International Communications in Heat and Mass Transfer 96 (2018) 27–36

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Effects of the geometric parameters on the thermal-hydraulic performance of the wavy tubes

Samaneh Arman, Rahim Hassanzadeh*

Department of Mechanical Engineering, Urmia University of Technology, Urmia, Iran

ARTICLE INFO

Keywords:
Heat transfer enhancement
Wavy tube
Dean vortices
Wave amplitude
Wavelength

ABSTRACT

This research presents details of heat and fluid flow inside the wavy tubes with circular cross-sections at laminar regime under the Reynolds numbers in the range of 100 and 1000. To enhanced visualization, effects of non-dimensional geometric parameters such as the wave amplitude (H/D) varying between 0.1 and 0.5 and the wavelength (P/D) varying from 4 to 6 on the heat transfer process and flow nature are investigated in detail. The obtained results are validated against the available data in the literature. It is concluded that due to development of the centrifugal forces inside the wavy passage, a pair of Dean vortices appearances within the tube. The size of these vortical structures is strongly affected by the Reynolds number and geometric parameters of the wavy tube. On the other hand, at all Reynolds numbers under consideration, increasing the H/D and P/D enhances and diminishes the rate of heat transfer between the fluid flow and tube wall, respectively. Moreover, it is demonstrated that at low Reynolds numbers, the pressure drop penalty outweighs the heat transfer enhancement. It is found that the maximum thermal-hydraulic performance occurs in the case of H/D = 0.5, P/D = 6, and Re = 1000 with 42%.

1. Introduction

Heat transfer enhancement in the pipe flow has been the major challenge for thermal designers to date. Several passive and active methods have been proposed in order to increase the pipe heat transfer rate with a reasonable pressure drop penalty. Some methods such as the use of the extended surfaces with various shapes and dimensions [1–4], inserting the tabulators and winglets in the pipes [5–8], suspending the nanoparticles in the working fluid [9–15] and utilization of the corrugated tubes [16–20] are more attractive for engineers among the proposed methods in practice. The main impact of such improvements is related to the space and material saving, reducing the size of the systems, and reduction in the initial and ongoing costs. As a kind of the passive methods, wavy passages have been investigated widely in order to enhance the heat exchange rate in channel flows. Xie et al. [21] investigated the heat and fluid flow inside a wavy passage using a numerical approach. Computations were performed at various Reynolds numbers ranging from 100 to 1100 under constant Prandtl number of 0.7. They concluded that increasing the wave height and decreasing the wave pitch increase the friction factor and overall Nusselt number. Akbarzadeh et al. [22] utilized various profiles for wavy passages such as the sinusoidal, trapezoidal, and triangular shapes in order to obtain the heat transfer and pressure drop within the passages at Re = 400–1400. They recommended the sinusoidal profile in comparison to the other shapes due to higher thermal performance and lower entropy generation. Mills et al. [23] used the lattice Boltzmann method to study the laminar flow inside an asymmetric sinusoidal channel. They reported some valuable results. For example; they stated that although the wavy passages provide considerable heat transfer augmentation, however, this increase in the heat exchange rate should be considered with increased pressure losses. In addition, in steady state flow condition, increasing the pressure drop outweighs the heat transfer enhancement leading to the thermal-hydraulic performance less than that of the straight passage. On the other hand, under the unsteady condition, at low wave amplitudes, this performance is greater than that of the straight channel. Moreover, at large amplitude of the wavy channel, the performance is worse in comparison to the straight passage. In a work performed by Ramgadia and Saha [24] about the heat and fluid flow in an asymmetric wavy channel, it was demonstrated that the maximum thermal performance was achieved for $\alpha = 0^{\circ}$ (α is the phase angle of the upper and lower plates). In a similar research with the same authors [25], it was found that for wavy channels with $H_{min}/H_{max} = 0.4$ (H_{min} and H_{max} are the minimum and maximum heights between two wavy walls, respectively) the critical Reynolds number was between 350 and 400.

Fluid flow in a curved passage provides an additional feature of so-

* Corresponding author.
E-mail addresses: samaneh.arman@mee.uut.ac.ir (S. Arman), r.hassanzadeh@uut.ac.ir (R. Hassanzadeh).

https://doi.org/10.1016/j.icheatmasstransfer.2018.05.012

called secondary flow as a result of the centrifugal forces, which lead to the development of counter-rotating vortices in the cross-stream plane. This secondary flow, although increases the pressure loss in a passage, however, it has some benefits such as the heat transfer enhancement due to providing a higher rate of the flow mixing within the passage.

