada kedudukan selepas keadaan masukan menuju keluaran. Aliran denyutan didapati telah mengurangkan taburan suhu pada dinding berbanding aliran normal. Frekuensi dan amplitud yang dikaji tidak memberikan kesan terhadap suhu dinding. Namun peningkatan frekuensi dan amplitud telah meningkatkan nisbah pemindahan haba dan nisbah pekali pemindahan haba.

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LIST OF SYMBOLS

Nomenclature

A	-	velocity amplitude
a, b	-	length of the two side of a rectangular duct
Br	-	Brinkman number
C	-	Pouiseulle Constant
c_p	-	specific heat at constant pressure
CFD	-	Computational Fluid Dynamics
D_h	-	hydraulic diameter
DSMC	-	Direct Simulation Monte Carlo
EDL	-	Electric Double Layer
$\vec{F}$	-	external body forces vector
f	-	friction factor
g	-	gravitational acceleration
h	-	heat transfer coefficient
K	-	constant in equation (3-14)
k	-	thermal conductivity
Kn	-	Knudsen number
L	-	length of channel
M	-	relative part of conductive axial heat transfer in walls in equation (1-3)
MEMS	-	micro-electro-mechanical
Nu	-	Nusselt number
P	-	pressure
PML	-	Porous Medium Layer
Pr	-	Prandtl Number
Q	-	heat flux
r	-	radius

Re	-	Reynolds number
R_t	-	thermal resistance
T	-	temperature
t	-	time (s)
TDMA	-	Tri-Diagonal Matrix Algorithm
u	-	velocity in *x*-direction
v	-	velocity in *y*-direction
w	-	velocity in *z*-direction
Wo	-	Womersley number

Greek symbols

μ	-	viscosity
ρ	-	density
υ	-	kinetic viscosity
λ	-	mean free path of gas
δ	-	lattice spacing of liquid
τ	-	time scale
$\overline{\overline{\tau}}$	-	stress tensor
Γ	-	periphery of the inner wall of channel
ω	-	oscillating frequency
Φ	-	viscous dissipation
α^*	-	duct aspect ratio

Subscripts

e	-	entrance
in	-	at inlet of channel
l	-	*liquid*
m	-	mean
st	-	steady

unst	-	unsteady
w	-	substrate wall
x	-	local value along the horizontal direction
y	-	local value along the vertical direction
z	-	local value along the flow direction

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CHAPTER 1

INTRODUCTION

1.1 Background

The advantages of compact structure and high heat transfer performance make the micro-scale heat exchangers showing a strong foreground on microelectronics, micro-devices fabrication, bioengineering, micro-electromechanical system (MEMS) and so on, thus becoming popular, both for commercial purposes and in scientific research. The recent trend in the electronic equipment industry toward denser and more powerful products requires higher thermal performance from a cooling technique. Thermal management is, and will continue to be, one of the most critical areas in electronic product development. It will have a significant impact on the cost, overall design, reliability and performance of the next generation of microelectronic devices.

Thermal management is required whenever power dissipation is involved in the operation of any system. The present computer technology owes much of its progress to the miniaturization of circuits of silicon chip. The demand for faster circuits and increased capacity, however, has led to an increase in power densities and a need for continuous improvement in the methods of heat removal**.** Microchannel heat sink is known for an excellent cooling capacity due to the high surface to volume ratio that enhances the heat removal. A study by Belhadj et al. (2003) on the temperature distribution in the active region using Transmission-Line-Matrix technique reveals that the use of microchannels to cool microprocessor improved thermal resistance behaviour and reduced active region temperature in steady state.

The expected life of a solid-state device depends on the operating temperature and the temperature cycling, making the cooling problem very challenging. An efficient cooling system is required to maintain an isothermal environment in the presence of highly transient thermal loads. As a micro fluidic device (i.e. micro pumps) essentially work under a pulsed regime, it is necessary to consider unsteady flows in microchannels.

The understanding and evaluation of steady and unsteady flows with transient forced convection have recently become more important in connection with the precise control of modern high-performance heat transfer systems. Accurate prediction of the transient response of thermal systems is important for the understanding of such adverse effects as reduced thermal performance and severe thermal stresses that they can produce, with eventual mechanical failure.

