International Communications in Heat and Mass Transfer 97 (2018) 72–77

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Nanofluids and converging flow passages: A synergetic conjugate-heat-transfer enhancement of micro heat sinks

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ARTICLE INFO

Keywords:
KKL (Al_2O_3-water) nanofluid
Converging channel
Microchannel heat sink
Enhanced convection heat transfer
Brownian motion

ABSTRACT

Simultaneous effects of using nanoparticle (Al_2O_3) in water along with the converging flow passages on the forced convection heat transfer coefficient in a microchannel heat sink (MCHS) are investigated using a finite volume numerical simulation. The accurate KKL (Koo-Kleinstreuer-Li) model, considering particles' material density, volume fraction, diameter and Brownian motion, is implemented to model the thermophysical properties of Al_2O_3-water nanofluid. The numerical simulation is performed based on a non-uniform structured grid. Results have shown that nanoparticles can enhance the convection heat transfer coefficient of the base fluid and the enhancement obtained by the nanoparticles are 33% higher for the case of the converging flow passages than that of straight passages. Simulation results have proved that implementation of an enhanced working fluid (i.e. Al_2O_3-water nanofluid) and using geometrical enhancement (i.e. converging flow passages) reveal synergetic thermal response and shows an effective enhancement on the convection heat transfer coefficient as high as 2.35 times greater than the heat transfer coefficient of a pure water flows through a straight channel with no convergence. The present results suggest implementing nanofluids along with converging flow passages to achieve the effective enhancement in the convection heat transfer coefficient and to boost the improvement obtained by each individual enhancement technique, especially in the thermally developed regions wherein the convection heat transfer coefficient cannot be increased by increasing the inlet velocity/pressure in the laminar flow regime.

1. Introduction

Nowadays, the ever-increasing demand of dealing with high heat fluxes, as high as mega Watts per square meter, motivates researchers toward enhancing the thermal response of the heat exchangers using different techniques like porous materials [1,2], nanofluids [3,4], reducing the size of flow passages toward minichannels [5] and microchannels [6,7], boiling heat transfer [8], turbulators [9], secondary flows and curved passages [10], or mixing the above-mentioned techniques [11,12]. Hereafter, some novel techniques used to enhance the forced convection heat transfer rate of miniature heat exchangers are presented briefly. For the first time, the definition of microchannel was introduced by Tuckerman and Pease [13]. They showed that high heat fluxes as high as 10^6 W/m^2 can be removed by this new array of microscale channels in practice.

Haddad et al. [14] numerically studied the enhancement obtained by inserting porous materials within a microchannel in the slip-flow regime of natural convection heat transfer phenomenon. Simultaneously, Nield and Kuznetsov [15] investigated the implementation of porous media in microchannel to enhance the Nusselt number of forced convection in a microchannel. Using porous material in microchannels is accompanied by some new theoretical questions and hence, a great attention has been dedicated to complete the classic convection heat transfer in recent years [16–19].

Using nanoparticles to enhance the thermophysical properties of the working fluid leads to the idea of nanofluids and has been used extensively within the last two decades as a heat transfer rate enhancement technique [20,21]. New researches proved the implementation of nanofluids in improving the convection heat transfer rate of nanofluid-cooled microchannels [22,23].

Besides using new materials (like porous materials and/or nanofluids), enhancing heat transfer rate by optimizing the geometrical aspects has been studied thoroughly [24]. Most of the aforementioned geometrical optimization concern to find the optimum wall thickness as

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https://doi.org/10.1016/j.icheatmasstransfer.2018.03.022

well as channel dimensions. Another king of geometrical optimization is to use channels with zig-zag or wavy flow passages to enhance the thermal dispersion and as well the heat transfer rate [25,26]. Li et al. [27] numerically investigated the heat transfer enhancement obtained by cavities and ribs in microchannels. One of the most recent methods to enhance the convection heat transfer coefficient of microchannel heat sinks is to use converging flow passages [28]. Dehghan et al. [28] recently have proved that the heat transfer rate can be enhance with a reduction in the pumping power by using converging flow passages in microchannel heat sinks.

According to the literature review, it is questioned whether the heat transfer rate can be enhanced more effectively by combining two different enhancement techniques or not? The present study aims at investigating a nano-fluid (Al_2O_3-water) cooled microchannel heat sink with converging flow passages numerically to find if these two enhancement techniques (i.e. enhancement in thermophysical properties of working fluid along with enhancing the flow geometry) are synergetic or not. To predict the thermophysical properties of Al_2O_3-water nanofluid, the accurate KKL (Koo-Kleinstreuer-Li) model is used [29]. The finite volume method (FVM) over a non-uniform structured mesh is adopted to simulate the fluid flow as well as the conjugate heat transfer.

