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Research paper

Heat transfer enhancement by combination of chaotic advection and nanofluids flow in helically coiled tube

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HIGHLIGHTS

- Nanofluids in a chaotic coil were investigated for heat transfer improvement.
- Chaotic flow with water was more efficient than normal coil with nanofluids.
- Nanofluid in chaotic flow resulted in significant enhancement of heat transfer.
- Heat transfer improvement increased with higher concentration of nanoparticles.

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ABSTRACT

In this study, two passive techniques are simultaneously investigated for heat transfer improvement (i.e. chaotic advection and nanofluids) in coiled heat exchangers. Performance of these two different coils (one with normal configuration and another with chaotic configuration) is numerically analyzed and compared for both water and nanofluid as fluid. Effects of different parameters such as geometry, types of nanofluids, nanoparticle volumetric concentration and Reynolds number on heat transfer and pressure drop are studied. The CuO and Al_2O_3 base water nanofluids with different nanoparticle concentrations 1–3% were simulated. Equations of conservation of mass, momentum and energy were discretized using a finite element based technique and were solved using ANSYS software. Numerical results showed that heat transfer in the chaotic coil with water as fluid was higher than that in the normal coil with nanofluids at various volumetric concentrations and addition small amount of nanofluid in the chaotic coil flow resulted in significant enhancement of heat transfer.

1. Introduction

In recent decades, many attempts have been undertaken for making efficient heat exchanging instruments in order to save energy and raw materials and consider economic and environmental issues. The main purpose has been to reduce size of the required heat exchanger for a specific heat load and also increase capacity of the existing one.

Convective heat transfer could be enhanced by increasing heat transfer area, mixing or thermal conductivity. Chaotic advection, which is production of chaotic particle paths in the laminar regime, is a passive technique for increasing heat transfer. Increase in mixing and heat transfer in the chaotic advection regime compared to the regular flow has been already established [1]. Chaotic mixing improves heat transfer by reducing temperature gradients and temperature profiles become more uniform. A signature of chaotic flows is that they are characterized by rapid divergence of fluid particles with close initial conditions. Stretching and folding exponentially increase in the chaotic flow and mixing is significantly enhanced [2]. Chaotic mixers fall into one of two categories: 1) active mixers [3–6] that use moving parts and 2) passive mixers [7,8] that utilize no energy input.

Chaotic coil flow is one of the passive mixers which has been addressed by Jones et al. [9], Acharya et al. [10,11], Mokrani et al.

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Nomenclature

C_1	constant
C_2	constant
C_3	constant
C_4	constant
$C_{p,w}$	water specific heat [J kg^{-1} K^{-1}]
d	coil pipe diameter [m]
d_{np}	diameter of nanoparticle [m]
f	friction factor
f_{nf}	friction factor of nanofluid
f_w	friction factor of water
h	convection heat transfer coefficient [W m^{-1} K^{-1}]
h_w	convective heat transfer coefficient of water [W m^{-1} K^{-1}]
h_{nf}	convective heat transfer coefficient of nanofluid [W m^{-1} K^{-1}]
k	constant
k_w	water thermal conductivity [W m^{-1} K^{-1}]
k_{np}	nanoparticles thermal conductivity [W m^{-1} K^{-1}]
k_{nf}	nanofluid thermal conductivity [W m^{-1} K^{-1}]
P	pressure [Pa]
q_w	heat flux [W m^{-2}]
Re	Reynolds number
T	fluid temperature [K]
T_0	constant temperature [K]
T_w	wall temperature [K]
T_b	fluid bulk temperature [K]
u	fluid velocity [m s^{-1}]
U_m	mean velocity [m s^{-1}]
β	Brownian motion coefficient
β_2	Brownian motion constant
β_1	Brownian motion constant
ε_1	constant for Brownian motion
ζ_1	constant
ζ_2	constant
μ_w	water viscosity [Pa s]
μ_{nf}	dynamic viscosity of the nanofluid [Pa s]
ρ	fluid density [kg m^{-3}]
ρ_{nf}	nanofluid density [kg m^{-3}]
ρ_{np}	nanoparticles density [kg m^{-3}]
ρ_w	water density [kg m^{-3}]
τ_w	shear stress on the wall [Pa]
φ	cylindrical coordinate
Φ	particle volumetric concentration [%]

