International Communications in Heat and Mass Transfer 59 (2014) 17–23

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Heat transfer enhancement with laminar pulsating nanofluid flow in a wavy channel☆

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ARTICLE INFO

Available online 22 October 2014

Keywords:
Nanofluids
Pulsating flow
Wavy channel
Heat transfer enhancement

ABSTRACT

In this study, the heat transfer characteristics of Al_2O_3–water based nanofluids in a wavy mini-channel under pulsating inlet flow conditions are investigated numerically. The simulations are performed for nanofluid volume fractions, pulsating frequency and amplitude while the other parameters are kept constant by using control volume based cfd solver. The flow is both thermally and hydrodynamically developing while the channel walls are kept at a constant temperature. Results indicate that there is a good potential in promoting the thermal performance enhancement by using the nanoparticles under pulsating flow. Pulsation in nanofluids is a new idea for enhancement of heat transfer. Furthermore, the pulsating flow has an advantage to prevent sedimentation of nanoparticles in the base fluid. Results show that the heat transfer performance increases significantly with increase in nanoparticle volume fraction and with the amplitude of pulsation while the pulsation frequencies have a slight effect. In the pulsating flow conditions the combined effect of pulsation and nanoparticles is favorable for the increasing Nusselt number when compared to the steady flow case. The obtained results are given as dimensionless parameters.

1. Introduction

Recently, many heat transfer enhancement techniques have been proposed to increase the efficiency of heat transfer devices in industrial applications. The use of additives of nanometer-sized particles dispersed in the base fluid-like water or ethylene glycol so called as nanofluids is one of the techniques to augment the heat transfer. It is confirmed by several researchers that the nanofluids show a challenge potential for increasing heat transfer rates [1–5]. On the other hand, usage of wavy walls leads to better heat transfer performance due to enhanced mixing of the fluid by self-sustained fluid oscillations in the wavy surfaces. Furthermore, pulsations applied to the velocity inlet of wavy cannel lead to higher heat transfer efficiency. Using the nanoparticles under pulsating flow is a new idea for fluid flow mechanisms and heat transfer enhancement. Moreover, the pulsating flow has an advantage to prevent sedimentation of nanoparticles in the base fluid.

Flow and heat transfer of conventional fluid in a wavy channel have been studied numerically and experimentally by many researchers [6–10]. The heat transfer characteristics and pressure drop in the channel with V corrugated upper and lower plates under constant heat flux are experimentally performed and numerically studied by Naphon [11,12]. The corrugated plates with three different corrugated tile angles of 20°, 40°, and 60° are simulated by using the $k-\varepsilon$ standard turbulent model. It is reported that the corrugated surface has significant effect on the enhancement of heat transfer. A numerical study of fully developed fluid flow and heat transfer through a sinusoidal wavy surface was presented by Ramgadia and Saha [13]. The effect of Reynolds numbers, for *Re* in the range of 25–1000, on the flow field and heat transfer has been presented. For steady flow the heat transfer rates are found to be very low and for unsteady flow with increased mixing between core and near wall fluids enhanced as heat transfer rates are obtained.

Heat transfer and flow mixing under pulsating flow are often used in different engineering fields. Earlier many studies were made to the investigation of flow pulsation effects on heat transfer from the wavy channels [14–16]. Nandi and Chattopadhyay [17] denoted that the wavy channels do not provide any important heat transfer enhancement when the flow is steady. Nishimura and Kojima [18] experimentally investigated mass transfer characteristics in a sinusoidal wavy-walled channel for pulsatile flow. They reported that combination of flow separation and fluid oscillation leads to a significant enhancement in the mass transfer rate under laminar flow conditions. Jin et al. [19] experimentally investigated heat transfer enhancement by pulsating flow in a triangular grooved channel. They reported that the heat transfer improved up to 350% at $Re = 270$ and $St = 0.34$ compared with the steady flow case. Jafari et al. [20] investigated the effects of the pulsating flow on forced convection in a corrugated channel using the Lattice Boltzmann Method. Strouhal number and oscillation amplitude are studied at a wide range $0.05 \leq St \leq 1$ and $0 \leq A_{pulse} \leq 0.25$. Numerical results showed that the role of flow pulsation on the heat transfer

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2014.10.008
0735-1933/

Nomenclature

A_o	dimensionless pulsation amplitude
A_w	wavy wall amplitude
C	specific heat
f	frequency of pulsation
H	channel height
k	conductivity
L	heated wall length
L_t	total channel length
Nu	Nusselt number
P	pressure
Pr	Prandtl number
Re	Reynolds number
St	Strouhal number
x_m	amplitude of pulsation
x_o	unheated starting length
T	temperature
T_w	wall temperature
u,v	velocity components
u_{in}	instantaneous velocity
U_o	average inlet velocity
t	time [s]
x,y	catesian coordinates

