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Assessment of the Effectiveness of Nanofluids for Single-Phase Heat Transfer in Micro-Channels

Abstract

In this study, microchannel heat sink (MCHS) performance using nanofluids as coolants is addressed. We first carried out a simple theoreticalanalysis that indicated more energy and lower MCHS wall temperature could be obtained under the assumption that heat transfer could be enhanced by the presence of nanoparticles.A silicon MCHS was madeand Al_2O_3- H_2O mixtures without a dispersion agent were used as the coolants.The Al_2O_3 particle volume fraction was in the range of 5% .It was found that nanofluid-cooled MCHS could absorb more energy than water-cooled MCHS.

Keywords: Microchannel heat sink (MCHS); Nanofluid; Particle volume fraction

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Introduction

The miniaturization of devices like computers or optoelectronic installation raised the issues regarding the proper thermal management of the high heat fluxes dissipated by them.Microchannel heat sinks are used in a variety of devices incorporating single-phase liquid flow as one of the most promising high efficiency heat exchange technologies. The application involves the cooling of electronic devices, automotive heat exchangers, laser process equipment and aerospace technology, etc.

Since the pioneering work by Tuckerman and Pease [1] in theearly 1980s, there has been a great deal of interest in the studyof fluid flow and heat transfer in microchannel s. In order to generatea set of design equations to predict the pressure drop occurring in microchannel flow devices, Steinke and Kandlikar [2] reviewedthe available literature on single–phase liquid friction factors inmicrochannel s, generated a database to critically evaluate theexperimental data available in the literature and performed anin-depth comparison of previous experimental data to identifythe discrepanciesin reported literature.

Xu et al. [3,4] demonstrated a new silicon microchannel heat sink composing of parallel longitudinal microchannel and several transverse microchannel s, and provided three-dimensional numerical simulations of conjugate heat transfer in the newly proposed interrupted microchannel heat sink. Cheng [5] used computational fluid dynamics to simulate the flow and heat transfer in a stacked two–layer microchannel s with multiple MEMS easy-processing passive microstructures. Xia et al. [6,7] analysed the effect of geometric parameters on water flow and heat transfer characteristicsin the microchannel heat sink with fan-shaped and triangular re-entrant cavities, and obtained the optimal geometric parameters on the basis of the thermal enhancement factor performance. Choi and Eastman [08] invented a method and apparatus for enhancing heat transfer in fluids such as deionized water, ethylene glycol and oil by dispersing Nano crystalline particles of substances such as copper, copper oxide, aluminium oxide in the fluids. Nano crystalline particlesproduced and dispersed in the fluid by heating the substance to be dispersed in a vacuum while passing a thin film of the fluid near the heated substance. The fluid is cooled to control its vapor pressure.

Zhang and Lockwood [09] invented a fluid media such as oil or water and a selected effective amount of carbon as oil or water and a selected effective amount of carbon nanomaterial's necessary to enhance the thermal conductivity of the fluid. One of the preferred carbon materials is a high thermal conductivity graphite, exceeding that of the neat fluid to be dispersed therein in thermal conductivity, and ground, milled, or naturally prepared with mean particle size less than 500 nm,and preferably less than 200 nm, and most preferly less than 100 nm.The graphite is dispersed in the fluid by one or more of various methods, including ultra-sonication,milling,and chemical dispersion.Carbon nanotubes with graphitic structure are another preferred.

Nomenclature

Cp	specific heat . . . . .J kg−1 K−1
h	local heat transfer coefficient . . ……………………………….Wm−2 K−1
k	thermal conductivity . .Wm−1 K−1
Q	heating rate absorbed by working fluid . . . …………………………… . W
q	heat flux. . .. . Wm−2
Tw	microchannel wall temperature . .K
Wch	width of microchannel . . . . m
Wfin	width of microchannel wall . . . .m
Wb	bottom width of the microchann. m
Re	Reynolds number
Nu	Nusselt number
Greek symbols	
*μ*viscosity. . . . . kgm−1 s−1	
*ρ*density . . . . kgm−3	
*φ*particle volume fraction . . . . %	
Subscript	
f	pure fluid
nf	nanofluid
p	particle

The thermal conductivity enhancement, compared to the fluid without carbon material, is proportional to the amount of carbon nanomaterials (carbon nanotubes and /or graphite) added. Egawa and Tsujii [10] invented a heat of metal and/or metal oxide particles and high in the thermal conductivity characterized by comprising water and/or alcohol as the main component, and (a) one kind or two or more kinds selected from metal and or/ metal oxide particles having an average particle diameter of from 0.001 to 0.1 μm, (b) one kind or two or more kinds selected from polycarboxylic acids and/or salts thereof, and (c) at least one kind of a metal corrosion inhibitor.

