Numerical Simulation of Heat Transfer and Pressure Drop of Pseudo-Plastic Fluid in a Pipe Heat Exchanger Equipped with a Modified Twisted Tape

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ABSTRACT

The present paper, heat transfer and flow of shear-thinning non-Newtonian fluids in a circular tube under constant heat flux with a modified twisted tape, have been numerically studied in a laminar, steady state and three-dimensional regime. The finite volume method was used to numerically solve the governing equations, modified power law model be used to describe the dependence between the stresses and shear rates. The physical model is a circular tube with a standard twisted tape with decreasing its width, also a hollow tape in circular tube with increase in the central cavity of the tape. The heat transfer and the overall performance are unfavorable by cutting off the tape edge. Instead decrease tape width ratio, hollow tape with different removal ratio was used to improve thermal efficiency. the numerical results show that the removal ratio (hollow width of the tape divided by the initial width) equal to 0.3 in the fluids with behavioral indexes 0.86, 0.55 and 0.41 can cause 17.95%, 18.49% and 19.69% increases thermal performance compared to the best thermal performance mode, respectively. Therefore, the hollow twisted tape is a promising technique for laminar convective heat transfer enhancement.

KEYWORDS

Pseudo-Plastics Fluid, Modified Twisted Tape, Heat Transfer Enhancement, Pipe Heat Exchanger, Modified Power Law.

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1. Introduction

Enhancing the thermal efficiency of heat exchangers is a challenging task to meet the heat removal capability needed for development of new devices with better performances. The use of non-Newtonian fluids, and especially of pseudoplastic liquids (shear-thinning), has received much attention in industrial applications [1]. The use of shear-thinning non-Newtonian fluids in heat transfer systems as working fluid can increase the thermal performance of the system. Aqueous solutions of carboxymethyl cellulose (CMC) are shear-thinning non-Newtonian liquids (also known as pseudoplastic liquids) that have been used for heat removal applications.[2]

Another way to increase heat transfer in heat exchangers is to use turbulence. Twisted bands have been widely used as a passive turbulent to increase heat transfer in heat exchangers due to the reduction in size and cost of these systems [3].

According to the best of the author's knowledge and to the reviewed literature, the influence of the non-Newtonian fluid flow behaviour on the thermo-hydraulic performance of circular tubes equipped with hollow twisted tape is not addressed yet. The primary aim of this study is to understand the influence of shear-thinning behaviour on fluid flow structure and heat transfer characteristics in circular tubes equipped with hollow twisted tape.

2. Model description

2.1. Physical model

The geometries of the conventional, short-width and hollow twisted tapes are depicted in Fig. 1. Twisted tapes with thickness (*d*) of 0.001 m are fitted in the full length of all tubes. The diameter (*D*) and length (*L*) of the tube are 0.02 m and 0.5 m, respectively. The 180 deg twist pitch (*H*) is 0.05 m.

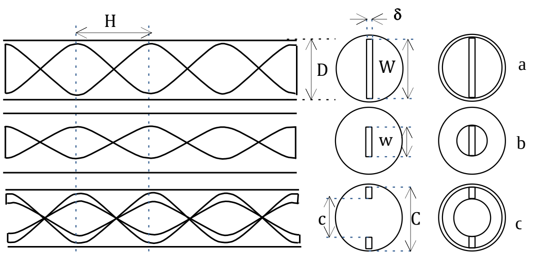

Figure 1. Schematic design of geometry a) Standard twisted tape b) twisted tape with outer edge removal c) hollow twisted tape

2-2. Fluid properties

The shear-thinning non-Newtonian fluids used in the present study comprise of three grades of aqueous solutions of Carboxylmethyl cellulose (CMC) polymer. CMC 7H3SF (high grade), CMC 7M8SF (medium grade) and 7LFPH (low grade) are the three grades of CMC polymers used as working fluids to investigate the viscous fluid flow and heat transfer phenomenon in this study. The apparent viscosity of a non-Newtonian fluids whose shear-thinning behavior is described using the modified power law model is given as[4]

$$\mu_a = \left[\left(\mu_0\right)^P + \left(K \times \dot{\gamma}^{(n-1)}\right)^P \right]^{1/P} \qquad (1)$$

The modified power-law parameters for the non-Newtonian fluids under consideration are presented in Table 1.

