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Research paper

Heat transfer enhancement utilizing chaotic advection in coiled tube heat exchangers

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HIGHLIGHTS

- A novel chaotic coil heat exchanger is introduced in this study.
- It is shown that mixing is increased significantly due to the altered chaotic advection mechanism.
- By increasing the Reynolds number, results show impressive enhancement in chaotic heat exchanger performance.
- Reorientation in chaotic flow leads to higher pressure loss than that in the normal helical coil.

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ABSTRACT

The present study introduced a novel chaotic coil heat exchanger utilizing chaotic advection to enhance heat transfer at low Reynolds numbers. Using Lagrangian tracing of fluid particles and their sensitivity to the initial condition and fluid element calculations, it was shown that mixing was significantly increased due to the chaotic advection. Heat transfer performance in the coil and chaotic configuration was visualized by isotherms contours of temperature in different cross-sections. In order to evaluate the hydraulic-thermal performance of heat exchangers, Nusselt numbers and friction factor were calculated and comparison was made between the two configurations. Numerical calculations revealed that the chaotic coil configuration displayed heat transfer enhancement of 4–26% relative to the fully developed Nusselt numbers in the regular coil with only 5–8% change in the pressure drop.

1. Introduction

Curved pipes are widely used in various industrial applications owing to their compact structure and relatively high heat transfer coefficients. Spiral and helical coils are widely used in thermal recovery processes, air conditioning and refrigeration systems, chemical reactors, and food and dairy processes [1].

Helically coiled circular tubes were studied in early years by Dean [2,3], who showed that a pair of symmetrical circulation zones was formed over the cross-sectional area of coils due to centrifugal force. Dravid et al. [4] investigated the effect of secondary flows on laminar flow and heat transfer in coiled tubes in the entrance and hydrodynamically fully developed region. Mori and Nakayama [5] obtained an analytical solution by analyzing the velocity and temperature profiles, while Patankar et al. [6] numerically studied the heat transfer in curved tubes using uniform wall heat flux and explained the effects of Dean number on friction factor and heat transfer in developing and fully developed regions of helical coils.

Kurnia et al. [7–9] addressed the heat transfer performance of various configurations of coiled non-circular tubes, e.g. in-plane spiral ducts, helical spiral ducts, and conical spiral ducts. They quantified and discussed the effects of tube Reynolds number, fluid Prandtl number, and coil diameter.

Raju and Rathna [10] studied the problem of heat transfer of power-law fluid flowing through a curved pipe and showed that the isotherms of temperature contained segregated cold and hot regions. Fluid particles inside the Dean roll-cells were prevented from approaching the hot wall. Hence, mixing was poor, which led to the observed non-uniform temperature distribution.

In order to overcome this phenomenon, “chaos theory” can be used. Hypothesis of generating chaotic advection by simple geometric perturbations has attracted great attention in recent years. This phenomenon can be described as the generation of chaotic

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Nomenclature

a (m)	coil pipe radius
b (m)	helical coil pitch
c_p (J kg^{-1} K^{-1})	specific heat capacity
d (m)	tube diameter
D (m)	coil diameter
De	Dean number
f	friction factor
j	current global iteration number
k (J m^{-1} K^{-1} s^{-1})	fluid thermal conductivity
l_t	vector length at each time
l_0	length of the initial vector
M_ψ	convergence monitor
N	total number of finite element nodes
Nu	Nusselt number
P (Pa)	fluid pressure
Pr	Prandtl number
Re	Reynolds number
U_m (m s^{-1})	mean velocity
U_a (m s^{-1})	axial velocity
q_w (W m^{-2})	heat flux
Str	fluid element stretching
t (s)	time
T (K)	temperature
T_b (K)	mean bulk temperature
T_w (K)	wall temperature
T_0 (K)	inlet temperature
u (m s^{-1})	x component of fluid velocity
v (m s^{-1})	y component of fluid velocity
V (m s^{-1})	velocity vector of fluid element
w (m s^{-1})	z component of fluid velocity
τ_w (Pa)	shear stress at wall
σ	exponential variation of fluid elements stretching
$\overline{\sigma}$	time-averaged of the exponential stretching
Ψ	degree of freedom
ρ (kg m^{-3})	density of fluid
μ (Pa s)	viscosity
φ	cylindrical coordinate

trajectories of particles in laminar flow affected by viscous forces. By making a chaotic flow with the appropriate design of geometry, mixing and heat transfer can be enhanced while causing negligible increase in pressure drop [11].

