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Influence of three-start spirally twisted tube combined with triple-channel twisted tape insert on heat transfer enhancement

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ABSTRACT

In the present article, heat transfer enhancement by three-start spirally twisted tube combination with triple-channel twisted tape is studied numerically using RNG k-ε turbulence model. Influences of the tape width ratio (w/D = 0.1, 0.25, 0.34 and 0.5) and tube/tape arrangement (belly-to-belly and belly-to-neck arrangements) are described. The numerical results of a twisted tube without tape and a circular plain tube are also given for comparison. The results are reported in terms of velocity field, temperature field, turbulent kinetic energy, local Nusselt number distribution, average Nusselt number, pressure loss and thermal performance factor. It is found that heat transfer and friction factor increase with tape width ratio. At a given tape width, the systems in belly-to-neck arrangement are more efficient for heat transfer enhancement than the ones in belly-to-belly arrangement. The three-start spirally twisted tubes with twisted tapes in belly-to-neck arrangement at w/D = 0.1, 0.25 and 0.34 give higher Nusselt numbers than the twisted tube without tape up to 1.2%, 21% and 36%, respectively. The twisted tubes with triple-channel twisted tape in belly-to-belly arrangement provide higher Nusselt numbers than the twisted tube without tape up to 1.23%, 6.7%, 10% and 17%, respectively. The superior heat transfer of the combined devices in belly-to-neck arrangement (especially at large w/D) is attributed to the stronger interaction between the swirling flows induced by the tubes and those induced by the tapes. Moreover, the systems in belly-to-neck arrangement cause lower friction loss than the ones in belly-to-belly arrangement. Thus, the systems in belly-to-neck arrangement yield higher thermal performance factors. Among the studied cases, the twisted tube combined with triple-channel twisted tape in belly-to-neck arrangement at w/D = 0.34 possesses the maximum thermal performance of 1.32 at Reynolds number of 5000.

1. Introduction

Heat transfer enhancement techniques play a significant role in many thermal engineering applications such as heat transfer processes, power engineering, heat exchanger system, aviation engineering, chemical engineering, refrigerating engineering, and food industries, etc. [1–4]. Twisted tubes are used as the parts of shell and tube heat exchangers which applied in many industrial sectors such as refrigeration, automotive, chemical power plant, chemical reactor, and electronic cooling etc. Twisted tube heat exchangers were developed in the 1980s [5,6] to overcome the limitations inherent with conventional shell and tube technology. As compared to the conventional shell and tube heat exchanger, the twisted tube heat exchanger offers more efficient heat transfer, thus smaller exchanger or fewer shells are needed. In general, twisted tubes are formed into an oval section with a superimposed twist by some special techniques. Two ends of the tubes remain round on the consideration of assembling them with the tube sheet. The tubes are formed into an elliptical or oblate cross section with superimposed twists as illustrated in Fig. 1.

The thermal performances of twisted tube heat exchangers were widely investigated using experimental and numerical methods. Yang et al. [5] studied the effect of the twisted elliptical tubes with various aspect ratios and twist pitches on the heat transfer enhancement, pressure loss and thermal performance behaviors. Their results indicated that the use of twisted elliptical tubes with larger tube aspect ratios and smaller twist pitches resulted in higher heat transfer coefficients and friction factors. Zhang et al. [6] employed horizontal twisted elliptical tubes for steam condensation. Their results showed that the condensation heat transfer coefficients decreased with the increase of wall sub-cooling, while the enhancement factor of twisted elliptical tubes

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Nomenclature

D_h hydraulic diameter of twisted tube
e depth of groove wall (m)
f friction factor
Nu Nusselt number
p static pressure (Pa)
P corrugation pitch of twisted tube (mm)
T temperature (K)
u_i velocity component in x_i-direction (m s^{-1})
u_j velocity component in
u_j velocity component in y_j-direction (m s−1)
u_0 mean or uniform velocity in tube (m s−1)
x_i coordinate direction in x_i-direction (m s−1)
x_j coordinate direction in y_j-direction (m s−1)
y twist length of twisted tape (mm)
w width of twisted tape (mm)

Greek letter
μ dynamic viscosity (kg s^{-1} m^{-1})
Γ thermal diffusivity
η thermal performance enhancement factor $((Nu/Nu_s)/(f/f_s)^{1/3})$
ρ density (kg m^{-3})