In spite of the rapid development in the micro-fabrication technologies for MEMS devices, a fundamental understanding of fluid flow and heat transfer in microchannel is not satisfactory. A study of unsteady heat transfer in micro-flow is rarely found while most previous theoretical or numerical works regarding micro-systems have concentrated on the flow characteristics. Practically, a detailed analysis of micro-flow with heat transfer would be very helpful in designing an efficient and reliable micro-device.

1.2 Literature Review

1.2.1 Flow and heat transfer in microchannel heat sink.

A microchannel heat sink is based on the idea that the heat transfer coefficient is inversely proportional to the hydraulic diameter of the channel. A large number of micro size flow channels are fabricated in a solid substrate which usually has high thermal conductivity such as silicon or copper. An electronic component is then mounted on the base surface of the heat sink. The heat generated by the component is first transferred to the channels by heat conduction through the solid, and removed by the cooling fluid which is forced to flow through the channels (Qu and Mudawar, 2002).

The use of silicon in the cooling system is critical. Because photolithographic and etching technologies are so well developed for silicon, arrays of precision microchannels can be easily and inexpensively fabricated in this material. It also allows multiple bars to be located on a single substrate, with an equal number of cylindrical microlenses, all attached in a single fabrication step.But why use silicon rather than materials with higher thermal conductivities, such as copper? In compact heat sink structures with flowing water, the best way to control the overall temperature rise is to minimize the thickness of the boundary layer where stagnant water meets flowing water. It is in this boundary layer that the largest temperature rise occurs. Because boundary-layer thickness scales relative to channel width for the flow conditions in microchannel, the best material for the cooling system is one that permits easy fabrication of narrow channels. It turns out that better thermal performance is gained by using a material that permits tiny microchannel fabrication (silicon) rather than a material with higher thermal conductivity.

Microchannels had been classified as channels with hydraulic diameter, D_h, ranging from 10 μm to 200 μm. The Reynolds number for flows in microchannels is generally very low as the flow velocity in these small hydraulic diameter passages is quite small. The friction factors and pressure gradients are both quite high in microchannels flows since the available surface area for a given flow volume is high (Kandlikar, 2003).

Fluid flow and heat transfer in microchannels is a developing knowledge that is not well understood. The critical issue is the small length scale of microchannel heat sink and what that might imply about modelling transport phenomena.

Many reported experiments as reviewed by Hetsroni et al. (2005) indicate that remarkable differences and conflicts exist in the microchannel flow and heat transfer characteristics compared with those in conventional size channels. There may be several main factors responsible for the inconsistency (Kandlikar, 2003):

(1) *Compressibility effect*. The compressibility is significant when the Mach number approaches unity. In a microchannel, the high Mach number and large pressure drop can be reached even at low Reynolds numbers. As a result, the variation of fluid density and acceleration can occur along the channel, which will lead to an increase in friction factor. In addition, the local Nusselt number increased along the channel due to the compressibility effect.

(2) *Rarefaction effect*. As the channel dimension becomes smaller, it approaches the mean free path between the molecules in a fluid flow and the continuum assumption starts to break down. A measure of the departure from the continuum is introduced through the Knudsen number, *Kn*, defined as:

$$K_n = \frac{\lambda}{D_h} \quad (1\text{-}1)$$

where D_h is the hydraulic diameter of the flow channel, and λ is the mean free path of the gas. For rectangular ducts, the hydraulic diameter D_h is given by:

$$D_h = \frac{4ab}{a+b} = \frac{4b}{1+\alpha^*} \quad (1\text{-}2)$$

where 2a and 2b are length of the two sides of a rectangular duct with 2a > 2b and the duct aspect ratio $\alpha^* = 2b/2a$. Liquid molecules do not have mean free path, but the lattice spacing, δ, may be used as similar measure. For water, the lattice spacing is 0.3 nm. Rarefaction effects can be neglected for *Kn* less than 0.001. When the Knudsen number is in the range from 0.001 to 0.1, the flow can not be considered as a continuum flow. Velocity slip and temperature jump occur at the wall surface. As the Knudsen number getting higher, the flow becomes rarefied and the motion of individual molecules must be modelled and then treated statistically.

