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Pulsating flow effects on convection heat transfer in a corrugated channel: A LBM approach☆

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ABSTRACT

At the present study, the effects of the pulsating flow on forced convection in a corrugated channel are investigated using Lattice Boltzmann Method (LBM) based on Boundary Fitting Method (BFM). The dimensionless frequency of pulsating velocity (at a form of Strouhal number) and oscillation amplitude are studied at a wide range ($0.05 \leq St \leq 1$ and $0 \leq A_{pulse} \leq 0.25$) which $A_{pulse} = 0$ represents the steady constant flow. The study is carried out for different Reynolds numbers (50, 100 and 150) when the Prandtl number is equal to 3.103. Temporal variations of streamlines, isotherms, and relative pressure drop and Nusselt number are presented for appropriate dimensionless groups. Also, the time-averaged values of Nusselt number and relative pressure drop along a pulse period time are calculated and presented in the form of relevant correlations aspect to the Strouhal number. The results show that the role of flow pulsation on the heat transfer enhancement on the target surface is highly dependent on pulsating velocity parameters. It is found that the variation of heat transfer rate according to Strouhal number has an extremum peak. In this extremum value pulsating velocity gradient has best effects on heat transfer rate and heat transfer rate start to drop for higher frequencies.

1. Introduction

Pulsating flow through the different geometrical conditions is of general interest in various scientific fields [1–4]. At engineering point of view, heat transfer under pulsating flow is often found in different industrial applications. Usage of pulsate flow in cooling system of gas turbine engines, Sterling engines and in mini or macro scale engineering problems such as electronics devices emphasizes on the importance of pulsating flow in modern industrial purposes. The flow of convective coolant in nuclear power systems in ocean environments pulsates periodically. Therefore, pulsating flow and its heat transfer play an important role on thermal hydraulic analysis and safety evaluation of nuclear reactors [5].

Carpinlioglu and Gundogdu [6] presented a widespread review on the pulsating flow in the thermal engineering. Their research points out that the reverse effects of a pulsating flow on the flow and heat transfer are confusing at different problem domains. In last decades, transport phenomena of flow development and heat transfer in channels and ducts under pulsating flow condition were investigated entirely [7–10]. Nield et al. [7] investigated laminar forced convection in a channel under pulsating flow using perturbation method. 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. At an experimental and theoretical work, Shahin [8] investigated the heat transfer in a tube and also in a concentric annulus tube. His presented results show that pulsation of flow has about 25% enhancement in heat transfer for certain frequencies of the pulsate inlet. Besides, it was demonstrated that at higher frequencies the heat transfer starts to reduce. Conversely, Chattopadhyay et al. [9] did a numerical analysis on 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 rang of frequency and pulsate amplitude. Rahgoshay et al. [10] did a numerical effort on pulsating flow of nanofluids through an isotherm pipe. They investigated a range of different parameters such as pulse amplitude, Strouhal and Reynolds numbers, they revealed that increase of the frequency and amplitude of pulsating inlet flow lead to a slight increase in heat transfer rate. Although, they are many researches [11,12] which were conducted to study oscillating flow effects on convection heat transfer in different geometries, a lack of more needed studies to explore the comprehensive details of flow pulsation effects in other applicable convectional ducts can be sensible.

Processes of heat transfer Enhancement by affecting the flow characteristics have been treated in many studies as an important goal [13–16]. It is important to make heat transfer enhancement using specific geometric characteristics or special inlet flow conditions without applying active forcing. At geometrical point of view, a large part of studies performed corrugated, grooved and communicating channels to enhance heat transfer rate. In these geometries, the existence of self-sustained instabilities can develop flow oscillations which augment the convection rate. The corrugated wall channel is one of

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Nomenclature

A_w	Amplitude of corrugated wall
A_{pulse}	Amplitude of velocity oscillation
f, g	Distribution function
K	Thermal conductivity $(W.\ m^{-1}.\ k^{-1})$
L	Characteristic Length (m)
Nu	Nusselt number
Pr	Prandtl number (ν/α)
Re	Reynolds number $(u_{ave}.\ L/\nu)$
St	Strouhal number $\left(\mathrm{St} = \frac{\vartheta L}{u^*_{ave}}\right)$
T	Dimensionless temperature $\left(T = \frac{T^* - T^*_w}{T^*_{in} - T^*_w}\right)$
t_p	Dimensionless period time $\left(t_p = \frac{1}{St}\right)$

Greek symbols

α	Discrete lattice direction
ϑ	Dimensional frequency $(Hz \approx s^{-1})$
P	Dimensionless Pressure drop $\left(\frac{P}{\rho u^2_{ave}}\right)$
Δt	Lattice time step
ω	Dimensionless angular frequency $(\omega = 2\pi.\ St)$
κ	Number of applied pulse periods