[12], Castelain et al. [13,14], Changy et al. [1], Kumar and Nigam [15,16], Kumar et al. [17], Vashisth and Nigam [18] and Yamagashi et al. [19]. Normal coil flow generates a pair of vortices called Dean-roll-cells due to centrifugal force. Fluid particles could not escape from Dean-roll-cells; therefore, mixing and heat transfer decline in radial direction. In order to overcome this phenomenon, chaotic advection could be used by a simple geometrical perturbation in the chaotic coils by rotating axis of each coil with respect to the neighboring coil. Chaotic flow enables fluid particles to escape from trap of Dean-roll-cells by breaking and reassembling them.

Recently, the new science of nanofluids has been greatly considered. Metals in their solid phase have higher thermal conductivity than their fluid form. Nanofluids as a new category of passive techniques improve heat transfer through suspending nanoparticles in a fluid. The related literature contains studies about the number of coil heat exchangers that use nanofluids to enhance heat transfer. Akhavan et al. [20], Hashemi and Akhavan-Behabadi [21] and Fakoor et al. [22] have studied heat transfer and pressure drop characteristics of nanofluid flows inside the helical tube and concluded that, by using the helically coiled tube instead of the straight one, heat transfer performance is improved. Applying helical tube instead of the straight tube is a more effective way to enhance convective heat transfer coefficient than applying nanofluids instead of the pure liquid.

Sasmito et al. [23] numerically evaluated laminar heat transfer increase for a nanofluid flow in the coiled square tubes. Their results indicated that adding small amounts of nanoparticles up to 1% (volumetric concentration) significantly improved heat transfer performance.

Akbaridoust et al. [24] investigated steady state laminar nanofluid flow in helically coiled tubes at constant wall temperature both numerically and experimentally. They investigated pressure drop and convective heat transfer behavior of nanofluid and used homogeneous model with constant effective properties. Their results showed that utilization of base fluid in helical tube with greater curvature than using nanofluid in straight tubes more effectively enhanced heat transfer.

Mohammed and Narrein [25] investigated different geometrical parameters by combining nanofluid on heat transfer and fluid flow characteristics in a helically coiled tube heat exchanger (HCTHE) and demonstrated that certain geometrical parameters such as helix radius and inner tube diameter affected performance of the HCTHE under laminar flow conditions.

Kannadasan et al. [26] compared heat transfer and pressure drop characteristics of CuO/water nanofluids in a helically coiled heat exchanger held in horizontal and vertical positions. The experimental results showed that there was not much difference between horizontal and vertical arrangements in terms of enhancing convective heat transfer coefficient and friction factors of nanofluids compared to water.

The aim of this study was to employ the combination of two passive thermal performance improvement techniques simultaneously (i.e. chaotic advection and nanofluids) in order to maximize advantages of heat transfer enhancement. Accordingly, normal helical coil and chaotic configuration were used. A chaotic coil heat exchanger with no change in axis of coil which was introduced by Tohidi et al. [27] was used in this study. They showed that mixing and heat transfer were significantly increased due to the chaotic advection using Lagrangian tracing of fluid particles and their sensitivity to the initial condition and fluid element calculations. Briefly, in the present work: (i) Heat transfer performance of chaotic and normal coil configurations was compared using water as fluid, (ii) passive heat transfer enhancement-chaotic advection and fluid thermo-physical properties was simultaneously evaluated in coiled tubes filled with nanofluids, and (iii) effects of nanofluids flow in the normal coil and chaotic configuration were analyzed by computing convective heat transfer coefficient and friction factor. Two different nanofluids of water–Al_2O_3 and water–CuO were studied at various nanoparticle concentrations.

2. Coil geometries

In the present work, chaotic flow was generated using flow inversion phenomenon by assembling two regular coil tubes. The