(3) *Electric Double Layer* (EDL). Most solid surfaces have electrostatic charges on their surface. When liquid containing even a small number of ions flows over the surfaces, the electrostatic charge on non-conducting surfaces attracts counter ions (Mohiuddin Mala et al., 1997). The balancing charge in the liquid is called the EDL. The thickness of this layer is very small, on the order of a few nm. This effect becomes important only for small diameter microchannels, generally less than 10 μm.

In addition to the three main issues discussed by Kandlikar (2003), as stated above, there are also some other issues studied by several researches such as viscous energy dissipation (Hetsroni et al., 2005) and axial conduction (Gael Maranzana et al., 2004).

Mohamed Gad-el-Hak (2003) argued that traditional treatments of transport phenomena may not be appropriate for certain situations involving micro devices. There are three fundamental assumptions that must be satisfied in order for the Navier-Stokes equation (traditionally used to model conventional macro device) to be valid. The three assumptions are the Newtonian framework of mechanics, the continuum approximation and thermodynamic equilibrium;

(1) Newtonian framework which specifies that mass and energy are conserved separately is an excellent modelling tool for most problem including micro-electro-mechanical system as long as we are not dealing with atomic or subatomic particles.
(2) Exact thermodynamic equilibrium is impossible as each fluid particle is continuously having volume, momentum and energy added and removed. Thermodynamic equilibrium additionally gives rise to the no-slip and no-temperature-jump boundary condition.
(3) The continuum approximation is almost always met, but exception does exist. However as the characteristic dimension of the microchannels shrinks beyond submilimeter, the continuum assumption starts to break down.

If the traditional method fails, it is then necessary to find out the alternative modelling tools. For gases at least, there are first principles equations that give the precise amount of slip or temperature jump to include in case the Knudsen number exceeds the critical limit of 0.001. Higher order equations such as those of Burnett can replace the Navier-Stokes equations when *Kn* exceeds 0.1. Finally, if the continuum approximation fails altogether, the fluid can be modelled as it really is, a collection of molecules (Mohamed Gad-el-Hak, 2003).

Under some conditions, the heat released due to viscous dissipation leads to drastic change of flow and temperature field, in particular, it leads to flow instability, transition to “turbulence hydrodynamic thermal explosion”, oscillatory motions

(Hetsroni et al., 2005). To estimate the real effect of viscous dissipation on heat transfer it is necessary to determine the dependence of the Nusselt number on the Brinkman number at fixed values of the Reynolds and the Prandtl numbers. Table 1.1 shows the definition of nondimensional numbers commonly used in heat and fluid flow.

Table 1.1: Nondimensional numbers commonly used in heat and fluid flow

Parameter	Description	Formula	Nomenclature
Nusselt number, *Nu*	nondimensionalize heat transfer coefficient which measure the heat transfer efficiency	$Nu = \frac{hl}{k}$	h - heat transfer coefficient *l* - characteristics dimension in the fluid flow field k - thermal conductivity
Reynolds number, *Re*	measures the relative magnitude of the inertia effects in a fluid compared to viscous effects	$\mathrm{Re} = \frac{\rho V l}{\mu}$	P – fluid density V – fluid velocity *l* – characteristics dimension in the fluid flow field μ – fluid viscosity
Prandtl number, *Pr*	Measures the rate of development of velocity and temperature profiles.	$\mathrm{Pr} = \frac{\upsilon}{\alpha}$	υ – kinematic viscosity of fluid α – thermal diffusivity of fluid.
Brinkman number, *Br*	the ratio of the heat production due to viscous forces, to heat transferred from the wall to the fluid	$Br = \frac{\mu V^2}{k \nabla T}$	μ – fluid viscosity k - thermal conductivity V – liquid velocity ΔT – wall-fluid temperature difference

For incompressible fluid, the density variation with temperature is negligible compared to the viscosity variation. Hence, the viscosity variation is a function of temperature only and can be the cause of radical transformation of flow and transition from stable flow to oscillatory regime. Channel size, the Reynolds number and Prandtl number are the key factors which determine the impact of viscous dissipation. However, most studies as reviewed by Hetsroni et al. (2005) showed that the Brinkman number did not affect the Nusselt number when the Reynolds number and the Prandtl number did not change significantly and therefore dissipation effects can be neglected.