Subscripts

ave	Average
f	Fluid
in	Inlet
rel	Relative variables
w	Wall

Superscript

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

several devices utilized to enhance the heat transfer efficiency of industrial transport processes. The wavy corrugation channels are used in industrial and engineering applications, such as compact heat exchangers, oxygenators, hemo-dialyzers, solar collectors and wavy condensers in refrigerators. These channels are mainly attractive for their simplicity of produce and potential to provide significant heat transfer enhancement if operated in an appropriate conditions [17–23]. The changes in flow mixing, the disruption and thinning of boundary layer may cause to enhance heat and mass transfer. Despite flows with high Reynolds number, the early researches presented adverse results for heat transfer enhancement at low Reynolds number flows. First time Burns and Parks [17] analytically investigated the problem of viscous flow in wavy channels. After that, heat transfer characteristics of laminar, transitional, and low Reynolds number turbulent flow in a corrugated channel were studied experimentally by Goldstein and Sparrow [18]. They showed that for a laminar flow even at a high Reynolds number (Re = 1000–1200), convection rate was only moderately larger than those for a flat channel. On other hand, they obtained a triple enhancement in the average heat transfer in the turbulent regimes (Re = 6000–8000) at comparison of flat-plate channels. Wang and Vanka [19] investigated the rates of heat transfer through a periodic array of wavy passages. They reported that in the steady regime, the average Nusselt numbers for the wavy-wall channel were just a little larger than average Nusselt number of the flat channel, however for the transitional regime, the enhancement of heat transfer had remarkable value about 2.5. At a numerical and experimental study for a laminar convectional flow in a symmetric triangular wavy channel, Sparrow and Prata [20] reported that the wall waviness has no enhancement on heat transfer with Reynolds number up to 1000. Metwally and Manglik [21] investigated periodically developed laminar flow and heat transfer in wavy channels, they found that wall waviness induces steady flow recirculation or lateral vortices in the furrow regions of the corrugated channel, an increase of wavy wall amplitude increases the strength of these vortices which lead to substantial heat transfer enhancement in comparison with flows in a flat channel. Rahimi-Esbo et al. [23] numerically investigated the turbulence flow in a two-dimensional confined sinusoidal converging jet. They reveal that the bending walls can improve heat transfer by changing of the flow behavior.

Through this brief literature review, there is conflicting evidence with regards to the effects of pulsating flow on the heat transfer from convectional channels or tubes. Also, as presented, the wavy channels have inconsistent effects on heat transfer enhancement in laminar steady regimes. Beside of this fact that the convection problem of the corrugated channels had been studied comprehensively in the past, to the best of author knowledge, heat transfer enhancement at presence of pulsating flow in this kind of convectional devices is still a perspective which is not understood heretofore. Therefore the investigation of flow pulsation effects on heat transfer from the wavy corrugated channel is one of the major tasks of the current research.

Considering the explicit nature of Lattice Boltzmann Method, this method is selected to simulate unsteady pulsating flow over a channel bound by two sinusoidal corrugated walls at the present study. The progress of using the Lattice Boltzmann Method (LBM) as a powerful numerical technique to simulate the heat transfer and fluid flow has been obvious in the last decade [24–28]. The Lattice Boltzmann Method (LBM) has well-known advantages such as easy implementation, possibility of parallel coding and simulating of complex geometries. The Boundary Fitting Method (BFM) is applied to deal with curved boundaries of wavy walls in LBM.

The studied geometry is the same as that earlier investigated by Wang and Chen [22]. The effects of various parameters of oscillating flow such as pulsating amplitude ($0.05 \le A_{Pulse} \le 0.25$) and dimensionless oscillating frequency at form of Strouhal number ($0.05 \le St \le 1$) on flow and temperature fields are investigated in details for different Reynolds numbers at range of 50 to 150. 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 variation of Nusselt number and pressure drop aspect to Strouhal number are derived considering curve fitting of obtained results. Also, the results of pulsating flow are compared with those obtained for steady constant flow at same Reynolds number.

2. The Lattice Boltzmann Method

2.1. Flow and thermal fields

The basic form of the Lattice Boltzmann Equation with an external force by introducing BGK approximations can be written as follows for the both flow and the temperature fields [24]:

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

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

where $f_\alpha(x,t)$ is a distribution function at the mesoscopic level. Here $c = \Delta x/\Delta t$ is a streaming speed where Δx and Δt are the lattice cell size and the lattice time step size, respectively. While e_α is the discrete lattice velocity in direction α. Also, τ_m and τ_t are the dimensionless