Subscript
s straight tube

was almost constant. They also found that the tubes with larger twist pitches gave higher condensation heat transfer coefficients. Tan et al. [7] numerically investigated the effect of twisted oval tube on the heat transfer and friction factor characteristics at different geometrical parameters. Their result indicated that both heat transfer coefficient and pressure drop decreased with the decreasing axis ratio and increasing twist length. Again, Tan et al. [8] numerically investigated the heat transfer, friction factor, fluid flow and overall heat transfer performance characteristics in the shell side ofoval tube heat exchangers consisted of oval tubes with different twisted pitch lengths and aspect ratios, by using the Realized k-ε turbulence model. They found that the heat transfer rate and friction factor increased with increasing twisted pitch length and aspect ratio while the overall heat transfer performance increased with the increasing aspect ratio. The intensity of the spiral flow became more drastic with the decreasing twisted pitch length and the increasing aspect ratio. They also showed that the magnitude of the secondary flow increased with increasing aspect ratio but decreased with the increasing twisted pitch length. Tan et al. [9] studied the tube side and shell side heat transfer coefficient and overall performance characteristics of a twisted oval tube heat exchanger, compared with those of a typical round tube heat exchanger. Evidently, the tube side heat transfer coefficient and pressure drop in the twisted oval tube heat exchanger were higher than those in the smooth round heat exchanger. The optimum condition was found at low tube side flow rate and high shell side flow rate. Again, Tang et al. [10] studied the heat transfer enhancement characteristics in a twisted tri-lobed tube and twisted oval tube at different cross section shapes. The effect of the twisted tri-lobed tube with right–left hand twisted directions on the thermal performance was also examined. Their results found that the heat transfer rate and friction factor of the twisted tri-lobed tube were increased up to 5.4% and 8.4% over those the twisted oval tube. Recently, Bhadouriya et al. [11] examined the heat transfer, pressure drop, fluid flow and thermal performance behaviors in a twisted square duct at different twist ratios. They found that the highest heat transfer enhancements factor of twisted square duct is 10.5 times at twist ratio of 2.5 for the lowest Reynolds number of 3000.

For further heat transfer enhancement, twisted tubes were inserted by twisted tapes, for example, two/three single-start spirally corrugated tubes with conventional twisted tape [12,13], spirally corrugated tube with conventional twisted tape [14,15], eight single-start, spirally corrugated tubes with conventional twisted tape [16], corrugated tubes with conventional twisted tape [17], corrugated tube equipped with conventional twisted tape [18,19], circular duct having integral spiral rib roughness with twisted tapes with oblique teeth [20], and circular duct having integral spiral corrugation roughness with conventional twisted tape [21], etc. In general, the use of twisted tubes together with twisted tapes gave better heat transfer than using the tubes without the tapes. Regarding to the above literature, only conventional twisted tapes were employed in twisted tubes. The use of three-start spirally twisted tubes inserted with triple-channel twisted tapes has not been reported. In the present work, the three-start spirally twisted tubes are expected to induce the swirl flows near tube twisted wall while the triple-channel twisted tapes are used to generate triple swirling flows around the core tube. The simultaneous use of the tubes and tapes are supposed to give synergetic swirling effect which efficiently reduces the thermal and velocity boundary layer developments and thus gives effective heat transfer enhancement. In addition, the arrangements of triple-channel twisted tapes and twisted tubes are presumed to affect heat transfer enhancement and thermal performance characteristics. In the present work, the modified twisted tapes in form of triple-channel twisted tapes are proposed instead of the conventional ones. The present investigation aims to study the heat transfer (Nusselt number), pressure drop (friction factor) and thermal performance factor in three-start spirally twisted tubes inserted with triple-channel twisted tapes. The effects of the of tape width ratio (w/D = 0.1, 0.25, 0.34 and 0.5) and tape arrangements (belly-to-neck and belly-to-belly arrangements) are also numerically investigated using RNG k-ε turbulence model. The study is carried out for Reynolds numbers between 5000 and 15,000, using water as the working fluid. The flow and thermal structure mechanisms (velocity field, stream line, turbulent kinetic energy, and temperature field) and local Nusselt number distributions around the tube wall of water in three-start spirally twisted tubes combined with triple-channel twisted tapes are also described.

2. Geometry and configuration of three-start spirally twisted tube and triple-channel twisted tape

The system of interest is a three-start spirally twisted tube combined with a triple-channel twisted tape. The triple-channel twisted tape is installed in the three-start spirally twisted tube as shown in Fig. 2. The twisted tube is formed with 360° twist pitch (P: corrugation pitch) and its depth of the groove wall (e) to outer tube diameter (D) ratio is 0.16. The triple-channel twisted tapes with constant twist ratio of y/P = 0.5 (180°) and different width ratios (w/D = 0.1, 0.25, 0.34 and 0.5) are inserted into the twisted tubes. The tape/tube alignments are in belly-to- neck and belly-to-belly forms. Note that, the tape with w/D of 0.5 is applied only for belly-to-belly arrangement (not for the belly-to- neck arrangement due to the dimension limit).

3. Flow configurations and boundary conditions

The computational domain for the flow in tube fitted with three-start spirally twisted tube combined with triple-channel