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Laminar heat transfer performance of power law fluids in coiled square tube with various configurations ☆

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ABSTRACT

This study addresses heat transfer performance of laminar non-Newtonian fluid flow in various configurations of coiled square tubes e.g., in-plane spiral ducts, helical spiral ducts and conical spiral ducts. The non-Newtonian fluid considered in this study is the aqueous solution of carboxymethyl cellulose (CMC) which is modeled as power-law fluid. Effects of tube geometries, power-law index (concentration of CMC) and other parameters are quantified and discussed to analyze flow behavior and heat transfer performance. Results are compared with those for a straight square tube of the same length as that used to form the coils. A Figure of Merit is defined to compare the heat transfer performance of different geometries with respect to the pumping power. The results suggest that CMC solution yields better heat transfer performance of about twice than that of water at Re ~ 1000. Among all considered designs, helical coil gives the best heat transfer performance; however, when the pumping power is considered, in-plane coil design performs the best in term of Figure of Merit.

1. Introduction

For decades, improving heat transfer rate has been one of the major focuses in engineering field. Heat transfer rate can be enhanced by active as well as passive methods. While the former usually provide better enhancement, it requires additional external forces and/or equipment which can increase the complexity, capital and operating costs of the system. In contrast, passive heat transfer enhancement can be achieved by changing flow geometry or modifying thermo-physical properties of working fluid. The latter (passive approach) is more desirable compared to the former (active approach). One passive method to enhance heat transfer rate is by utilizing curved/coiled tube.

Since its first introduction in the 19th century [1], curved/coiled tubes have been widely implemented in engineering application due to their higher heat transfer performance, compact structure and ease of manufacture. They have been extensively used in heat exchangers and chemical reactors. They have also been utilized in other applications such as rocket engine, fuel cell coolant channel, power plants, viscometers and many other engineering applications. In tandem with their industrial application, complex transport phenomena in coiled duct due to the presence of secondary flow have also attracted considerable attention from engineering researchers. The presence of secondary flows inducted by centrifugal forces significantly affect heat and mass transport in coiled duct.

Among the first few studies on the fluid flow inside was conducted by Dean et al. [2,3]. By investigating flow behavior in a toroidal (in-plane) constant radius duct, they revealed that circular tubes develop a secondary flow when the Dean number exceeds a critical value. Since then, numerous experimental [4–10] and numerical [11–14] investigations on heat transfer and flow characteristics inside curved/coiled tube were carried out and reported. In addition to the extensive numerical and experimental studies, reviews on the flow characteristic and heat transfer performance of a coiled tube and its potential applications have also been reported [15,16]. Majority of these studies were conducted to investigate fundamental transport phenomena that occur on the coiled tubes and develop correlations for the heat transfer coefficient (or mass transfer); very few of them compare the heat transfer performance of various coiled tubes of noncircular cross-section. In our previous studies, we have investigated and evaluated various factors affecting flow behavior and heat transfer performance of laminar flow in coiled tube [17–22]: inlet velocity, addition of nanofluid, cross-section area, coiled tube geometry and addition of micro-encapsulated phase change materials (MEPCM). Application of coiled channel in fuel cell cooling and micro-reactor applications have also been studied and reported [23–25].

Meanwhile, studies on the flow behavior and heat transfer of non-Newtonian flow have attracted considerable attention worldwide. Poh et al. studied heat transfer of a laminar impinging jet of a power-law fluid [26]. The power-law fluid used was solution of CMC (carboxymethyl

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Nomenclature

A_c	cross section area [m^2]
c_p	specific heat capacity of gas mixture [$J\ kg^{-1}\ K^{-1}$]
D_h	hydraulic diameter ($=4A_c/P_c$) [m]
$\mathbf{e}_x$, $\mathbf{e}_y$, $\mathbf{e}_z$	coordinate vectors
FoM	Figure of Merit
k	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
K	consistency index [$Pa\ s^n$]
$\dot{m}$	mass flow rate [$kg\ s^{-1}$]
n	power law index
p	pressure [Pa]
P	power [Watt]
P_c	cross section perimeter [m]
Pr	Prandtl ($C_p\mu/k$)
Q	total heat transfer [W]
R	radius of coil [m]
Re	Reynolds number $\mathrm{Re} = \frac{\rho U^{n-1} D^n}{8^{n-1} K}\left(\frac{4n}{1+3n}\right)^n$
s	spacing [m]
T	temperature [C]
$\mathbf{u}$, u, v, w, U	velocities [$m\ s^{-1}$]
V	mean velocity [m^3]
$\dot{V}$	volumetric flow rate [$m^3\ s^{-1}$]
x, y, z	coordinates [m]