Axial conduction in the fluid and wall, affects significantly the heat transfer in microchannels. A study by Gael Maranzana et al. (2004) reveals the importance of this effect. A new non-dimensional number, *M,* quantifying the relative part of conductive axial heat transfer in walls has been introduced as:

$$M = \frac{\text{Total convective heat transfer in the flow}}{\text{Heat flux characterising axial heat transfer in the wall}} \tag{1-3}$$

They noticed that in the simulation of most cases that were studied, axial conduction can be neglected as soon as the *M* number gets lower than 10^{-2}.

The importance of considering axial conduction had been further investigated experimentally and numerically by Tiselji et al. (2004). It was shown that the bulk water temperature, as well as the temperature of the heated wall does not change linearly along the channel. Both water and heated surface temperatures do not change monotonously. The non-monotonous behaviour of fluid and heated wall temperature is due to high values of axial heat flux in the silicon wafer. The behaviour of the Nusselt number along the channel has a singular point. At this point, the difference between the temperature on the wall and the bulk water becomes negative and the flux changes the sign and is directed from the fluid to the wall.

Due to the larger surface to volume ratio for microchannels, factors related to surface area have more impact to the micro scale flow and heat transfer. The surface friction induced flow compressibility in microchannels makes the fluid velocity profiles flatter and leads to higher friction factors and Nusselt numbers. The surface roughness of the microchannel is likely responsible for the early transition from laminar to turbulent flow and the increased friction factor and Nusselt number. Besides, other effects such as the axial heat conduction in the channel wall, the channel surface geometry, and measurement errors as well, could lead to different flow and heat transfer behaviours from the conventional scales (Zeng-Yuan Guo and Zhi-Xin Li, 2003).

Koo and Kleinstreur (2005) investigated the surface roughness effects on heat transfer phenomena for liquid flow in micro-conduits by implementing porous medium layer (PML) model to a steady laminar fully developed liquid flow in microchannels. They summarized that the Nusselt number can be either higher or lower than the conventional value depending on the actual surface roughness condition. However, the surface roughness effect on heat transfer is less significant than on momentum transfer. The Reynolds number effect on the Nusselt number is negligible compared to its effect on the friction factor.

A comprehensive review by Hetsroni et al. (2005) shows that numerical solution of full Navier-Stokes and energy equation, which account for 'new effects' such as real geometry of the microchannel, axial conduction in the fluid and wall, energy dissipation, non-adiabatic thermal boundary condition at the inlet and outlet of the heat sink, dependence of physical properties of fluid on temperature, etc, demonstrate a fairly well correlation with available experimental data.

Recently, Poh-Seng Lee, Suresh V. Garimella, and Dong Liu (2005) investigated the validity of classical correlation based on conventional-sized channels for predicting the thermal behaviour in single-phase flow through rectangular microchannels. Numerical predictions obtained based on classical, continuum approach were found to be in good agreement with the experimental data suggesting that conventional analysis approach can be employed in predicting heat transfer behaviour in microchannels with hydraulic diameters of 318-903 μm. However, the entrance and boundary conditions imposed in the experiment need to be carefully matched in the predictive approach.

1.2.2 Thermal analysis of a microchannel heat sink

One of the famous experiment analyses of single-phase flow in microchannel is that conducted by Kawano et al. (2001) which has been studied numerically by Fedorov and Viskanta (2000), Qu and Mudawar (2002), Li et al. (2004), and Wong Wai Hing (2005).

Kawano et al. (2001) provided experimental data on the friction and heat transfer in rectangular, silicon based microchannel heat sinks. It was found that the heat transfer efficiency of the heat exchanger indicated by thermal resistance in the range of $0.1 Kcm^2/W$, and the pressure loss can be predicted from the theoretical values of the fully developed flow inside the channel to the level of $Re = 200$ or thereabout.

Fedorov and Viskanta (2000) developed a three dimensional model to investigate the conjugate heat transfer in microchannel heat sink with the same channel geometry used in the experimental work done by Kawano et al. (2001) assuming the thermophysical properties are temperature dependent. This investigation indicated that the average channel wall temperature along the flow direction was nearly uniform except in the region close to the channel inlet, where very large temperature gradients were observed.

