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Convection heat transfer of SWCNT-nanofluid in a corrugated channel under pulsating velocity profile☆

Mohammad Jafari [a,*], Mousa Farhadi [b], Kourosh Sedighi [b]

[a] Faculty of Mechanical Engineering, Lorestan University, P.O. Box 465, Khoramabad, Iran
[b] Faculty of Mechanical Engineering, Babol University of Technology, P.O. Box 484, Babol, Iran

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ABSTRACT

This study focuses on the effects of single-walled carbon nanotubes (SWCNT) on convection heat transfer in a corrugated channel under a pulsating velocity profile. The volume fraction of added nanotubes to water as base fluid is lower than 1% to make dilute suspensions. A theoretical model is used for effective thermal conductivity of the nanofluid containing carbon nanotubes. This model covers different phenomena of energy transport in nanofluids. Also, an analytical model is applied for effective viscosity of the nanofluid which includes the Brownian effect and other physical properties of nanofluids. The Strouhal number and amplitude of pulsating velocity are studied at the range of 0.05–0.25 and 0–0.5, respectively, for various Reynolds numbers (50, 100 and 150). The study uses lattice Boltzmann method based on boundary fitting method to simulate flow and thermal fields. The time-averaged values of Nusselt number and relative pressure drop along a pulse period time are calculated and presented as the target outcomes. The results approved that the use of SWCNT particles in convectional channels can be an applicable method to enhance convection rate and also to reduce the pressure drop.

1. Introduction

The enhancement of convection heat transfer is a very interesting topic for different kinds of industrial and engineering applications. A well-known way to enhance the heat transfer rate of conventional fluids such as water, oil and ethylene glycol, which has low thermal conductivity [1,2], is adding nanoscale conductive particles. The added particles can be metals [3], nonmetals [4] or carbon nanotubes [5,6]. Because of the high thermal conductivity of these particles, they can improve the conductivity of these suspensions systematically. Nanoparticle-added fluids are known as nanofluids, according to Choi [7], who first named these kinds of fluid suspensions. He showed the enhancement of convection heat transfer by adding nanoparticles to the fluids.

In recent years, many studies have been conducted to study heat transfer of nanofluids numerically and experimentally [8–12]. In 1991, Iijima [12] discovered carbon nanotubes as an allotrope of carbon which is made of long-chained molecules of carbon with carbon atoms arranged in a hexagonal complex to form a tubular structure. Single-walled (SWCNT), double-walled (DWCNT) and multi-walled (MWCNT) carbon nanotubes are different classes of nanotubes depending on the number of tubules of carbon in their structure. In the last decade, carbon nanotubes have been mentioned as an attractive topic by many researches, which is generally due to their special properties and physical aspects such mechanical and thermal properties. With this point of view, the carbon nanotubes have extraordinary thermal properties such as thermal conductivity that is about twice as high as diamond [13] or thermal stability up to 2800 °C in vacuum. The higher thermal conductivity of carbon nanotubes relative to other nanoparticles leads to nanofluids containing cylindrical carbon nanotubes which are expected to have better heat transfer properties compared with the other nanofluids with spherical nanoparticles [14,15].

In an engineering point of view, heat transfer under pulsating flow is often found in different industrial applications [16–18]. Usage of pulsate flow in cooling systems of gas turbine engines, Stirling engines and in mini or macro scale, engineering problems such as electronics devices emphasize the importance of pulsating flow for modern industrial purposes. Carpinlioglu and Gundogdu [19] presented a widespread review on pulsating flow in thermal engineering. Their research points out that the reverse effects of a pulsating flow on the flow and heat transfer is confusing at different problem domains. Nield et al. [20] investigated laminar forced convection in a channel under pulsating flow. They presented that although the fluctuating part of the local Nusselt number changes in magnitude and phase aspect to frequency, pulsating flow leads to no enhancement in convection rate. In a numerical study, Chattopadhyay et al. [21] investigated laminar pulsating flow in a tube with constant temperature. They illustrated that pulsating flow profile has no positive outcome in heat transfer for a considered range of frequencies and pulsate amplitudes.

The corrugated wall channel is one of several devices utilized to enhance the heat transfer efficiency of industrial transport processes.

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* Corresponding author.
E-mail address: m.jafari177@gmail.com (M. Jafari).

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Nomenclature

A_w	Amplitude of wavy wall
c_p	Specific heat at constant pressure ($kj.\ kg^{-1}.\ k^{-1}$)
f, g	Distribution function
Nu	Nusselt number
Pr	Prandtl number (ν/α)
Re	Reynolds number ($u_{ave}.\ L/\nu$)
St	Strouhal number ($\mathrm{St} = \frac{\vartheta L}{u^*_{ave}}$)
T	Dimensionless temperature ($T = \frac{T^* - T^*_w}{T^*_{in} - T^*_w}$)
t	Dimensionless time ($\mathrm{t} = \frac{u^*_{ave} t^*}{L}$)
u	Dimensionless velocity ($u = \frac{u^*}{u^*_{ave}}$)
w_α	Weighting factor

Greek symbols

ϑ	Dimensional frequency ($Hz \approx s^{-1}$)
ΔP	Dimensionless pressure drop ($\frac{P_{out} - P_{in}}{\rho u^2_{ave}}$)
ω	Dimensionless angular frequency ($\omega = 2\pi.\ St$)

Subscripts

ave	Average
bf	Base fluid
eff	Effective
eq	Equilibrium
np	Nanoparticle
rel	Relative variables

Superscript

*	Dimensional variables
< >	Local-averaged variables
—	Time-averaged variables

These channels are mainly attractive for their simplicity to produce and potential to provide significant heat transfer enhancement if operated in appropriate conditions [22–26]. The changes in flow mixing, the disruption and thinning of boundary layers may cause enhancements of heat and mass transfer. Despite flows with high Reynolds numbers, early research presented adverse results for heat transfer enhancement at low Reynolds number flows.