2. Mathematical modeling

2.1. Governing equations

The schematic diagram of the problem, the dimensions and properties of Al_2O_3 nanoparticles are shown in Fig. 1, Table 1 and Table 2, respectively.

The forced convection heat transfer in the laminar regime is governed by:

$$\nabla.\,(\rho_{eff}\vec{V}) = 0$$
$$\vec{V}.\,\nabla(\rho_{eff}\vec{V}) = -\nabla p + \nabla.\,(\mu_{eff}\nabla\vec{V})$$
$$\vec{V}.\,\nabla((\rho c_p)_{eff}T_f) = (\vec{V}.\,\nabla)p + \nabla.\,(k_{eff}\nabla T_f) \quad (1)$$

Eq. (1) shows the mass, momentum and energy conservation equations of the working fluid. The heat transfer in the solid parts or the microchannel is governed by:

$$\nabla.\,(k_s\nabla T_s) = 0 \quad (2)$$

Table 1
Dimensions of microchannel (μm).

W_i	W_o	W_c	H	fL	t
200	200, 150, 100, 75	400	1000	1200	500

Table 2
Al_2O_3 nanoparticle properties.

d_p (nm)	38.4
$\rho_p\left(\frac{kg}{m^3}\right)$	3970
$C_P\left(\frac{W}{kgK}\right)$	760
$k_p\left(\frac{W}{mK}\right)$	40

2.2. Thermophysical properties of nanofluid

The density and specific heat coefficient of the nanofluid are given by:

$$\rho_{eff} = (1-\phi)\rho_{bf} + \phi\rho_p \quad (3)$$

$$(\rho C_p)_{eff} = (1-\phi)(\rho C_p)_{bf} + \phi(\rho C_p)_p \quad (4)$$

The KKL model is used to define the viscosity and thermal conductivity of the working Al_2O_3-water fluid. This model can consider effects of diameter, volumetric concentration, density and Brownian motions of nanoparticles on the thermophysical properties. Hence, the KKL model gives predictions that are close to experiments for a wide range of parameters:

$$k_{eff} = k_{static} + k_{Brownian}$$

$$\frac{k_{static}}{k_{bf}} = 1 + \frac{3\left(\frac{k_p}{k_{bf}} - 1\right)\phi}{\left(\frac{k_p}{k_{bf}} + 2\right) - \left(\frac{k_p}{k_{bf}} - 1\right)\phi}$$

$$k_{Brownian} = 5\times10^4\phi\rho_{bf}C_{p,bf}\sqrt{\frac{\kappa_{bf}T}{\rho_p d_p}}\,g'(T,\phi,d_p) \quad (5)$$

where $g'(T,\phi,d_p)$ is [29]:

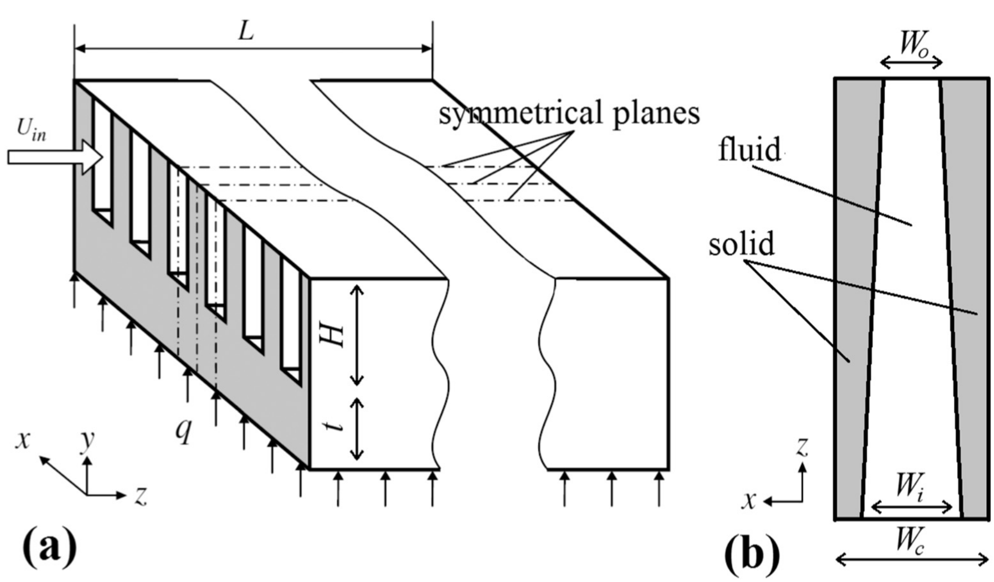

Fig. 1. Schematic diagram of the problem; (a) isometric view of MCHS and (b) top view of a channel [28].