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Performance improvements of microchannel heat sink using wavy channel and nanofluids

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ABSTRACT

To improve the heat transfer performances of microchannel heat sink (MCHS), the advanced channel structures and working fluids can be applied. In this paper, the wavy channel structure and application of nanofluids are investigated. The effects of wavy amplitude, wavelength, volumetric flow rate and volume fraction of different type of nanofluids are presented. Three wave amplitudes of 25 μm, 50 μm and 75 μm with two wavelength of 250 μm and 500 μm at volumetric flow rate ranges from 0.152 L/min to 0.354 L/min are considered. Three different types of nanofluids with volume concentration ranges from 1% to 5% are applied. The effect of wavy MCHS is shown on thermal resistance, pressure drop, friction factor. It is found that in case of the pure water is applied as the coolant the heat transfer performance of the MCHS is significantly improved comparing with the traditional straight channel MCHS, while the replacement of the pure water by nanofluids makes the effect of wavy wall unnoticeable.

1. Introduction

With the recent development in computing technology over the past few decades, electronics have become smaller, faster and more powerful, which leads to an ever-increasing heat generation rate from electronics devices. To maintain the temperature of electronic components in safety zone, the chips are cooled by using forced air flow. However, standard cooling methods are not sufficient enough to deal with component that contains billions of transistors working at high frequency as the temperature can reach a critical level. Therefore microscale cooling devices, such as microchannel heat sinks are important in heat removal applications in devices such as laser diode arrays and high-energy mirrors. In the past few decades, in order to meet the high heat dissipation rate requirements and maintain a low junction temperature, there are a lot of cooling technologies have been searched. After all the research have been done, the microchannel heat sink (MCHS) has attracted much attention due to the ability of producing high heat transfer coefficient, small size and volume per heat load, and small coolant requirements. Recent progress in the development of microchannel heat sinks was provided by Kandlikar and Grande [1].

A MCHS usually composed by a lot of parallel microchannels with a hydraulic diameter ranging from 10 μm to 1000 μm. A coolant flow through the micromachined or etched conduits with the purpose of removing heat from and generate uniform temperature distributions in micro-electro-mechanical systems, integrated circuit boards, laser-diode arrays, high-energy mirrors and other compact products with high transient thermal loads. The concept of MCHS cooling was first proposed by Tuckerman and Pease [2]. Since then, different kinds of materials were used by MCHS and channel dimensions have been investigated widely as well. These studies can be split into three categories, there are theoretical [3,4], numerical [5–8], and experimental approaches [9,10]. In the theoretical approach, the main purpose is to optimize MCHS performance by improving design structure. In this approach, most studies implemented the classical fin theory which models the solid walls separating microchannels as thin fins. The process of heat transfer process is summarizing as one dimensional, constant convection heat transfer coefficient and uniform fluid temperature. Nonetheless, the nature of the heat transfer process in MCHS is conjugated heat conduction in the solid wall and convection to the cooling fluid. The MCHS performance is inaccurate when the simplifications were used in theoretical approach. The simplifications used in the theoretical approach inaccurate MCHS performance.

Recently, the heat transfer and fluid flow processes in microchannel had been studied by Lee and Garimella [11] and detailed equations for designing microchannel geometries had been provided. After a while, another numerical and experimental

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Nomenclature

A	area (m^2)
c_p	specific heat (J/kg · K)
D_h	hydraulic diameter (m)
f	Fanning friction factor
h	heat transfer coefficient (W/Km^2)
h_{nf}/h_f	dimensionless heat transfer coefficient
H	height (m)
k	thermal conductivity (W/km)
l	length (m)
N	number of micro-channels
Nu	Nusselt number
Δp	pressure drop (Pa)
P_{pump}	pumping power (W)
$\hat{P}$	dimensionless pressure
Pr	Prandtl number
q	heat flux (W/cm^2)
R_{th}	total thermal resistance (K/W)
Re	Reynolds number
t	thickness (m)
T	temperature (K)
U	velocity vector (m/s)
u, v, w	flow velocity (m/s)
W	width (m)
x, y, z	Cartesian coordinates

Greek symbols

α	aspect ratio
β	width ratio
δ	thickness of interfacial layer
η	fin efficiency
$k(\infty)$	Hagenbach factor
μ	viscosity (N · s/m^2)
ρ	density (kg/m^3)
ϕ	viscous dissipation
φ	volumetric concentration of nanoparticles

