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Research Paper

Thermo-hydraulic analysis for a novel eccentric helical screw tape insert in a three dimensional tube

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HIGHLIGHTS

- Effect of eccentricity between centers of helical screw tape and tube is studied.
- Swirl effect created by helical screw is transferred from tube core to near wall.
- There is 33% increase in PEC at $Re = 5000$ when eccentricity increases from 0 to 3.5.

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ABSTRACT

The effects of eccentricity between the centers of helical screw tapes and tube on heat transfer, friction factor and performance evaluation criteria are numerically studied in this paper. A three-dimensional turbulence model is used to simulate the flow inside the tube with helical screw tape insert. All simulations are performed for four values of eccentricity (0, 0.5, 2, and 3.5) and Reynolds numbers in the range of 5000 to 12000. The obtained results indicated that the swirling effects created by helical screw tape insert are transferred from the tube core to near wall of the tube. This leads to the more mixing of fluid and centrifugal force near the wall, which has significant ability to improve the heat transfer rate at this region. There are 33%, 16.94%, 8.45%, and 7.3% increments in performance evaluation criteria for $Re = 5000$, 7500, 10233, and 12000 when the eccentricity value is increased from 0 to 3.5.

1. Introduction

There are various passive techniques to enhance the thermal performance of heat transfer devices containing heat exchangers, heat recovery, refrigeration systems, microelectronics industries, solar heating, air-conditioning systems, chemical reactors, etc. Some examples of these techniques are treated surfaces, rough surfaces [1], insert of porous material with high thermal conductivity [2,3], usage of nanoparticles [4,5], and incorporations of inserts (i.e. turbulators or swirl flow equipment) [6–8]. Some researchers investigated heat transfer enhancement of various pure fluids [9–11]. Among these techniques, helical screw tape inserts are recognized as most promising methods, which has been widely used for heat transfer enhancement in a wide range of Prandtl and Reynolds numbers [12]. Recently, many numerical and experimental researches are available in this field. A literature review on these works is useful to classify them. There are some experimental researches about applications of twisted or helical screw tape for heat transfer enhancement of various pure fluids. Manglik and Bergles [13] performed an experimental work on turbulent water and ethylene glycol flows in-tube with twisted tape inserts. They estimated Nusselt number based on an asymptotic model for isothermal wall condition by presenting a correlation equation. Bhuiya et al. [14] investigated experimentally the effects of triple twisted tapes on thermal characteristics of air flow in a heat exchanger tube. They reported that the Nusselt number for the modified tube with triple twisted tape inserts is 3.85 times higher than that of the conventional tube. Bas and Ozceyhan [15] used experimentally twisted tape inserts to improve the heat transfer rate of air flow in a tube. The twisted tape inserts were located separately from the tube wall. Their results indicated that usage of twisted tape separately from the tube wall can supply more enhancement on heat transfer in comparison to the attached type. Bhuiya et al. [16] investigated experimentally the turbulent air flow in a tube fitted with perforated twisted tape inserts. They reported that

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Nomenclature

Cp	specific heat at constant pressure (kJ kg^{-1} K^{-1})
d_1	inner diameter of helical screw tape (m)
d_2	outer diameter of helical screw tape (m)
D	tube diameter (m)
e	eccentricity of helical screw tape (m)
f	friction factor (–)
h	average heat transfer coefficient in the tube (W m^{-2} K^{-1})
k	turbulent kinetic energy (m^2 s^{-1})
L	length of tube (m)
Nu	Nusselt number (–)
$\overline{Nu}$	surface-averaged Nusselt number (–)
$\langle\overline{Nu}\rangle$	time-averaged Nusselt number (–)
p	pressure (Pa)
PEC	performance evaluation criteria (–)
Re	Reynolds number (–)
S	pitch of helical screw tape (m)
t	thickness of helical screw tape (m)
t	time (s)
t_p	period of time integration (s)
T	temperature (K)
u	velocity (m s^{-1})
W	tape width (m)

Greek symbols

δ	Kronecker delta
μ	dynamic viscosity (kg/ms)
ν_t	kinematic eddy viscosity (m^2 s^{-1})
ρ	density of the fluid (kg m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
τ	shear stress (Pa)
ω	specific turbulence dissipation rate (s^{-1})

Subscripts

m	mean
P	plain tube
w	wall

the Nusselt number and friction factor for the modified tube with perforated twisted tape inserts are 110–340% and 110–360% higher than those of the values for the conventional plain tube, respectively. Vashistha et al. [17] investigated experimentally the effects of multiple inserts on heat transfer and pressure drop of water flow in the circular tube. They observed a higher heat transfer and friction for counter-swirl inserts in comparison to the co-swirl inserts.