Although the effect of flow pulsation in a corrugated channel has been studied by the authors [27], to the best of the authors' knowledge, the effects of carbon nanotubes on heat transfer enhancement in the presence of pulsating flow in this kind of convectional device is still a perspective which is not understood heretofore. Therefore, the investigation of SWCNT nanoparticles' effects on heat transfer from a corrugated channel under pulsating velocity profile is the major task of the current research.

The study used a lattice Boltzmann method coupled with a double population approach for flow and temperature fields. Also, the bounce back method is applied in LBM to model the boundary conditions in straight solid boundaries. Also, the boundary fitting method (BFM) is applied to deal with curved boundaries of wavy walls in LBM. The effects of various parameters of oscillating flow such as pulsating amplitude ($0.05 \le A_{\mathrm{Pulse}} \le 0.5$) and dimensionless oscillating frequency ($0.05 \le St \le 0.25$) on flow and temperature fields are investigated in details for different Reynolds numbers (50–150). Also, the volume fraction of the SWCNT nanoparticles (0%–1%) is studied as a main parameter of the nanofluid at different physical conditions of both constant and pulsating inlet flow.

In this simulation, effective conductivity and viscosity are calculated based on the new theoretical models. The Sabbaghzadeh and Ebrahimi [28] and Masoumi et al. [29] models are applied for effective thermal conductivity and effective viscosity of the nanofluid, respectively. This new thermal conductivity model captures the effects of different phenomena of energy transport in nanofluids. From a molecular point of view, some of the most important incidents in energy transport are: collision among the base fluid molecules, thermal diffusion of nanoparticles, thermal diffusion in the nanolayer in the fluid, thermal interaction of dynamic complex nanoparticles with the base fluid molecules and finally collision between nanoparticles caused by Brownian motion. The temporal and time-averaged values of local and surface-averaged Nusselt number and pressure drop are presented for different case studies. Finally, a series of practical correlations for the variation of Nusselt number and pressure drop aspects to amplitude of pulsating velocity are derived considering curve fitting of the obtained results. Also, the results of pulsating flow are compared with those obtained for steady constant flow at the same Reynolds number.

2. The lattice Boltzmann method

2.1. Flow and thermal fields

The progress of using the lattice Boltzmann method (LBM) as a numerical technique to convectional flows has been obvious in recent years [30–32]. The basic form of the lattice Boltzmann equation with an external force by introducing BGK approximations can be written as follows for both the flow and the temperature fields [32]:

$$f_\alpha(x + e_\alpha \Delta t, t + \Delta t) = f_\alpha(x,t) + \frac{\Delta t}{\tau_m}\left[f^{eq}_\alpha(x,t) - f_\alpha(x,t)\right] \quad (1)$$

$$g_\alpha(x + e_\alpha \Delta t, t + \Delta t) = g_\alpha(x,t) + \frac{\Delta t}{\tau_t}\left[g^{eq}_\alpha(x,t) - g_\alpha(x,t)\right] \quad (2)$$

Where $f_\alpha(x,t)$ is a distribution function on the mesoscopic level and e_α is the discrete lattice velocity in direction α. Also, τ_m and τ_t are the dimensionless collision-relaxation times for the flow and temperature fields, respectively. The characteristic velocity for force convection regime ($\mathrm{V_{force}} = \mathrm{vRe/L}$) must be small in comparison with the fluid speed of sound. By considering the D2Q9 model for applied lattice scheme for both flow and temperature fields, equilibrium distribution functions for flow field (f^{eq}_α) and temperature field (g^{eq}_α) are calculated as follows in different α directions:

$$\begin{aligned} f^{eq}_\alpha &= w_\alpha \rho\left[1 + 3\left(e_\alpha.\vec{u}\right) + \frac{9}{2}\left(e_\alpha.\vec{u}\right)^2 - \frac{3}{2}\vec{u}^2\right] \\ g^{eq}_0 &= -w_0 \rho RT\left[\frac{3}{2}\vec{u}^2\right] \end{aligned} \quad (3)$$

$$\begin{aligned} g^{eq}_\alpha &= w_\alpha \rho RT\left[\frac{3}{2} + \frac{3}{2}\left(e_\alpha.\vec{u}\right) + \frac{9}{4}\left(e_\alpha.\vec{u}\right)^2 - \frac{3}{2}\vec{u}^2\right] \quad \text{for } \alpha = 1-4 \\ g^{eq}_\alpha &= w_\alpha \rho RT\left[3 + 6\left(e_\alpha.\vec{u}\right) + \frac{9}{2}\left(e_\alpha.\vec{u}\right)^2 - \frac{3}{2}\vec{u}^2\right] \quad \text{for } \alpha = 5-8 \end{aligned} \quad (4)$$

where w_α is the weighting factor and ρ is the lattice fluid density. The D2Q9 lattice is a Cartesian 2D lattice with nine velocity directions. For these models, the values of e_α and w_α have special values for various α directions [32]. In LBM, Eqs. (1) and (2) are solved in two important steps that are called collision and streaming steps. Finally, after macroscopic variables can be calculated as follows:

$$\begin{aligned} &\text{Flow density}: \ \rho = \sum_\alpha f_\alpha, \ \text{Momentum}: \ \rho u_i = \sum_\alpha f_\alpha c_{i\alpha}, \\ &\text{Temperature}: \ T = \sum_\alpha g_\alpha, \ \text{Pressure}: \ P = \rho {C_S}^2 \end{aligned} \quad (5)$$

2.2. Boundary fitting method

For simulating curved boundaries, the treatment used is the same as those presented by Mei et al. [33] for velocity fields and those reported