Subscripts

app	apparent
av	average
ch	channel
eff	effective
f	fluid
j	junction
i	inlet
nf	nanofluid
o	outlet
s	solid

investigation of heat transfer in rectangular microchannels was performed by Lee and Garimella [12] whose width ranged from 194 mm to 534 mm. Based on the results, the conventional Navier–Stokes equations could be used to predict flow and heat transfer in the microchannels. Xie et al. [13,14] investigate numerical studies on the laminar and turbulent flow and heat transfer characteristics of water-cooled straight microchannel heat sink. It showed that the removed heat flux increased from 256 W/cm^2 to 350 W/cm^2 with a nearly-optimized microchannel. Also, the pumping power increased from 0.205 W to 5.365 W. Yin et al. [15] designed and optimized AlN – based MCHS for power electronics packaging. Sakanova et al. [16] optimized and compared three different structures of MCHS.

Wavy channel is an innovative concept to achieve higher heat transfer by modifying a plane straight channel and only cost of a slightly additional pressure drop. An experimental study regarding to wavy-walled channel to estimate heat and mass transfer for laminar and low Reynolds number flow was carried out by Goldstein and Sparrow [17]. It was found that the characteristic of heat transfer of the wavy channel was better than a parallel-plate channel within the Reynolds number range of 1000–1200. An experimental study of flow past a sinusoidal cavity by Saidi et al. [18] discovered that the heat and mass transfer properties were influenced by vortex evolution pattern, and that both pressure drop and heat transfer in the wavy channel were higher than those of a parallel-plate channel.

By using MCHS, high thermal performance can be achieved. However, further improvement is still essential to fulfil the demands from other device applications. Bergles and Webb [19,20] provided other reviews on the techniques for heat transfer enhancement in macroscale dimensions. Add additives to the working fluids are one of the methods to improve heat transfer. By adding additives, the fluid transport properties and flow features are changed which lead to enhance the heat transfer. In recent studies, metal particles implanted in the fluid were used to enhance the heat exchanger performance. However, there is a clogging issue occurred due to the particle sedimentation. By using this concept, the recent studied focused on enhancing heat transfer by using nanofluid in which nanoscale particles were suspended in the base fluids. Several experimental and analytical investigation showed that thermal conductivity are higher than pure fluids and therefore more efficient for cooling electronic devices [21,22].

In recent years, more studied focused on using a nanofluid as the heat transfer working fluid. There are two theoretical models were proposed by Xuan and Roetzel [23] to predict the heat transfer characteristics of nanofluid flow in a tube. Both convection heat transfer and pressure drop had been measured for nanofluid tube flows by Li and Xuan [24], Xuan and Li [25] and Pak and Cho [26]. Their results showed that the heat transfer coefficient could be greatly enhanced by modifying the flow Reynolds number, particle Peclet number, particle volume fraction, and particle size and shape. These studies also showed that there is no extra pressure drop after adding nanoparticle in the fluid. Lately, Yang et al. [27] implemented an experimental study regarding to construct a heat transfer correlation based on the parameters that influenced heat transfer. For example, in a laminar flow in a circular tube, it showed that the heat transfer coefficient by using nanofluids working flow had a lower increase than predicted not only in the conventional heat transfer correlation for the homogeneous but also particle-suspended fluid. Several recent studies investigated the design of MCHS as well as double-layered MCHS with different geometric parameters by using nanofluids [28–31].

The flow characteristics of nanofluid heat transfer were carried out in macro-scale dimensions in most of the studies mentioned above. There are studies that analyzed the nanofluid flow and heat transfer in micro-scale dimensions [32–34]. In numerical aspect, different models of MCHS performance had been studied by Koo and Kleinstreuer and Jang and Choi [35,36] for the effective thermal conductivity of the nanofluids. In order to predict microchannel heat sink performance, a macro-scale correlation was carried out by Chein and Hunag [37]. In experimental aspect, Chein and Chuang [38] studied the behavior of heat sink performance and effect of particle deposition when nanofluid is used as the working fluid. In the study of Lee and Mudawar [39], Al_2O_3–H_2O nanofluid