In recent studies [12–25], chaotic coils have been introduced based on the flow inversion by changing the direction of centrifugal force in helically coiled tubes. The main mechanism generating the flow is the production of spatially chaotic path by changing the direction of flow using a 90° bend in helical coils. If the direction of centrifugal force is rotated by any angle, the plane of vortex formation also rotates with the same angle. Thus, in helical flow, a 90° shift in the direction of centrifugal force causes a complete flow inversion [12].

Jones et al. [13] and Duchene et al. [14] have demonstrated the appearance of chaotic particle trajectories in steady, laminar, incompressible flow through a twisted pipe of circular cross-section. They have demonstrated enhanced longitudinal particle dispersal due to the coupling between chaos in transverse direction and the non-uniform longitudinal transport of particles.

Acharya et al. [15], Peerhossaini et al. [16], Peerhossaini and Le Guer [17], Mokrani et al. [18,19], Lemenand and Peerhossaini [20], Changy et al. [21], Kumar et al. [22], Kumar and Nigam [12,23], Mridha and Nigam [24], and Yamagishi et al. [25] have numerically and experimentally investigated the effects of chaotic mixing on heat transfer through modifications in the geometry of helical heat exchangers. By tracing the particles and computing positive Lyapunov exponentials, they have represented that the flow within the modified heat exchanger is chaotic, the temperature profile is flatter, and performance of heat transfer is improved.

In most recent chaotic coils, the axis of each coil is rotated by 90° with respect to the neighboring coil, which can be a limitation due to the increased spatial volume of the chaotic coil that needs to occupy a larger space. A novel chaotic coil heat exchanger was introduced in this study, which had no change in the axis of coil. The aim of this work was to characterize flow development and temperature field in this chaotic coil. The most important information in the design of the helical coil device is the pressure drop and heat transfer coefficient. Therefore, hydrodynamics and thermal development studies were conducted, using Newtonian fluid, for a range of Reynolds numbers from 100 to 500. In order to precisely assess the effects of chaotic advection on mixing efficiency, stretching of fluid elements and particle trajectories were computed to show their high sensitivity to initial conditions. Furthermore, to evaluate their hydraulic-thermal performance, heat transfer and friction coefficients were calculated and comparison is made between the two configurations.

2. Studied coil geometries

Two configurations were simulated in this study: the novel chaotic configuration and the common helical one. Fig. 1(a, b)

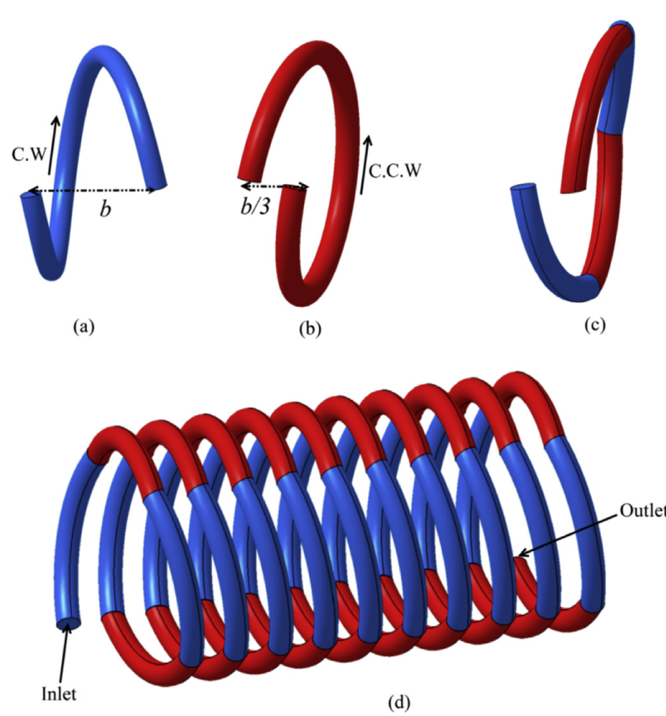

Fig. 1. (a) Coil with clockwise orientation; (b) coil with counterclockwise orientation; (c) one period of the chaotic configuration; (d) 10 periods of the chaotic configuration.