Greek symbols

Δ	difference of variable inlet and outlet of channel
η	enhancement ratio
φ	volume fraction of particles, %
μ	dynamic viscosity
λ	wavelength of the wavy wall
ω	angular frequency [rad/s]
ωt	phase angle
ρ	fluid density
τ	cycle time ($\tau = \omega t$)
υ	kinematic viscosity

Subscripts

bf	base fluid
nf	nanofluid
p	pulsating
pt	particle
s	steady
w	wall

enhancement on the target surface is highly dependent on pulsating velocity parameters. The simultaneously developing unsteady laminar fluid flow and heat transfer inside a two-dimensional wavy microchannel, due to sinusoidally varying velocity component at inlet were numerically investigated by Nandi and Chattopadhyay [17]. Based on the comparison with the steady flow in wavy channel they found that imposed sinusoidal velocity at inlet can provide improved heat transfer performance at different amplitude and frequency.

The nanofluids can be applied to enhance the heat transfer. It has been reported that adding nanoparticles to the traditional heat transfer fluids can lead to improvement in their thermal conductivity [21,22]. Heidary and Kermani [23], numerically studied laminar flow and heat transfer of nanofluid in sinusoidal-wall channel. They investigated the effects of changing the Reynolds number, the nanoparticle volume fraction and the wavy amplitude on the flow and thermal characteristics. Their results showed that the addition of nanoparticle to the base fluid dramatically enhances the heat transfer in wavy channel. Ahmed et al. [24] numerically investigated laminar copper–water nanofluid flow and heat transfer in a wavy channel. The Reynolds number and nanoparticle volume fraction considered are in the ranges of 100–800 and 0–5% respectively. In their second paper, Ahmed et al. [25] numerically investigated heat transfer of copper–water nanofluid in trapezoidal-corrugated channel. Both numerical results showed that the average Nu number enhances with increase in nanoparticle volume fraction and with the amplitude of corrugated channel. Yang et al. [26], numerically studied the influences of the Reynolds number, the particle volume concentration, and the wavy channel amplitude on the heat transfer enhancement of nanofluids. They reported that the thermal enhancement achieved 24% in the wavy channel flow compared with pure fluid, with the particle volume concentration of $\varphi = 5\%$ of Cu/water nanofluids.

Pulsation in nanofluids was for the first time considered the simultaneous effect of pulsating and nanofluid by Selimefendigil and Oztop [27]. They presented a numerical study of pulsating rectangular jet with nanofluids. In the pulsating flow case, the combined effect of pulsation and inclusion of nanoparticles is not favorable for the augmentation of the stagnation point Nu number at $Re = 200$ and $Re = 400$ at $\varphi =$ 1%, 3% when compared to the steady case. Also, in the stagnation point, for $Re = 200$ and $\varphi =$ %6, heat transfer enhancement increased at 18.8% above. Some researchers investigated the effects of nanofluids on pulsating heat pipe [28–30]. Pulsating flow of nanofluids through a pipe with isothermal walls was numerically investigated by Rahgoshay et al. [31]. They reported that increasing both the frequency and amplitude leads to a slight increase in Nu number but by increasing Reynolds number and volume fraction, more rate of heat transfer is observed.

Pulsation in nanofluids is not implemented in a sinusoidal wavy channel in the literature. Therefore, in this paper, the convective heat transfer of Al_2O_3–water based nanofluids in a sinusoidal wavy channel under pulsating inlet flow conditions is numerically investigated for Reynolds number of 100 and nanoparticle volume fractions with ranges 0–6%. The numerical simulations are obtained by solving the governing equations using finite volume approach. The effects of nanoparticle volume fraction, pulsating frequency and amplitude on heat transfer rate are analyzed.

2. Numerical study

2.1. Definition of physical model

Fig. 1. shows the basic geometry of wavy mini-channel used in the present study. The geometry is considered such as 21 mm total length of the mini-channel (L_t), 1 mm straight section at the inlet of channel (x_o), and 1 mm hydraulic diameter of channel (H). The wavy geometry of the channel is described by the sinusoidal function as follows;

$$y = A_w \sin\left(\frac{2\pi}{\lambda}x\right). \quad (1)$$

The geometric parameters are kept constant such as wave amplitude $A_w = 0.2$ and wavy length $\lambda = 1$ mm. The fluid is a suspension of Al_2O_3 nanoparticles in water and three different nanoparticle volume fractions (φ) as 1%, 3% and 6% were considered. The channel length is assumed too long to compare to the height of channel. Hence, the problem is considered two-dimensional. The geometry and flow parameters are non-dimensionalized by using the channel height (H).

2.2. Governing equations

It can be assumed that the flow is fully developed, laminar, incompressible, two-dimensional and unsteady. Additionally, nanofluid is