Greek

μ	dynamic viscosity [$kg\ m^{-1}\ s^{-1}$]
$\dot{\gamma}$	shear rate
ρ	density [$kg\ m^{-3}$]

Subscripts

ave	average
c	coil
h	helical
i	inner
in	inlet
L	length
mean	mean
o	outer
out	out
p	in-plane
total	total
wall	wall

cellulose) in water. It was found that, at a given generalized Reynolds number (Re), the magnitude of Nusselt number (Nu) increases with the decrease of power law index. However, when the jet exit velocity is kept constant, the effect of Re and CMC concentration on Nu is marginal. Lin et al. numerically investigated heat transfer performance of power-law fluids through parallel-plate double-pass heat exchangers with external recycle [27,28]. The results suggested that smaller power-law index provide higher heat transfer efficiency. However, they concluded that for device performance improvement of double-pass operations relative to the single-pass operation is better for a power-law fluid with large power index. Ming et al. evaluated heat transfer of power law fluid over rotating disks [29]. Their study revealed that the velocity and temperature fields are strongly affected by parameters of power-law index and Prandtl number. The thickness of the boundary layer decays with power-law index. The peak of the radial velocity was marginally affected by the power- law index. Similar study was conducted by Attia [30] who investigated rotating disk flow and heat transfer of a non-Newtonian fluid through porous medium with injection and suction. The results indicated that the non-Newtonian characteristics have an apparent effect on the flow for all values of suction or injection velocities. In addition it was found that the effect on the flow is more pronounced in the case of suction than in the case of injection. Given the importance of the characteristic of non-Newtonian fluid to the flow and heat transfer, it is therefore of interest to study the flow behavior and heat transfer of non-Newtonian fluid in coiled tube.

Here, we extend our previous study by investigating flow behavior and heat transfer performance of non-Newtonian fluid inside various coiled non-circular tubes: conical, helical and in-plane. The effect of geometries, power-law index (concentration of CMC) and other parameters are quantified and discussed to analyze flow behavior and heat transfer performance. The objective of this study to evaluate the potency of power law fluid in improving heat transfer in coiled tubes heat exchanger.

2. Model development

In this paper, incompressible laminar non-Newtonian fluid flow inside various coil geometries with square cross-section is considered. The configuration of coiled non-circular tubes and their cross-section schematic are presented in Fig. 1. Boundary condition constant wall temperature is investigated in this study.

2.1. Governing equations

Conservation of mass, momentum and energy for the flow inside the tubes is given by

$$\nabla \cdot \rho \mathbf{u} = 0 \tag{1}$$

$$\nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla P + \nabla \cdot \left[\mu\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right)\right], \tag{2}$$

$$\rho c_p \mathbf{u} \cdot \nabla T = k \nabla^2 T \tag{3}$$

where ρ is the fluid density, $\mathbf{u}$ is the fluid velocity, P is the pressure, μ is the dynamic viscosity of the fluid, c_p is the specific heat of the fluid and T is the temperature.

2.2. Constitutive relations

As stated in the Introduction section, this paper addressed heat transfer performance of non-Newtonian fluid in coiled tubes. The non-Newtonian fluid studied here is aqueous CMC (carboxymethyl cellulose) solutions. Numerous empirical relationships have been suggested to describe the changes in viscosity of non-Newtonian fluids [31]. Here, power-law model was chosen to simulate the changes in viscosity of the non-Newtonian fluid. This model describes sufficiently the behavior of the fluid within acceptable shear rate range. Meanwhile, the density, thermal conductivity and specific heat of water are taken as those of water [31,32]. The thermo-physical property of the fluid can then be expressed as [31,32]

$$\rho = -3.570 \times 10^{-3} T^2 + 1.88T + 753.2, \tag{8}$$

$$\mu = K \dot{\gamma}^{n-1} e^{\frac{T}{T_0}}, \tag{9}$$

$$k = -8.354 \times 10^{-6} T^2 + 6.53 \times 10^{-3} T - 0.5981, \tag{10}$$

$$c_p = 4200 \tag{11}$$