The heat transfer medium liquid composition that can be used as a coolant for an internal-combustion engine, a motor and the like, a heat transfer medium for a hot water supply, heating, cooling and freezing system, or a heat transfer medium for a snow melting system, road heating and the like. In particular, the invention relates ti a heat transfer medium liquid composition which is excellent in dispersion stability of metal and /or metal oxide particles and high in thermal conductivity.

Davidson and Bradshaw [11] invented heat transfer compositions and methods for using same to transfer heat between a heat source and a heat sink in a transformer, and in particular to the utilization of nano-particle size conductive material powers such as nano-particle size diamond powders to enhance the thermal capacity and thermal conductivity of heat transfer compositions such as transformer oil.

The thermal conductivity was greatly improved with same volume fraction nanoparticle addition.Murray [12] invented a system combining the thermal conductivity characteristics of certain nanoparticles with the high specific heat of appropriate fluids to enhance the overall heat transfer characteristics of a heat exchanger. The system comprises a fluid channel disposed in a heat exchanger unit with slurry as the convective heat transfer medium. The slurry comprises an appropriate fluid with field reactive nanoparticles suspended therein, Field emitters are located along the walls of the fluid channel whereby the distribution of nanoparticles within the slurry is manipulated to achieve enhanced heat transfer characteristics.

In this study, the pressure drop and heat transfer characteristics of a single-phase micro-channel heat sink are investigated both numerically. The numerical results are compared with the water and nanofluid transport models in depicting the transport characteristics of micro-channel heat sinks. A detailed description of the heat transfer characteristics is presented and discussed. These results provide new, fundamental insight into the complex three-dimensional characteristics of this heat sink.

Physical models

A microchannel heat sink of water-based nanofluids containing 5 vol. % alumina -nanoparticle is considered. Figures 2.1 and 2.2describe the physical and numerical domains. The top surface is insulated and the bottom surface is uniformly heated. The material used for microchannel heat sink is silicon (k_s = 400 W/m K). In analyzing the problem, the flow can be assumed to be laminar and both hydro dynamically and thermally fully. All the thermo-physical properties are assumed to be constant. The dimension of microchannel is height=300μm, width=320 μm and length=0.6cm.

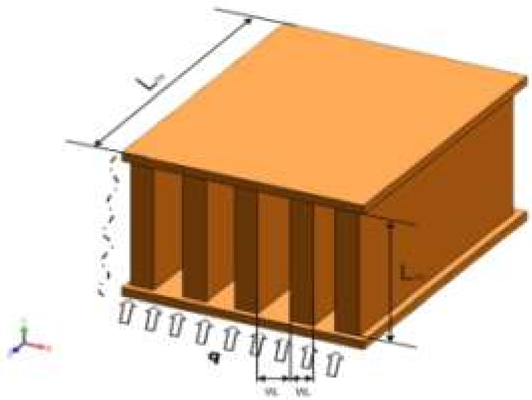

Figure: 2.1. Schematic of a microchannel heat sink physical domain

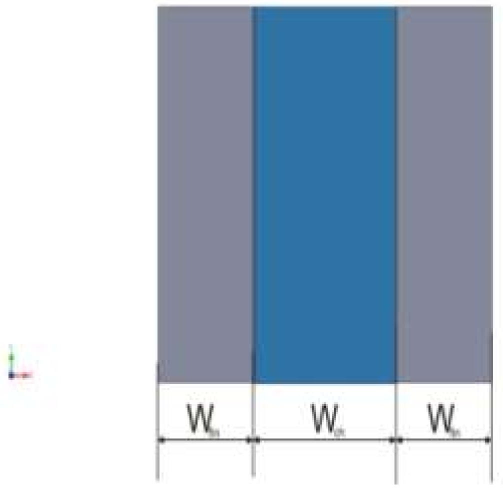

Figure: 2.2 Schematic of a microchannel heat sink numerical domain.

Meshing

The modelling and the meshing of the microchannel is performed in Gambit 2.4.16. It is known that with an increase of meshing intensity, the accuracy of the computational results improves. However, higher the mesh compactness, the higher will be the computational time required to get the convergence, and hence, it becomes computationally inefficient. As a result, it is necessary to have a mesh that compromises between the simulation time and the accuracy. Considering this fact, the idea of non-uniform meshing is implemented. The meshing of the microchannel is done using Hexagonal element (spacing 1mm) in GAMBIT software after series of meshing performed 250000 cells.

