Journal of the Taiwan Institute of Chemical Engineers 58 (2016) 8–18

Contents lists available at ScienceDirect

Journal of the Taiwan Institute of Chemical Engineers

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

Al_2O_3–water nanofluid inside wavy mini-channel with different cross-sections

M. Khoshvaght-Aliabadi [a,*], S.E. Hosseini Rad [b], F. Hormozi [b]

[a] Department of Chemical Engineering, Shahrood Branch, Islamic Azad University, 36199-43189, Shahrood, Iran
[b] Faculty of Chemical, Petroleum, and Gas Engineering, Semnan University, Semnan, Iran

ARTICLE INFO

Article history:
Received 28 January 2015
Revised 12 May 2015
Accepted 17 May 2015
Available online 10 June 2015

Keywords:
Wavy mini-channels
Cross-section
Nanofluid
Laminar flow
Numerical approach

ABSTRACT

Laminar convection of water and 1% vol. Al_2O_3–water nanofluid through the straight mini-channel (SMC) and wavy mini-channel (WMC) with various cross-section geometries is studied numerically. The nanofluid flow is simulated by using the mixture model, which has been verified to be the appropriate model to simulate nanofluid behavior. The results depict higher values of the heat transfer rate and pumping power for the WMC compared to the SMC. It is also found that the hexagonal cross-section causes a considerable heat transfer enhancement inside the SMC in comparison with the other cross-sections. However, the highest heat transfer rates are obtained for the WMC with the rhombic and triangular cross-sections. It is necessary to note that for all the cases, the nanofluid flow presents higher values of the heat transfer rate and pumping power compared to the water flow. Finally, correlations are developed for the SMC and WMC with different cross-sections in the range of the studied Reynolds number, *i.e.* 300–1500.

1. Introduction

Heat transfer and fluid flow in channels or ducts are the traditional issues in many engineering applications such as heat exchangers, chemical reactors, electronic systems, solar collectors, or power plants. Replacing complicated channels like the wavy channels instead of the straight ones is a promising method to enhance the thermal performance and provide higher compactness in these instruments [1]. Also in the recent years, different metallic and oxide-metallic nanofluids are introduced and applied by many researchers. However, most of the studies are for the nanofluid flow inside the straight channels with the circular cross-section, and there are very limited studies on the nanofluid flow inside the indirect channels [2].

Heat transfer and flow field characteristics of the Cu–water nanofluid in a wavy channel were studied by Heidary and Kermani [3]. The results show that this compound technique, *i.e.* nanofluid flow inside the wavy channel, enhances the heat transfer up to 50%. Thermal-hydraulic performance of the Cu–water nanofluid in the corrugated channels with triangular, sinusoidal, and trapezoidal waves was investigated by Ahmed et al. [4–6]. The effects of nanoparticle shapes on the forced convection flow of the SiO_2–ethylene glycol nanofluids inside the wavy channels were investigated by Vanaki et al. [7]. The nanofluid with the platelets nanoparticle shape gives the highest heat transfer enhancement. Recently, Khoshvaght–Aliabadi [8] analyzed heat transfer and flow characteristics of the sinusoidal-corrugated channel with Al_2O_3–water nanofluid. The effects of different geometrical parameters were evaluated at the nanoparticle volume fraction below 4%. The channel height and wave amplitude show the highest influences on Nusselt number and friction factor values. Heat transfer performance of the Al_2O_3–water nanofluid in a wavy mini-channel under pulsating inlet flow conditions was examined by Akdag et al. [9]. Results show that using the nanoparticles under pulsating flow promotes the thermal performance. The effect of the Al_2O_3–water nanofluid flow on performance of the sinusoidal-wavy channel with different wall phase shifts was investigated by Ahmed et al. [10]. Results indicate that the optimal performance is achieved by 0° phase shift channel over the ranges of Reynolds number and nanoparticle volume fraction. Also, they studied the effect of the corrugation profile and depicted the trapezoidal channel has the highest Nusselt number [11].

All the mentioned studies were conducted numerically for 2-D nanofluid flow, and experimental studies on the nanofluid flow inside the wavy or corrugated channels are very scarce. Application of the nanofluid (Al_2O_3 in water 2, 3 and 4 vol.%) inside a counter flow corrugated plate heat exchanger was investigated experimentally by Pandey and Nema [12]. The results indicate that the heat transfer performance improves with increasing both Reynolds number and Peclet number, while it declines with the concentration of the nanofluid. An experimental study on the forced convective flow

* Corresponding author. Tel.: +989151811311; fax: +985812244818.
E-mail address: mkhaliabadi@gmail.com, mkhaliabadi@yahoo.com (M. Khoshvaght-Aliabadi).

http://dx.doi.org/10.1016/j.jtice.2015.05.029
1876-1070/

Nomenclature

A_c	frontal area, m^2
A_t	total heat transfer area, m^2
C_p	specific heat capacity, J/kg.K
D_h	hydraulic diameter, m
g	gravitational acceleration, m/s^2
h	heat transfer coefficient. $W/m^2.K$
L	channel length, m
P	pressure, Pa
T	temperature, K
V	volumetric flow rate, m^3/s
V_m	velocity, m/s
x, y, z	coordinates

