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Numerical simulation of steady flow fields in coiled flow inverter

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Abstract

Flatter velocity profiles and more uniform thermal environments are extremely desirous factors for improved performance in flow reactors and heat exchangers. One means of achieving it in laminar flow systems is to use mixers and flow inverters. In the present study a new device is introduced based on the flow inversion by changing the direction of centrifugal force in helically coiled tubes. The objective of the present study is to characterize flow development and temperature fields in the proposed device made up from the configurations of bent coils. 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 (alternating Dean flow). 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 cause a complete flow inversion. Complete flow fields and thermal fields in helical coil and bent coil configuration were studied using computational fluid dynamics software (FLUENT 6.0). The three-dimensional governing equations for momentum and energy under the laminar flow conditions were solved with a control-volume finite difference method (CVFDM) with second-order accuracy. The flow pattern obtained for the helical coil was in good agreement to those observed by the previous investigators [S.W. Jones, O.M. Thomas, H. Aref, Chaotic advection by laminar flow in twisted pipe. J. Fluid Mech. 209 (1989) 335–357; Ch. Duchene, H. Peerhossaini, P.J. Michard, On the velocity field and tracer patterns in a twisted duct flow. Phys. Fluids 7 (1995) 1307–1317]. The comparison of the flow fields and temperature fields in the helical tube and bent coil configuration are discussed. The bent coil configuration shows a 20–30% enhancement in the heat transfer due to chaotic mixing while relative pressure drop is 5–6%. The results of the present study can be used to model transport processes for developing flows in curved tubes such as chromatographic columns (less axial dispersion [A.K. Saxena, K.D.P. Nigam, Coiled configuration for flow inversion and its effect on residence time distribution. AIChE J. 30 (1984) 363–368]), Chemical reactors (narrower RTD), heat transfer devices, and some biomedical devices.

Keywords: Heat transfer; Helical tube; Bent coils; CFD

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Nomenclature

a	radius of the helical pipe, m
A	area, m^2
C_p	specific heat, kJ/(kg K)
d_h	hydraulic diameter of the helical pipe ($=2a$), m
H	pitch, m
k	thermal conductivity, W/(m K)
n	coordinate direction perpendicular to a surface
p	pressure, N/m^2
q	heat flux, W m^{-2}
R_c	radius of the coil, m
N_{Re}	Reynolds number ($=\rho U_0 d_h/\mu$)
N_{Pr}	Prandtl number
N_{Nu}	Nusselt number
T	temperature, K
T_b	fluid bulk temperature on one cross-section $\left(\frac{1}{\overline{u_s}A}\int_0^A u_s T\,dA\right)$, K
U_0	inlet velocity, m/s
u_i	velocity component in i-direction ($i=1, 2, 3$), m/s
u_s	axial velocity component, m/s
U_s	non-dimensional axial velocity (u_s/U_0)
U_{2nd}	non-dimensional secondary velocity
x	spatial position, m
x_i	master Cartesian coordinate in i-direction ($i=1, 2, 3$), m

Greek symbols

α	angle, degree
δ	curvature ratio (a/R_c)
δ_{ij}	Dirac delta function
Θ	non-dimensional temperature, $\frac{T_w-T_0}{T_b-T_w}$
ρ	density of fluid, kg/m^3

Subscripts

0	inlet conditions
2nd	secondary flow
b	bulk quantity
w	wall condition

1. Introduction

Flow and heat transfer in helical pipes with a constant circular or rectangular cross-section has been a topic of important fundamental engineering interests during the past decades. Berger et al. [3] and Shah and Joshi [4] have presented extensive reviews of fluid flow and heat transfer in helical pipes. Helically coiled tubes are simple and effective means of augmenting heat and mass transfer in a wide variety of industrial applications ranging from stagnant batch heating and cooling to dynamic distillation processes. In the helically coiled tubes, the modification of the flow is due to the centrifugal forces (Dean roll cells [5,6]) caused by the curvature of the tube, which produce a secondary flow field with a circulatory motion pushing the fluid particles toward the core region of the tube. Because of the stabilizing effects of this secondary flow, laminar flow persists too higher Reynolds number value in helical coils as compared to straight tubes. Consequently, the differences in heat and mass transfer performance between coils and straight tubes are particularly distinct in the laminar flow region. In fact, there is global heat transfer enhancement, but Raju and Rathna [7] showed that in helical coiled tube the isotherms of temperature for different kinds of fluids contain segregated cold and hot regions. The Dean roll cells divide the cross-section into two zones in each of which the isotherms forms the closed curves. Fluid particles inside the Dean roll cells are prevented from approaching the hot walls; thus mixing is poor, giving rise to a heterogeneous temperature field. To overcome this phenomenon, Jones et al. [1], Acharya et al. [12] and Peerhossaini et al. [8] presented an alternative regime in laminar flow that has dispersive properties close to the turbulent regime. This phenomenon, called chaotic advection or Langrangian turbulence, is analogous to temporal chaos in which a small number of degrees of freedom can cause chaotic evolution over time. In chaotic advection, the fluid-particle trajectories are chaotic and enhance mixing, consequently increasing heat transfer. Such tools were addressed in Mokrani et al. [9]. The details of the chaotic and temporal flows are discussed in [8–21].

Acharya et al. [12,13] numerically showed that the mixing can be enhanced, by inserting a geometrical perturbation (by alternating sequence of bends) in the laminar flow. This perturbation is achieved by merely shifting each bend by an angle, χ between 0° and 90°. They have solved the problem numerically by using analytical flow field obtained by Dean. The energy equation, though linear is solved numerically, using Dean's velocity fields, to give the temperature distribution and heat transfer characteristics. They also reported that in the alternating axis coil, the temperature field becomes flatter than in helical coil. Duchene et al. [2] analyzed the formation and reorganization of Dean roll cells under abrupt curvature change in a twisted square duct.