Qu and Mudawar (2002) conducted a three dimensional fluid flow and heat transfer analysis for a rectangular microchannel heat sink with the geometry similar to that in Kawano et al. (2001) using a numerical method similar to that proposed by both Kawano et al. (2001) and, Fedorov and Viskanta (2000) assuming constant fluid thermophysical properties. This model considered the hydrodynamic and thermal developing flow along the channel and found that the Reynolds number will influence the length of the developing flow region. It was also found that the highest temperature is typically encountered at the heated base surface of the heat sink immediately adjacent to the channel outlet, and the temperature rise along the flow direction in the solid and fluid regions can be approximately linear.

Li et al. (2004) repeated the numerical simulation of the experimental done by Kawano et al. (2001) using a different method of solution that is solving sequentially the momentum equation and energy equation taking into account the temperature dependent thermophysical properties. The numerical modelling is developed using finite difference method of Tri-Diagonal Matrix Algorithm (TDMA). In addition, the pressure drop and velocity field as well as the relation between Nusselt number and Reynolds number were investigated. The results indicate that thermophysical properties of the liquid can significantly influence both the flow and heat transfer in microchannel heat sink.

Wong Wai Hing (2005) also solved sequentially the fluid flow and heat transfer using segregated solver available in a commercial CFD package, FLUENT. Viscosity of water was modelled as temperature dependent in his study. The distributions of temperature and heat flux along the channel were observed and results show the high temperature gradient at the solid region near the heat source.

All the numerical modelling conducted confirms that the continuum model is valid for the analysis of single-phase liquid flow in microchannel and the thermophysical properties have a significant influence on fluid flow and heat transfer in the channel. Moreover, FLUENT has been proved to successfully model the single-phase flow of experimental model of Kawano et al. (2001). All the numerical modelling discussed above assumed a steady flow inside the microchannel. The importance of unsteady analysis cannot be neglected for the reason of controlling the performance of the system. In fact, most micro pumps available in the literature as reviewed by Vishal Sighal et al. (2004), implement a vibrating diaphragm technique. Vibrating diaphragm pumps operate specifically at resonant frequency using the reciprocating motion of the diaphragm. As micro-pumps essentially work under a pulsed regime, it is necessary to consider unsteady flows in microchannels under this effect. There is very few published paper, at least to the author's knowledge, devoted to this unsteady single phase flow study in micro- channel heat sink.

Colin, Aubert, and Caen (1998) conducted an initial study of unsteady gaseous flow in a rectangular microchannel under the usual pressure and temperature conditions. The rarefied flow was modelled by the Navier-Stokes equation combined with slip and temperature jump condition at the walls. Their interest is on the feasibilities of pressure sensors for the measurement of the dynamic characteristics of gaseous flows in microchannels. By concentrating essentially on the pulsed sinusoidal regime (i.e. sinusoidal pressure fluctuation at the inlet), they pointed out that neglecting slip at the wall would underestimate the instantaneous flow rate. From their theoretical model of two pneumatic lines in series, they concluded that the pressure sensor should be placed in a second line mounted in series to avoid disturbance during unsteady flow measurement.

Jae Hyun Park and Seung Wook Baek (2003) investigated the effect of thermal accommodation coefficient on the unsteady one-dimensional micro-flow to account for the fraction of incident rarefied gas molecules interacting with solid surface in a diffusive manner by employing the unsteady Direst Simulation Monte-Carlo (DSMC) technique. A variation of thermal accommodation coefficient is observed to only affect the wall properties rather than flow properties. They stated that, when treating the fluctuating medium, the time step used should also satisfy $\nabla t << 2\pi / \omega$ to guarantee enough resolution for unsteady signals.

For Colin, Aubert and Caen (1998), Jae Hyun Park and Seung Wook Baek (2003) emphasized their study on slip flow and rarefied flow of gases. The only paper available in the literature for unsteady liquid flow in microchannel is the study of Linan Jiang et al. (2000). In this study, Linan Jiang et al. (2000) conducted an experiment to observe the effect of fluctuating temperature imposed at the inlet of the microchannel using heater and waveform generator before and after the liquid supple to the channel. They found that the frequency response of the dry device can be improved by driving liquid through the microchannels, which enhances the heat removal rate. Further enhancement was achieved by allowing two-phase change within the channels. The results showed that there exists a certain range of frequency response corresponding to a maximum heat removal before dryout.

