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Numerical studies on heat transfer and friction factor characteristics of a tube fitted with helical screw-tape without core-rod inserts

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A B S T R A C T

The principle of heat transfer enhancement in the core flow of tube has been proposed to improve the temperature uniformity and reduce flow resistance, which is different from that of heat transfer enhancement in the boundary flow of tube. Helical screw-tape inserts with four different widths (w = 7.5 mm, 12 mm, 15 mm and 20 mm) have been investigated for different inlet volume-flow rates ranging from 200 L/h to 500 L/h. A three-dimensional turbulence analysis of heat transfer and fluid flow is performed by numerical simulation. The simulation results show that the average overall heat transfer coefficients in circular plain tubes are enhanced with helical screw-tape of different widths by as much as 212 $\sim$ 351% at a constant tube-side temperature and the friction factor are enhanced by as much as 33% to 1020%. The PEC value of the helical screw-tape inserts of different width varies between 1.58 and 2.35. Physical quantity synergy analysis is performed to investigate the mechanism of heat transfer enhancement. The synergy angles α, β, γ, θ and η are calculated, and the numerical results verify the synergy regulation among physical quantities of fluid particle in the flow field of convective heat transfer, which can guide the optimum design for better heat transfer units and high-efficiency heat exchangers. Entropy generation analysis is also performed to explain how to get the optimum helical screw-tape.

1. Introduction

Heat exchangers, which are widely used in many fields such as power generation, chemical industry, metallurgy, steel production, refrigeration, air-conditioning etc., are indispensable general devices for heat transfer. The most significant variables in reducing the size and cost of a heat exchanger are heat transfer coefficient and pressure drop or flow resistance. An increase in the heat transfer coefficient often leads to an increase in the flow resistance, thereby reducing energy efficiency. The main challenge for heat exchangers design is to minimize the flow resistance while enhancing the heat transfer coefficients.

Generally speaking, tube flow can be divided into two parts [1]: boundary flow and core flow. The methods of surface-based heat transfer enhancement are the common methods to enhance heat transfer in the tube. While these measures are effective for heat transfer, however, viscous resistance of fluid initiated from the wall surface would lead to significant increase in flow resistance, which is a cost for more efficient heat convection. To overcome this inherent weakness of surface-based enhancement, a number of experiments have been conducted on fluid-based enhancement [2–4]. In theory, Liu and Yang have proposed four principles for increasing efficiency for core flow [5]. The first two principles have to do with enhancing the uniformity of core flow temperature by increasing the effective thermal conductivity of the fluid and disturbing the fluid of the core flow field. The third principle suggests that velocity gradient inside tube should be minimized to reduce fluid shear force. Finally, the continuous extended surface should be broken to avoid large surface friction so that the disturbance to the boundary may be reduced to avoid large momentum loss [6]. Nevertheless, few studies have been conducted to verify the four principles. This study intends to fill the gap by simulating the heat transfer and flow resistance in a tube fitted with helical screw-tape without core-rod inserts.

In the past work, the twisted-tape inserts are extensively used in the heat transfer enhancement of many heat exchangers. Manglik and Bergles [2,3] reported the experimental data for twisted-tape and presented predictive correlations for laminar and turbulent flows under uniform wall temperature condition. Saha and Gaitonde [7] used the regularly spaced twisted tape elements connected by thin circular rods to investigate heat transfer enhancement in a circular tube. Date and Gaitonde [8] introduced the correlations for predicting characteristics of laminar flow in a tube fitted with regularly spaced twisted tape elements. Ventsislav [9] presented the enhancement of heat transfer by a combination of a single start spirally corrugated tubes with twisted tapes in turbulent flow and presented empirical correlation along with

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Nomenclature

Be	Bejan number
c_p	the specific heat at constant pressure (kJ/kg K)
d_1	inner diameter of helical screw-tape (m)
d_2	outer diameter of helical screw-tape (m)
D	the tube diameter (m)
f	friction factor
h	the average heat transfer coefficient in the tube (W/m^2 K)
k	turbulent kinetic energy (m^2/s^2)
L	the length of tube (m)
Nu	average Nusselt number
$(N_S)_T$	entropy generation number from heat transfer irreversibility
$(N_S)_P$	entropy generation number from fluid friction irreversibility
N_S	entropy generation number
$\dot{m}$	mass flow rate in tube per unit tape length (kg/m s)
P	pressure (N/m^2)
q'	heat transfer rate per unit tape length (W/m)
Re	Reynolds number
$\dot{S}'_{gen}$	the entropy generation rate per unit tape length (W/m K)
s	pitch of helical screw-tape (m)
T	temperature (K)
u	the flow velocity (m/s)
v_t	kinematic eddy viscosity (m^2 s^{-1})
Greek symbols	
α	synergy angle (°)
β	synergy angle (°)
γ	synergy angle (°)
θ	synergy angle (°)
η	synergy angle (°)
ρ	density of water (kg/m^3)
δ	Kronecker delta
λ	thermal conductivity (W/m K)
τ	shear stress (Pa)
ω	specific turbulence dissipation rate (s^{-1})
Subscripts	
0	plain tube
m	mean
w	wall