Beside experimental works, there are some numerical works in this field. Zhang et al. [18] numerically investigated thermal and friction factor characteristics of flow in the tube with helical screw-tape with four different widths. They reported that the average overall heat transfer coefficients increases about 351% by inserting helical screw-tape in circular tube. Rios-Iribe et al. [19] performed a numerical study on a non-Newtonian fluid flow in a circular tube with twisted tape inserts. They found that the thermo-hydraulic performance increases with decrease in twist ratio. Li et al. [20] inserted centrally hollow narrow twisted tapes in a tube and investigated numerically the effect of the hollow width and clearance on heat transfer and resistance for laminar regime. They found the cross hollow twisted tape very useful with high-performance for laminar regime.

Some researchers used the twisted tapes with nanofluids as a useful technique. Sundar and Sharma [21] investigated experimentally turbulent nanofluid flow in circular tube with twisted tape inserts. They found that the heat transfer coefficient and friction factor of Al_2O_3 nanofluid at $\varphi = 0.5\%$ with twist ratio of five are 33.51% and 1.096 times respectively higher in comparison to pure water flow in a tube. φ is solid volume fraction of nanoparticles. Azmi et al. [22] developed a numerical model for turbulent nanofluid flow in a tube with twisted tape inserts. They observed enhancements of 94.1% and 160% in heat transfer coefficient and friction factor for nanofluid at $\varphi = 3\%$ with twist ratio of five at $Re = 19046$ in comparison to pure water flow in a tube.

Some researchers performed a literature review on this field and published their results. Hasanpour et al. [23] reviewed experimental studies performed on usage of twisted tape inserts in the heat exchanger for the turbulent regime. They concluded that the twin and the helical screw twisted tape inserts have the highest value of performance among the performed experimental works, which was in the range of 2–2.5. In another work, Varun et al. [24] reviewed previous works on heat transfer enhancement using twisted tape inserts. They reported that the short length twisted tapes have a better performance under the criterion of constant pumping power in comparison to the full length twisted tapes.

In this study, we attempt to present and analyze a novel eccentric helical screw tape insert in a three dimensional tube. A thermo-hydraulic analysis is performed and the effects of eccentricity in helical screw tapes on heat transfer, friction factor and performance evaluation criteria are numerically studied. The aim of this study is to increase of heat transfer and simultaneously decrease enhance of pressure drop occurring from using the helical screw tape insert. This can be conducted by using an eccentric helical screw tape insert.

Valipour et al. [28] investigated the MHD heat transfer around a solid obstacle covered by a porous substrate. They employed the least square approach [29–34] to define two empirical equations for mean Nusselt number that the influences of Darcy number and magnetic field were considered in these equations.

2. Physical model

The physical model of helical screw tape inserted in three dimensional tube is shown in Fig. 1. The calculation parameters on this figure are defined in Table 1. Water with inlet temperature of 353 K is selected as working fluid. Moreover, the wall temperature is kept at 298 K. The following assumptions are used to simulate this problem:

- The fluid is assumed to be incompressible and Newtonian with constant physical properties.
- The effect of gravity is negligible.

3. Mathematical model

For turbulence simulation, the velocity vector, u, should be broken into two parts containing the mean velocity ($\bar{u} = (u_1, u_2, u_3)^T$) and the fluctuation part ($\acute{u} = (\acute{u}_1, \acute{u}_2, \acute{u}_3)^T$). The mean velocity is defined by:

$$\bar{u} = \frac{1}{\Delta t}\int_t^{t+\Delta t} u dt. \quad (1)$$