Figure: 2.3 Meshing of microchannel

Numerical details

Governing equations

To focus on the effect of using nanofluid with nanoparticle volume fractions on the MCHS performance, the following assumptions are made: (i) both fluid flow and heat transfer are in steady-state and three-dimensional; (ii) fluid is in single phase, incompressible and the flow is laminar; (iii) properties of both fluid and heat sink material are temperature-independent; and (iv) all the surfaces of heat sink exposed to the surroundings are assumed to be insulated except the top plate of heat sink where constant heat flux boundary, laminar and fully developed flow condition simulating the heat generation from electronic chip is specified.

Based on the above assumptions, the governing differentialequations used to describe the fluid flow andheat transfer in the unit cell are expressed as follows. Forthe cooling water, the continuity, momentum, and energyequations are expressed, respectively, as

$$\nabla \vec{V} = 0, \tag{1}$$

$$\rho_f\left(\vec{V}\cdot\nabla\vec{V}\right) = -\nabla P + \nabla\cdot\left(\mu_f \nabla\vec{V}\right), \tag{2}$$

$$\rho_f c_{p,f}\left(\vec{V}\cdot\nabla T\right) = k_f \nabla^2 T. \tag{3}$$

For the solid regions, the continuity and momentumequations are simply

$$\vec{V} = 0,$$

and the energy equation is

$$k_s \nabla^2 T = 0.$$

Reynold number:

$$\mathrm{Re} = \frac{\rho_{nf} . u_{nf} . D_h}{\mu_{nf}}$$

Nusselt number:

$$Nu = \frac{h.D_h}{k_{nf}}$$

Hydraulic diameter:

$$D_h = \frac{2W_{ch}.L_{ch}}{(W_{ch} + L_{ch})}$$

Boundary conditions

Boundary conditions all boundaries are specified for this simplified computational domain. At the entrance of the heat sink assembly (Z=0) center of the boundary is encountered with nanofluid which flows through the microchannel and removes heat conducted to the surface of the heat sink. At the microchannel sections, the inlet nanofluid temperature is taken as 300 K .

Boundary types

While carrying out the simulation specific boundary types in microchannel are shown in the fig.[5.3] inlet velocity is in blue colour, pressure outlet is in red colour, heater wall face is at the bottom. And all the other faces are wall.

Continuum types

While specifying continuum type in microchannel, there are 2 zones called solid & fluid.

Input data for simulation

The following input parameters are considered for microchannel. In the first case, simulation is carried out for microchannel alone where only nanofluid allowed to flow through the inlet valve. Than water is allowed to flow. With initial temperature of 300K

Inlet Pressure	1-1.5 bar
Heat flux	2.2-14.4x10^5 (W/m²)
Inlet velocity	1.62-3.2(m/s)
Effective thermal conductivity	0.75 (W/mK)
Effective density	1001.1(kg/m^3)
Effective viscosity	1.007123e-3(kg/m-s)
Effective specific heat	10001(J/kgK)
Particle size	50nm
particle thermal conductivity	202.4(W/m²K)

Table-1

Result

Nusselt Number

It is assumed laminar flow in microchannel and under the constant wall temperature condition. Figure [4.1] represents the measurements of Nusselt

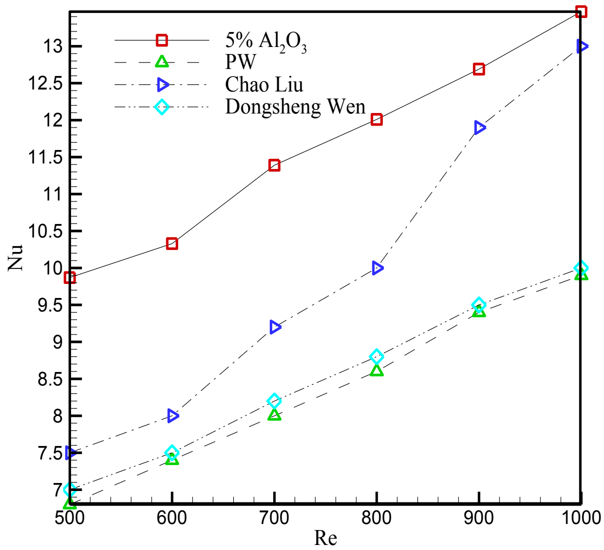

Figure: 4.1 Variation of Nusselt number with Reynolds number

Number over the Reynolds number in this work and compared between the experimental result Mlack [18], Wu and Cheng [17], PW (pure water) and simulated result. The Al_2O_3 – H_2O nanofluid is considered in this study, the particle volume concentration is 5% with 5 watt constant heat input. The obtained results match reasonably well with the experimental data. Also, an increase in Nu with the Reynolds number is observed (Fig. [4.1]).