In 1928, the analytical solution of Dean [26] showed this secondary flow in a curved pipe. His study illustrated that a pair of counter-rotating vortices is generated in the cross-stream plane which called Dean's vortices. The key parameter in such problems is the Dean number which was used widely in several investigations. Rosaguti et al. [27] studied the laminar flow and heat transfer in a periodic serpentine channel with a semi-circular cross-section for various Prandtl number in the range of 0.7 and 100 under two different wall boundary conditions such as the constant heat flux and temperature. They performed their study at various Reynolds numbers between the 5 and 450. It was stated that convective heat transfer increases with increasing the Prandtl number. In addition, increasing the wavelength and radius of the curvature decrease the heat transfer and pressure loss in the under consideration channel. In a research performed by Sui et al. [28] on the periodic wavy channel with a rectangular cross-section, it was concluded that the patterns of Dean vortices change considerably along the streamwise direction. Furthermore, it was illustrated that the pressure drop penalty of a wavy channel can be much smaller than the heat transfer augmentation. Pham et al. [29] examined the turbulent heat and mass transfer in the sinusoidal wavy channels using the large eddy simulation at $750 \leq Re \leq 4500$. The ratio of wall spacing to the wave amplitude and the ratio of wave amplitude to the wavelength were analyzed in this numerical work. Computations were performed for water flow ($Pr = 7.0$) and several results have been obtained in their study. They showed that although the flow unsteadiness is occurred at whole Reynolds number, no turbulent regime is detected at $Re \leq 1500$. They also reported that the turbulence pattern strongly depends on the ratio of wall spacing to the wave amplitude. Khoshvaght-Aliabadi et al. [30] presented a numerical work on the laminar alumina-water nanofluid flow inside a mini-wavy channels having different cross-sections such as square, rectangular, rhombic, triangular, hexagonal, trapezoidal, circular, and semi-circular shapes at various Reynolds numbers ranging from 300 to 1500. It was reported that compared with the straight mini-channel, the maximum ratio of the heat transfer to the pumping power of the water flow occurs in the mini-wavy channel with hexagonal and square cross-sections.

Examination of the wavy channels in micro size is also of interest among the researchers. For instance, Sui et al. [31] and Dai et al. [32] demonstrated that the existence of the Dean vortices in micro-wavy channels increases the chaotic mixing of the fluid and therefore, the overall heat transfer performance increases considerably with a much smaller pressure drop penalty. Abed et al. [33] performed a combined numerical and experimental work about the importance of the Dean number on the heat and fluid flow of the mixtures of glycerine-water as working fluids in a micro-scale serpentine channel. They found that both heat transfer and pressure drop increase as a function of the Dean number. However, enhancement of the heat transfer is more considerable than that of the pressure drop.

Examination of the previously published works indicates that the thermal-hydraulic performance of the wavy tube has not been investigated sufficiently due to existence of various geometric and non-geometric parameters in this issue. The wavy tubes with circular cross-section can be found many different applications due to not only the higher thermal-hydraulic performance in comparison to the straight tubes, but also for their benefits in the fouling formation period, which is one of the main problems in various applications such as the heating and cooling systems, chemical and petrochemical plants, heat exchangers, and the other similar industries. Therefore, it seems, having the enough knowledge about the wavy tubes is essential for engineers in various working fields. This paper provides details of the quantitative and qualitative information about the heat and fluid flow inside the wavy tubes with the circular cross-section in laminar regime in which effects of wavelength, wave amplitude, and the Reynolds number are investigated. It was hoped that the obtained results in this study arouse interest among the engineers in general and thermal designers in particular.

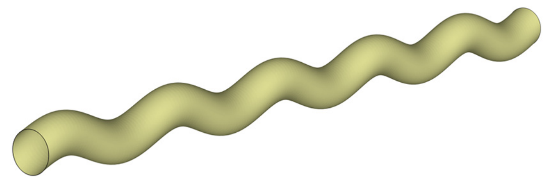

Fig. 1. A wavy tube with circular-cross section.

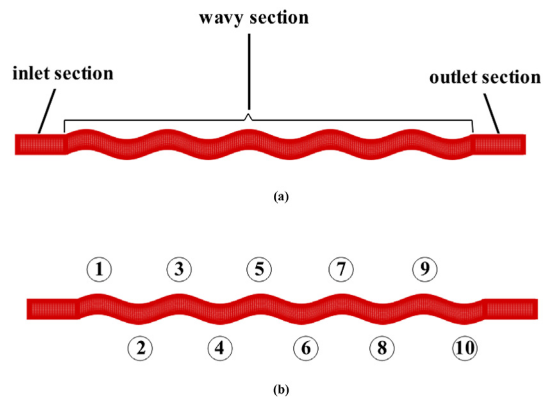

Fig. 2. (a) The physical flow domain considered in the present study; (b) Waves ID.

2. Problem description and numerical procedure

In the present study, the wavy tubes with various wavelengths and wave amplitudes are modeled using the computational fluid dynamics (CFD) technique. Fig. 1 shows a sample wavy tube with the circular cross-section. For this purpose, a physical flow domain as Fig. 2 (a) is designed for wavy tube with sinusoidal profile. The applied computational domain consists of three various sections; namely an incoming straight section ($L_i = 2.5D$), a main wavy section with ten waves in all cases (L_w), and an outlet straight section ($L_o = 2.5D$). Fig. 2 (b) identifies each wave with a separate number. Three different non-dimensional wavelengths such as P/D = 4, 5, and 6 and three various non-dimensional wave amplitudes of H/D = 0.1, 0.25, and 0.5 are examined in this study in order to reveal the effects of geometric parameters on the thermal-hydraulic performance of wavy tubes. On the other hand, heat and fluid flow is studied at several Reynolds numbers in the range of 100 and 1000 based on the mean velocity and tube diameter. All computations are carried out for water flow ($Pr = 7.0$).

The governing equations of the under consideration problem of laminar and steady flow are as follows;

- Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

- Momentum equations:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \upsilon\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$