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Numerical simulation of nanofluid application in a C-shaped chaotic channel: A potential approach for energy efficiency improvement

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ABSTRACT

This study aims to evaluate the energy efficiency of nanofluid as a heat transfer fluid in a chaotic channel. To this end, hydrothermal characteristics of the water–Al_2O_3 nanofluid are numerically investigated in C-shaped and straight channels using single- and two-phase methods and then, the results are compared with each other. In the C-shaped channel, heat transfer and pressure drop show higher values in comparison with the straight channel, which is due to intense mixing in the chaotic geometry, such that the velocity and temperature contours in the C-shaped channel are more uniform than those in the straight one. Using the two-phase method, the concentration distribution is obtained non-uniform at the cross section of the straight channel, while intense mixing in the C-shaped channel makes distribution of the nanoparticles uniform. In comparison with water, using the nanofluid through both channels presents higher heat transfer and pressure drop. However, merit of using the nanofluid in the C-shaped channel is greater than that in the straight one. In this regard, simultaneous application of nanofluids, as heat transfer fluids, and chaotic channel, as a modified geometry, can result in not only higher energy efficiency, but also preventing nanoparticles agglomeration due to the intense mixing.

1. Introduction

Taking into account the recent industrial advancements and the demanding need for high efficiency thermal systems, numerous efforts have been made to improve heat transfer. In this regard, several researchers have studied different methods such as using various fins and baffles [1] as well as vortex generators [2]. In thermal systems like heat exchangers, the rate of heat transfer increases by intensifying mixing in the flow. One method that has gained many researchers' attention in the recent years is creation of chaotic advection in a flow. In this method, it is tried to enhance mixing in the flow and thus the heat transfer by making geometrical perturbations. Various geometries have been examined for this purpose. Castelain et al. [3] experimentally studied the chaotic advection in a twisted duct flow. They demonstrated that Dean roll-cells, generated by centrifugal forces and the geometrical perturbation, are the source of the irregular trajectories of the fluid particles. Zheng et al. [4] investigated laminar flow and heat transfer in periodic zigzag channels with square cross-sections, considering the effect of chaotic advection. They concluded that heat transfer enhances highly in the regions where strong Dean vortices occur. Liu et al. [5] visualized the flow in a serpentine microchannel with a C-shaped repeating unit for the first time. Their results suggest the occurrence of chaotic advection in the serpentine micromixer. Lasbet et al. [6] evaluated the zigzag and C-shaped channels as alternatives to the 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.

In addition to geometry, thermal properties of the fluid also have a significant effect on heat transfer phenomenon. By development of nanotechnology, a new set of fluids, called nanofluids, has been introduced which is obtained by suspension of nanoparticles in a base fluid. Despite some contradictions in different studies, an overall review of the literature shows that addition of nanoparticles to a liquid may improve its thermal properties significantly. Several studies have been conducted on flow and heat transfer characteristics of nanofluids in various geometries. Kazemi-Beydokhti and Heris [7] investigated the application of nanofluids in combined heat and power system and the results demonstrated that using nanofluids enhances the thermal performance of the system. Bahiraei et al. [8] evaluated the hydrothermal characteristics of water–Al_2O_3 nanofluid in a narrow annulus. They demonstrated that smaller particles and higher concentrations

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Nomenclature

C_c	Cunningham correction factor to Stokes' drag law
c_p	specific heat (J/kg K)
d_f	molecule size of base fluid (nm)
d_{ij}	tensor of deformation (m/s)
d_p	nanoparticle diameter (nm)
$\mathbf{F}$	force per unit mass (N/kg)
h	convective heat transfer coefficient (W/m^{2}K)
k	thermal conductivity (W/mK)
k_B	Boltzmann constant (J/K)
Kn	Knudsen number
m_p	mass of particle (kg)
n_p	number of solid particles within a cell volume
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
s	direction of curvilinear coordinate
$S_{n,ij}$	spectral intensity (m^2/s^3)
$S_{P,e}$	energy source term (W/m^3)
$\mathbf{S}_{\mathbf{P,m}}$	momentum source term (kg/m^{2}s^2)
T	temperature (K)
t	time (s)
$\mathbf{v}$	velocity (m/s)
V	volume (m^3)
V_B	Brownian velocity (m/s)
W	pumping power (W)
x	axial direction