Pressure Drop

Equations describes that the suspension of solid particle in the base fluid increases the relative viscosity of base fluid and also increases the pressure drop as compare to base fluid. Figure [4.2] shows the variation of measured pressure drop at outlet of the microchannel with respect to the Reynolds number. It has been numerically analyzed pressure drop for both pure water and nanofluid in microchannel operated under same geometry. Difference between the pressure drop for both pure water and nanofluid is not large because the particle size is small. This is one of the reasons for using the nanofluid for heat transfer in various applications.

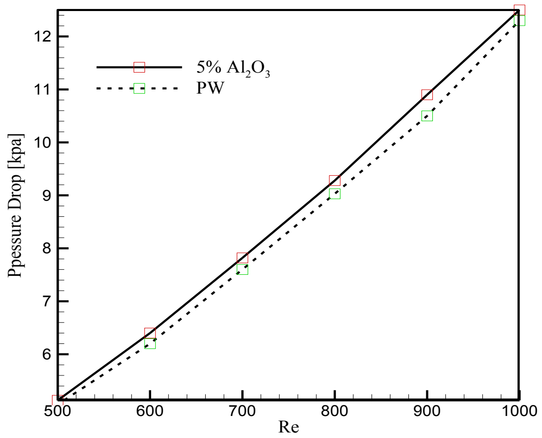

Figure: 4.2

Variation of pressure drop with Reynolds number

Co-efficient of heat transfer

Increase in the co-efficient of heat transfer with respect to Reynolds number is observed (Fig. [4.3]). In this study 5% of particle concentrations at constant heat flux 1222222.2 W/m^2. Also shown, is the comparison of the heat transfer co-efficient between the pure water and nanofluid.

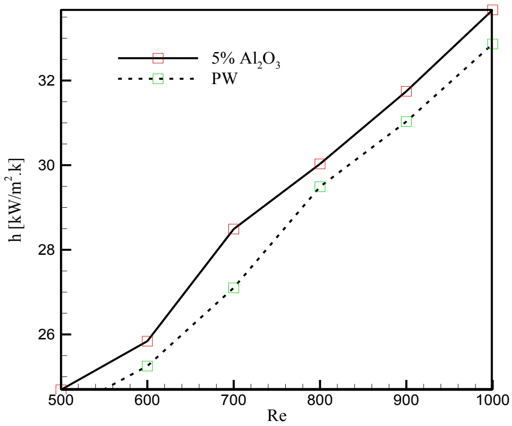

Figure: 4.3 Variation of co-efficient of heat transfer with Reynolds number

The effect of Reynolds number co-efficient heat transfer increase .Al_2O_3 shows the greatest heat transfer enhancement with respect to pure water, and results shows 22% higher co-efficient of heat transfer of nanofluid as compare to pure water.

Variation of wall temperature with Z-axis

Figure [4.4] represents the temperature distribution along the Z- axis and the comparison between nanofluid and pure water at constant heat flux 1222222.2 W/m^2, Re 500, inlet temperature 300k and 5% volume concentration. Results show that T_w is higher for pure water as compared to the nanofluid and temperature difference increases with the increase the particle concentration. This effect shows that nanofluids are more efficient for cooling purpose microchannel as compare to base fluid.

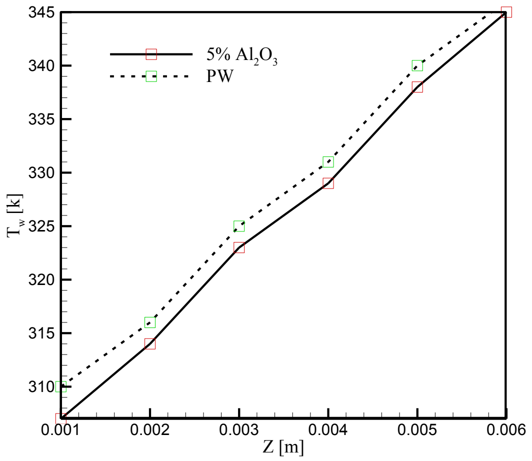

Figure: 4.4 Variation of wall temperature with Z-axis

Conclusion

In this article, the experimental results concerning hydraulicand thermal performances of a silicon microchannel heat sinkcooled by alumina–water nanofluid of 5 vol.% have been presented.The numerical analysis on the suitability of using nanofluids in microchannel heat sinks enhancement waspresented. The water based Al2O3 nanofluid with fixed volumefractions and particle diameters is considered and results are comparedwith those of a water. It is known that both thermal conductivityand viscosity of nanofluids are higher but also the specificheat is lower compared with a water.From the present study following conclusion can be derived:-

Increasing the particle concentration increases the pressure drop to pure fluid.

Increasing the concentration suspended particles in nanofluid increases the heat transfer rate.

Better Cooling performance is observed with the use of nanofluid in the microchannel

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