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Original Research Paper

Numerical investigation and optimization of flow and thermal characteristics of nanofluid within a chaotic geometry

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ABSTRACT

In this study, hydrothermal characteristics of the water–TiO_2 nanofluid are evaluated in the rectangular C-shaped chaotic channel by applying the two-phase Euler–Lagrange method. The results show that the fluid temperature distribution in the C-shaped channel is much more uniform than that in the straight rectangular channel due to the intense mixing in the chaotic geometry. By increasing the concentration and reducing the particle size, both convective heat transfer and pressure drop increase in the chaotic channel. For finer particles, due to more intense particle migration related to the Brownian motion, more uniform concentration distribution is obtained at the channel cross section. The model of mean convective heat transfer coefficient and pressure drop in terms of concentration and particle size was developed by neural network. In order to obtain some cases of the variables (i.e. size and concentration of nanoparticles) in which maximum heat transfer along with minimum pressure drop occurs, optimization on neural network model was implemented using methods of two-objective as well as single-objective (i.e. genetic algorithm coupled with compromise programming decision making method). Eventually, optimum cases were suggested for different importance levels of objective functions.

1. Introduction

In recent years, besides attention to improvement in heat transfer rate, miniaturization of heat transfer systems has been of considerable interest, since it can have numerous applications in various fields such as micro-chemical processing, compact heat exchangers, electronic cooling, and solar heat collectors. Regarding the fact that the more mixing in the flow, the higher heat transfer rate, many studies in the field of creating disturbance in the flow have been carried out by using different approaches [1–3]. One of the methods that have drawn great attention for increasing mixing in laminar flows is to make modifications in geometry for creating chaotic advection. Some researchers have studied chaotic flow and heat transfer in various kinds of tortuous channels. Sui et al. [4] numerically studied flow and heat transfer in periodic wavy channels with rectangular cross sections. They found that the patterns of Dean vortices may evolve along the flow direction, thus leading to chaotic advection which can greatly enhance the convective fluid mixing and heat transfer. Castelain et al. [5] experimentally studied the chaotic advection regime in a twisted duct flow. They demonstrated that Dean roll-cells, generated by centrifugal forces and the geometrical perturbation due to the change in curvature plane, are the source of the irregular trajectories of the fluid particles. Liu et al. [6] visualized the flow in a three-dimensional serpentine microchannel design with a C-shaped repeating unit. Their experimental results show the occurrence of chaotic advection in the serpentine micromixer. Lasbet et al. [7] evaluated the zigzag and C-shaped channels as alternatives to the simple straight channel in present heat exchangers integrated in the bipolar plate of a PEMFC stack. They demonstrated that both Nusselt number and pressure drop increase in the C-shaped channel.

Recent development in the field of nanotechnology and nanoparticles has led to the production of a new group of suspensions, called nanofluid, which has particularly attracted the researchers' attention in recent decade. Nanofluid is made by adding nanoparticles (with dimensions of 1–100 nm) to a base fluid. The first study on suspensions contained nanoparticles was performed by Masuda et al. [8] in 1993, but the term "nanofluid" for this group of suspensions was first assigned by Choi [9] in 1995. After these two studies, a great deal of research and studies have been conducted on nanofluids, which altogether show that adding nanoparticles to a base fluid can significantly improve its heat

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transfer characteristics [10–13]. In many implemented numerical studies, nanofluids have been considered as a homogenous (single-phase) fluid [14,15]. But in fact, nanofluid is a two-phase medium and considering it as a homogenous fluid may cause error in the results. In case of using two-phase methods, interaction between fluid and particles, heat transfer between them, slip velocity and so on can be considered. Haghshenas Fard et al. [16] showed that two-phase methods provide more accurate results than single-phase approach. Limited studies using two-phase methods have been carried out thus far, most of which have used the two-phase mixture method and a few have used the two-phase Euler–Lagrange method [17,18].

The studies that have been implemented on flow and heat transfer in chaotic geometries so far have been limited to the use of conventional fluids, such as pure water, the poor thermal properties of which can cause limitations in both heat transfer improvement as well as thermal systems miniaturization. In case of simultaneous implementation of nanofluids and chaotic geometries, the advantages of both approaches can be exploited in the direction of heat transfer augmentation and also thermal systems miniaturization. For this purpose, in the present study, flow and heat transfer of the water–TiO_2 nanofluid are studied in the chaotic C-shaped channel using the two-phase Euler–Lagrange method. The effects of parameters such as concentration and size of nanoparticles are evaluated. Eventually, optimization methods are employed to obtain optimal cases with maximum heat transfer and minimum pressure drop. To the best of our knowledge, this is the first study in the literature that optimizes the hydrothermal characteristics of nanofluids in a chaotic geometry.

2. Definition of geometry

The geometry under study is a C-shaped chaotic channel that was first introduced by Liu et al. [6]. The name "C-shaped" is used to define the channel due to its special geometry. Beebe et al. [19] showed that in this geometry, fluid particles move in chaotic paths. In fact, existence of geometrical perturbations causes chaotic advection which makes intense mixing in the fluid and hence, can increase heat transfer. Using chaotic geometries is rather effective, particularly for laminar regimes in which mixing is very poor in the flow.