performance prediction. Chang et al. [10] experimentally studied the axial heat transfer distribution and friction factor for the tubes fitted with broken twisted tapes of different twisted ratios, and found that local Nusselt number and mean friction factor increased with the decrease of twisted ratio. Naphon [11] compared tubes with twisted inserts with those without twisted-tape inserts, and proposed non-isothermal correlations for predicting the heat transfer coefficient and friction factor of the horizontal pipe with twisted-tape inserts.

Helical screw-tape is a modified form of a twisted tape wound on a single rod. Both the helical screw-tape and the twisted-tape generate a similar swirling flow in the circular tube, but they exhibit different characteristics of flow. For the helical screw-tape, the swirling flow rotates in single way smooth direction of flow like a screw motion, while the twisted-tape generates the swirling flow in two way directions of parallel flows simultaneously (two parallel flows separated by the twisted-tape). Sivashanmugam and Suresh [12–15] studied the heat transfer and friction factor characteristics of the laminar and turbulent flows in a circular tube fitted with full-length helical screw-tapes with different twist ratios, including the increasing and decreasing order of twist ratio sets. Eiamsa-ard and Promvonge [16] reported enhancement of heat transfer in a tube with regularly-spaced helical tape swirl generator with Reynolds number between 2300 and 8800 using water as working fluid, and concluded that the full-length helical tape with rod provides the highest heat transfer rate about 10% better than that without rod. Ibrahim [17] experimentally investigated the heat transfer a characteristics and friction factor in the horizontal double pipes of flat tubes with full length helical screw element of different twist ratio and helical screw inserts with different spacer length and found that the Nusselt number and friction factor decreased with the increase of spacer length for flat tube. Guo et al. [18] numerically studied the circular tube fitted with helical screw-tape inserts from the viewpoint of field synergy principle, they compared the results based on the RNG k-epsilon turbulence model with those based on the SST k-omega turbulence model, and concluded that the SST k-omega turbulence model performs much better than k-epsilon turbulence model both qualitatively and quantitatively, in terms of agreement with the experiment. Eiamsa-ard and Promvonge [4] experimentally investigated the enhancement of heat transfer in a concentric double tube heat exchanger fitted with loose-fit, regularly spaced and full-length helical screw-tape swirl generators. Contrasting the tape with core-rod and that without core-rod, it was found that the heat transfer rate obtained without core-rod was higher than that with core-rod around 25%–60% while the friction resistance without core-rod was around 50% lower. Furthermore, the enhancement efficiency for the helical screw-tape without core-rod was about 2 times higher than that with the core-rod. Focusing on the helical screw-tape without core-rod but varying the tape widths, this paper numerically investigates the heat transfer and friction factor characteristics of turbulent flow through a circular tube helical screw-tape.

However, as mentioned above, there are extensive literatures investigating the tubes fitted with helical tape inserts, they mainly focused on the performance of heat transfer and flow resistance, the mechanism of heat transfer enhancement is rarely reported. So it is worthwhile studying the novel mechanism of heat transfer enhancement, which could serve as a guideline to optimize heat exchangers and design new-type heat transfer enhancement apparatus. Guo et al. [19,20] proposed the field synergy principle which indicates that the heat transfer rate depends not only on the velocity and temperature fields but also on their synergy which is related to an integral of the inner product of the temperature gradient and the velocity field. Liu et al. [21–23] developed Guo's field synergy principle and proposed that there exists other synergetic relation among physical quantities besides the velocity and temperature fields. Improving synergetic relation among physical quantities is beneficial to heat transfer enhancement. In the recent design work of a thermal system, the efficient utilization of exergy has been treated as an essential consideration except the analysis from the view point of Thermodynamic First Law. Irreversibility and entropy generation in the flow field have been adopted as a gauge for evaluating the optimization of a thermal system. Based on the minimal entropy generation principle [24,25], considerable optimal designs of thermal systems have been proposed [26–31]. However, as for helical screw-tape, most of past researches were restricted to the Thermodynamic First Law. The relevant entropy generation analysis is still very rare.