Greek letters

α	thermal diffusivity (m^2/s)
δ	distance between particles (nm)
$\delta_{i,j}$	Kronecker delta function
λ	molecular mean free path (nm)
μ	dynamic viscosity (kg/ms)
ν	kinematic viscosity (m^2/s)
ξ_i	unit-variance-independent Gaussian random number
ρ	density (kg/m^3)
φ	concentration

Subscripts

f	fluid
nf	nanofluid
p	particle

cause greater heat transfer coefficients. Mahian et al. [9] analytically studied the entropy generation due to flow and heat transfer of nanofluids between co-rotating cylinders with constant heat flux on the walls. They concluded that TiO_2–water nanofluid is more suitable than Al_2O_3–EG nanofluid to be used as the working fluid. Peyghambarzadeh et al. [10] experimentally investigated convective heat transfer of nanofluid as compared to that of water in an automobile radiator and observed 45% enhancement in heat transfer efficiency. Saidi and Karimi [11] assessed free convection cooling in an L-shaped enclosure filled with copper–water nanofluid. They showed that for all ranges of Rayleigh number, increasing the volume fraction of the Cu nanoparticles enhances the heat transfer coefficient.

Considering the fact that traditional thermal management methods cannot meet the incremental advancement in industries, and also the great potential of nanofluids for heat transfer improvement, more research and studies in this field are strongly felt, especially on their application in different thermal systems that can be used in various industries. Having this in mind as well as numerous applications of chaotic geometries in heat transfer systems such as proton exchange membrane fuel cells and heat exchangers, this investigation aims to apply both single-phase and two-phase Eulerian–Lagrangian approaches in order to numerically study the hydrothermal characteristics of the water–Al_2O_3 nanofluid through a C-shaped chaotic channel and compare the results with the conventional straight channel. According to the best knowledge of authors, no study has been implemented on the flow and heat transfer characteristics of nanofluids in these modified and practical geometries. Such investigations can not only give us the comprehensive insight into nanofluids behavior, as modern heat transfer fluids, but also prepare the ground for achieving practical models to be used in various industries in which there is a pressing demand for efficiency improvement of thermal systems.

2. Definition of geometries

One reason for low heat transfer rate in laminar flows is the poor mixing in these conditions in comparison with turbulent flows. This disadvantage can be solved by creating chaotic advection in the flow with the help of the geometrical perturbations. The geometry in this study includes a C-shaped chaotic channel that was introduced by Liu et al. [5] for the first time. Beebe et al. [12] showed that the fluid particles in this geometry would reveal chaotic trajectories. Chaotic trajectories in the flow can intensify the mixing [3] and eventually lead to heat transfer improvement. Simulations were performed on five repeating periods of this geometry one of which is depicted in Fig. 1b. The term "C-shaped" is used to describe the channel due to its special geometry. For the purpose of comparison, simulations were also conducted for a straight channel (Fig. 1a). Cross section at the inlet of both channels is a rectangular with 1 mm height, 1.33 mm hydraulic diameter and aspect ratio of 2. Unfold length of a period of the C-shaped channel is 18 mm and length of the straight channel is 80 mm.

3. Numerical approaches

Two different approaches of single-phase and two-phase Eulerian–Lagrangian were utilized in numerical simulation.

3.1. Single-phase approach

In the single-phase approach, the nanofluid is considered as a homogeneous fluid, while the effective properties are used in the

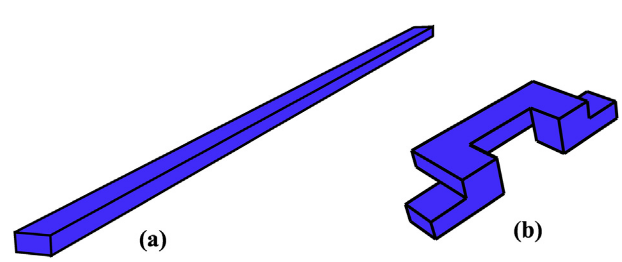

Fig. 1. Geometries under study: (a) straight channel; (b) C-shaped chaotic channel.