Greek symbols

ρ	density, kg/m^3
μ	dynamic viscosity, kg/m.s
κ	thermal conductivity, W/m.K
φ	nanoparticles volume fraction, %
ϕ	general variable
η	considered PEC

Subscripts

BF	base fluid
C	circular
in	inlet
m	mixture
NF	nanofluid
NP	nanoparticle
wall	wall

Dimensionless groups

f	Darcy friction factor
Gr	Grashof number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Acronyms

CFD	computational fluid dynamics
FVM	finite volume method
PEC	performance evaluation criteria
SIMPLE	semi implicit method for pressure linked equation
SMC	straight mini-channel
WMC	wavy mini-channel
3-D	three-dimensional

of different nanofluids through a corrugated channel was performed by Khoshvaght–Aliabadi et al. [13]. The effects of different factors including nanoparticle weight fraction (0.1–0.4%), type of nanoparticles (Cu, SiO_2, TiO_2, ZnO, Fe_2O_3, Al_2O_3 and CuO), and base fluid material (water–ethylene glycol mixture) were examined. In the other work by the authors [14], an experimental assessment of the Cu–water nanofluid flow through different plate-fin channels was carried out. It was detected that at the lower Reynolds numbers, the wavy channel has the best thermal-hydraulic performance in comparison with the other complicated channels.

However, the literature review shows that the effect of the cross-section geometry on thermal-hydraulic performance of the wavy channels has not been investigated in the past, especially when a nanofluid is applied as working media. Accordingly, the current study examines the 3-D laminar forced convective flow of the water and Al_2O_3–water nanofluid inside the wavy mini-channel (WMC) having different cross-section geometries and the results are compared with the straight mini-channel (SMC).

Table 1
Values of geometrical parameters.

Cross-section	*a* (m)	*b* (m)	Area (m^2)
1. Square	1×10^{-3}	1×10^{-3}	$(a \times b) = 1 \times 10^{-6}$
2. Rectangular	1.4142×10^{-3}	0.7071×10^{-3}	$(a \times b) = 1 \times 10^{-6}$
3. Rhombic	1×10^{-3}	2×10^{-3}	$0.5(a \times b) = 1 \times 10^{-6}$
4. Triangular	1.4142×10^{-3}	1.4142×10^{-3}	$0.5(a \times b) = 1 \times 10^{-6}$
5. Hexagonal	1×10^{-3}	1.3334×10^{-3}	$(1.5a \times 0.5b) = 1 \times 10^{-6}$
6. Trapezoidal	1.4142×10^{-3}	0.9415×10^{-3}	$(1.5a \times 0.5b) = 1 \times 10^{-6}$
7. Circular	1.1286×10^{-3}	1.1286×10^{-3}	$0.25\pi(a \times b) = 1 \times 10^{-6}$
8. Half-circular	1.5962×10^{-3}	0.7981×10^{-3}	$0.25\pi(a \times b) = 1 \times 10^{-6}$

Table 2
Water and Al_2O_3 nanoparticles properties.

Material	ρ (kg/m^3)	C_p (J/kg.K)	μ (kg/m.s)	κ (W/m.K)
Water	998.2	4182	998×10^{-6}	0.597
Al_2O_3 nanoparticles	3880	773	–	36

2. Numerical scheme

2.1. Channel geometric configurations

In this study, the effects of the square, rectangular, rhombic, triangular, hexagonal, trapezoidal, circular, and half-circular cross-section geometries are analyzed for both the SMC and the WMC. The physical configuration of the cross-sections is shown in Fig. 1. The detailed dimensions for each shape of the cross-sections are also given in Table 1. As depicted in the table, all the cross-sections have the same area, *i.e.* 1×10^{-6} m^2, and the channels have the same length, *i.e.* 5×10^{-2} m. For the WMCs, the wave-length and wave-amplitude values are 5 mm and 1 mm, respectively. The generated and considered SMCs and WMCs are depicted in Fig. 2.

2.2. Working fluids and their properties

In this paper, the water and Al_2O_3–water nanofluid at the volume fraction of 1% are adopted to investigate the effect of the working fluid. The thermo-physical properties of the nanofluid in the present study are the ones used by Manca et al. [15], where a mixture of the water and Al_2O_3 nanoparticles with a diameter of 38 nm is considered. The values of the density, specific heat, dynamic viscosity, and thermal conductivity, given by Rohsenow et al. [16], are reported in Table 2 for the water and Al_2O_3 nanoparticles.

2.3. Governing equations

The governing equations of the fluid flow and heat transfer are 3-D continuity, Navier–Stokes, and energy equations with the following basic assumptions:

(1) Newtonian and incompressible working fluids (water and Al_2O_3–water nanofluid) with constant physical properties due to the small temperature difference over the channel length;
(2) Steady-state, continuous, and laminar flow;
(3) Negligible viscous dissipation, radiation, and natural heat transfer, respectively, due to low velocity gradients and viscosity, low operating temperatures, and very small value of buoyancy force to inertia force ratio (Gr/Re^2);
(4) Thermal equilibrium state between the water and the Al_2O_3 nanoparticles.

The good prediction of the mixture model in nanofluid problems was proved by several previous works [17–22]. It was illustrated that the homogenous and Eulerian models underestimate Nusselt number in comparison with the available experimental data [20,22]. The Lattice Boltzmann Method (LBM) was proved to be an effective