Simulations are conducted on five repeating periods of this geometry one of which is shown in Fig. 1a. For the purpose of comparison, numerical solutions are also performed for a simple straight channel (Fig. 1b). The cross section at the inlet of both channels is rectangular with 1.33 mm hydraulic diameter, 1 mm height, and the aspect ratio of 2. Unfold length of a period of the C-shaped channel is 18 mm and the length of the simple channel is 80 mm.

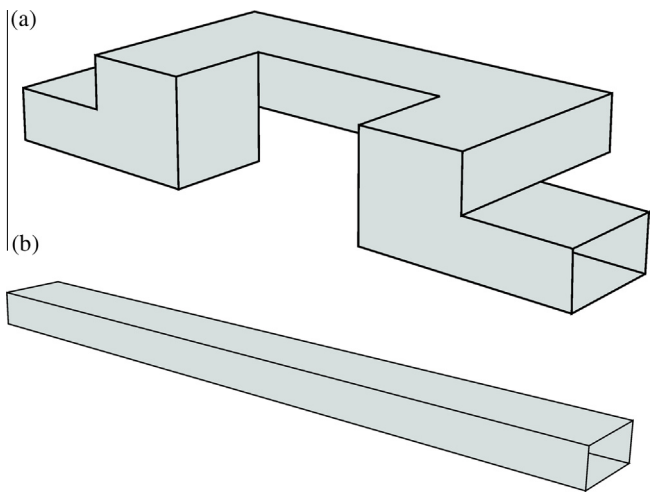

Fig. 1. Geometries under study: (a) C-shaped chaotic channel; and (b) straight channel.

3. Two-phase Eulerian–Lagrangian approach

In this approach, the fluid is considered as a continuous phase with the particles dispersed inside it. The interaction between particles and fluid is introduced as source terms in momentum and energy equations. Consequently, the conservative equations for the continuous phase would be written as below:

Continuity equation:

$$\nabla \cdot (\rho_f \mathbf{v}_f) = 0 \tag{1}$$

Momentum equation:

$$\nabla \cdot (\rho_f \mathbf{v}_f \mathbf{v}_f) = -\nabla P + \nabla \cdot (\mu_f \nabla \mathbf{v}_f) + \mathbf{S}_{p,m} \tag{2}$$

Energy equation:

$$\nabla \cdot (\rho_f c_{p,f} \mathbf{v}_f T_f) = \nabla \cdot (k_f \nabla T_f) + S_{p,e} \tag{3}$$

where ρ is density, k represents thermal conductivity, c_p is specific heat and μ denotes dynamic viscosity. Moreover, $\mathbf{v}$, T and P represent velocity, temperature and pressure, respectively. Subscript f refers to base fluid. In addition, the source terms of $\mathbf{S}_{p,m}$ and $S_{p,e}$ respectively denote the momentum and the energy transfer between the fluid and particles. They are defined as below [20]:

$$\mathbf{S}_{p,m} = \sum n_p \frac{m_p}{\delta V} \mathbf{F} \tag{4}$$

$$S_{p,e} = \sum n_p \frac{m_p}{\delta V} c_p \frac{dT_p}{dt} \tag{5}$$

where subscript p refers to particle, m_p and $\mathbf{F}$ respectively denote mass of the particle and total force per unit mass of the particle acting on it, δV represents the cell volume and n_p is the number of solid particles within a cell volume.

The total force (i.e. $\mathbf{F}$) in Eq. (4) is comprised of body forces and various hydrodynamic forces which includes the effects of drag force, Saffman's lift force, thermophoretic force, Brownian force and gravity force.

$$\mathbf{F} = \mathbf{F}_D + \mathbf{F}_L + \mathbf{F}_T + \mathbf{F}_B + \mathbf{F}_G \tag{6}$$

The drag force, i.e. $\mathbf{F}_D$, can be obtained from different formulas. For sub-micron particles, a form of Stokes' drag law can be used [21]. In this case, $\mathbf{F}_D$ is defined as:

$$\mathbf{F}_D = \frac{18\mu_f}{d_p^2 \rho_p C_c} (\mathbf{v}_f - \mathbf{v}_p) \tag{7}$$

where d_p represents the diameter of nanoparticles, and C_c is Cunningham correction factor to Stokes' drag law which can be evaluated from:

$$C_c = 1 + \frac{2\lambda}{d_p} (1.257 + 0.4 \exp(-1.1 d_p / 2\lambda)) \tag{8}$$

where λ is molecular mean free path.

The Saffman lift force ($\mathbf{F}_L$) is caused by pressure distribution developed on the particle due to the rotation induced by a velocity distribution [22].

$$\mathbf{F}_L = \frac{2K_s \upsilon^{1/2} \rho_f d_{ij}}{\rho_p d_p (d_{ij} d_{ij})^{1/4}} (\mathbf{v}_f - \mathbf{v}_p) \tag{9}$$