Table 1. Thermo-physical characteristics of CMC

Polymer	Concentration [mol/cc]	Asymptotic modified power law parameters (60°C)			
		μ_0	*K*	*n*	*p*
CMC 7H3SF	2.175×10^{-8}	2.3435	6.8506	0.4117	-1.22
CMC 7M8SF	1.667×10^{-7}	1.5155	5.1795	0.5544	-1.36
CMC 7LFPH	5.848×10^{-7}	0.1170	0.1828	0.8638	-5.58

The properties of the fluids used in this study are as follows:
Density, ρ = 983.20 kg/m3
Specific heat capacity, C_P = 4184.3 J/ Kg. K
Conductivity, k = 6.5432 W/m. K

2.3. Mathematical model

Based on these assumptions, the continuum heat and fluid flow in the tube were modelled using the equations of mass, momentum, and energy conservation that are introduced as follows: [2]

$$\nabla.\vec{v} = 0 \qquad (2)$$

$$\rho\left(\vec{v}.\nabla\vec{v}\right) = -\nabla p + \nabla.\left[\mu\left(\nabla\vec{v} + \nabla^T\vec{v}\right)/2\right] \qquad (3)$$

$$\rho C_p\left(\vec{v}.\nabla T\right) = K_t \nabla^2 T \qquad (4)$$

where $\bar{v}$ is the fluid velocity vector, ρ density, *p* the static pressure, μ dynamic viscosity, C_p specific heat capacity, *T* temperature, and K_t thermal conductivity.

2.4. Determinant Parameters

For non-Newtonian fluids, the generalized Reynolds number (*Re*) is defined as follows:[5]

$$\mathrm{Re}_{MR} = \frac{\rho U^{-2-n} D_H^n}{\eta'} \qquad (5)$$

where ρ is the density, *U* is the average velocity, D_H is the hydraulic characteristic length, and η' is the characteristic non-Newtonian viscosity, which is given by

$$\eta' = K\left(\frac{3n+1}{4n}\right)^{n}\left(\frac{8U}{D_H}\right)^{n-1} \tag{6}$$

The overall performance evaluation criterion or the surface goodness factor[6] is defined as

$$\eta = \frac{Nu / Nu_0}{\left(f / f_0\right)^{1/3}} \tag{7}$$

3. Results and Discussion

It is clearly seen from Fig. 2 that variation tendency of the thermal performance factor (η) is quite different from those of *Nu* and *f*. In other words, η decreases at first and then increases with the reduction of *w*. The magnitude of η declines sharply when *w* is reduced from 0.9 to 0.8, and reaches a minimum value approximately at *w*=0.4, then it ascends slightly with the further reduction of the width ratio. Moreover, it also could be noted that thermal performance factor at *w*=0.9 is much larger than those when *w*<0.9. All those show that it is unfavorable to enhance the thermohydraulic performance by reducing the outer edge of the twisted tape.
Fig. 3 presents the variation of the thermal performance factor (η) with the central clearance ratio (*c*) at different Reynolds numbers (*Re*) of laminar flow. It is shown that as c increases, η increases first until it reaches a peak at *c*=0.3 and then decreases. The maximum value of η is 1.17e1.20 times of that at *c*=0 in *Re* range of present study.

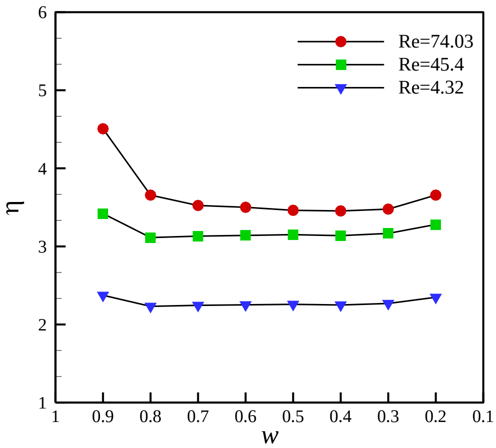

Figure 2. Variation of the thermal performance criteria versus the tape width ratio (*w*) for tube fitted with short-width twisted tape at *n*=0.55

More details about the enhancement of thermal performance factor for the hollow twisted tape compared with the smooth twisted tape (*c*=0) on fluid with *n*=0.55 are shown in Table 3.

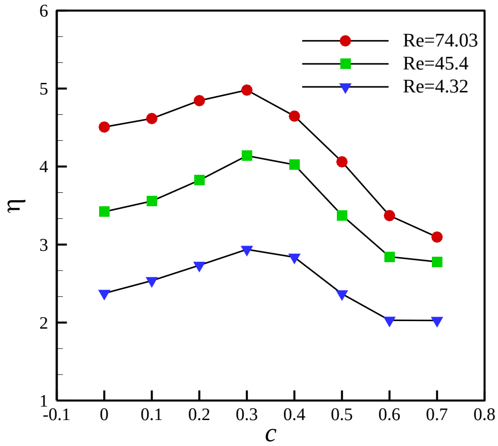

Figure 3. Variation of the thermal performance criteria versus the for the hollow twisted tape width and increment *c*, at *n*=0.55

4. Conclusions

Heat transfer and friction factor characteristics of laminar flow “non-newtonian shear-thinning fluid” in a circular tube with short-width and hollow twisted tapes have been investigated numerically. The computation results show that the flow resistance can be reduced by both methods but the heat transfer features are very different from each other. As compared with the tube with conventional twisted tape, the thermal performance factor of the tube with center void twisted tapes can be enhanced by 20%. In summary, one can achieve a satisfying overall performance by using a twisted tape with a suitable central clearance ratio. Therefore, the hollow twisted tape is a promising technique for laminar convective heat transfer enhancement.

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