The increased value of amplitude and input temperature results in a linear increase of the temperature field of the channel and the occurrence of a phase change. A sharp increase of the device average temperature with a slight reduction in amplitude was observed during complete single-vapour phase and dryout during the temperature cycle. The periodic temperature field was shown to stabilize the system and may avoid the occurrence of the dryout phenomena. The temperature amplitude of single-phase flow is almost constant reflecting a more stable temperature variation compared to two-phase (Linan Jiang et al., 2000). Flow instabilities is a very controversial issues in two-phase flow and had been investigated by several researches (Mosdorf et al., 2005) and yet there is no clear understanding of such behaviour due to the complexity of its analysis in micro-devices (Bergles and Kandlikar, 2005).

The frequency response analysis conducted by Linan Jiang et al. (2000) reveals the possibility of enhancing heat transfer in microchannels using pulsation. This possibility had been proposed as one of the enhancement technique from the review of conventional single-phase flow by Steinke and Kandlikar (2004) in the Second International Conference on Microchannels and Minichannels which was held on 2004 in USA.

Experimental investigation of flow pulsation effects on forced convection heat transfer in macro device was already carried out by Liao, Wang and Hong back in the 1985. The results show that the amplitude of pulsation is the major factor that determines the heat transfer coefficient. By comparing their result with other investigation as stated in the paper, they concluded that the heat transfer data can be classified into three regions: quasi-steady state, frequency independent and frequency dependent regions. Only in the frequency dependent region, an increase of heat transfer coefficient for pulsating flow is possible (Liao et al., 1985).

Heat transfer in a tube with pulsating flow and constant heat flux was investigated by Moschandreou and Zamir (1997). They indicated that in a range of moderate values of the frequency, there was a periodic peak in the effect of pulsations whereby the bulk temperature of the fluid and the Nusselt number were increased. However, the effect was reversed when the frequency was outside this range.

The rate of heat transfer is altered because oscillation changes the thickness of the thermal boundary layer and hence the thermal resistance. It was also demonstrated that the Nusselt number increased with increasing amplitude and frequency of oscillation (Cho and Hyun, 1990).

In the pulsatile flow problem, there are three intrinsic time scales (Hitt and McGarry, 2004);

$$\tau_1 = \omega^{-1} \qquad \tau_2 = \frac{D_h}{U} \qquad \tau_3 = \frac{\rho D_h^{\ 2}}{\mu} \tag{1-4}$$

which represent, respectively: the time scale of the pulsatility with circular frequency ω, the convective time scale, and the viscous diffusive time scale. U is the mean velocity and D_h, ρ, and μ are hydraulic diameter, density and viscosity respectively. Reynolds number is widely used to describe fluid flow. Reynolds number is interpreted as the ratio of viscous forces to flow inertia. An alternative and related parameter often used in pulsatile flows is the Womersley number, *Wo,*;

$$Wo = \left(\frac{\rho \omega D_h^2}{\mu} \right)^{1/2} \tag{1-5}$$

This parameter is commonly used in the biofluids literature (Hitt and McGarry, 2004).

Very little work has been done to explain the behaviour of pulsation flow in microchannel heat sink, in spite the possible heat transfer enhancement that can be brought by flow pulsation. In light of the possible heat transfer enhancement of flow pulsation in microchannel heat sink which can be related to the working behaviour of the micro pump; it is therefore relevant to study the effect of pulsating single-phase liquid flow in microchannel. Moreover, the study might reveal the possibility of heat transfer enhancement depending on the frequency range of the micro pump. Studying the distribution of bulk and wall temperature due to pulsation is vital to observe the level of thermal stresses in channels due to thermal cyclic loading (Al-Zaharnah et al., 2001).

In general, the pulsating flow field consists of a steady flow part and an oscillating part (Cho and Hyun, 1990). The wave form of the flow pulsation is not exactly sinusoidal; however, it is closer to the sinusoidal form (Liao et al., 1985).

As an initial study to gain an insight of possible enhancement by pulsation, this study will be restricted on the thermal analysis of single phase flow only. Air cooling techniques are unlikely to be able to meet the cooling needs of high heat flux electronic packages. Therefore, liquid will be considered as a coolant in this study. The effect of pulsation will be studied by imposing an oscillating pressure inlet to the microchannel geometry of Kawano et al. (2001), and the numerical result will be validated and compared with various published paper discussed above.

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