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Numerical simulation of turbulent flow forced convection in a twisted elliptical tube

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A B S T R A C T

The numerical simulations by turbulent water forced convection in a three-dimensional twisted elliptical tube with constant wall temperature are investigated in this study. Flow resistance and heat transfer characteristics of water in the twisted elliptical tube are studied with the parameters, including Reynolds number and the twist pitch. Effects of the above-mentioned parameters on the performance of the twisted elliptical tubes are analyzed and the overall thermal-hydraulic performance is evaluated. The thermal resistance of the heat exchanger is defined based on the entransy dissipation theory. The results show that in the twisted elliptical tubes, rotational motions are produced in the flowing fluid that improves the synergy between velocity vectors and the gradient of temperature and enhances the heat transfer performance compared with an oval tube. The twist elliptical tubes bring on the pressure drop because of the twisted wall. The results are then compared with the results of the oval tube, the pressure drop of the twisted elliptical tube with d = 96 mm increases 58%–60%. The averaged Nusselt number with d = 96 mm increases 16%–19% compared with the oval tube. In addition, the average Nusselt number and the pressure drop both increase with increasing Reynolds number, while both decrease with the increasing of the twist pitch. The twisted elliptical tube can reduce the entransy dissipation based thermal resistance that provides the great benefit in heat transfer. The twist pitch has an influence on the overall thermal-hydraulic performances. The results show that the twisted elliptical tube with d = 128 mm has the best overall thermal-hydraulic performance.

1. Introduction

Heat exchangers are widely used in the petrochemical plants, refrigeration, power stations, oil refineries, and chemical engineering industry. Because the heat transfer process is irreversible, the efficiency of energy utilization is considered to be improved for the purposes of energy saving. For example, the efficiency of the tube heat exchanger can be promoted by enhancing the heat transfer in the tube and that would offer advantages in performance and economy. There are certain methods to enhance the ability of heat dissipation in the forced convection, including installing fins to increase the cooling area, changing the geometry of the flow channel to break the boundary layer, and improving the convective heat transfer coefficient by impingement cooling. In this study, the thermal performance of tube heat exchangers is improved by changing the shape of the cross section. The twisted elliptical tube is one of the heat transfer enhancement tube, and has been studied by a few researchers experimentally and numerically [1–5]. Asmantas et al. [1] conducted the experiment of turbulent air flowing through twisted elliptical tubes with different twisted pitches "d." The results indicated that the average Nusselt number and the flow resistant increased as d decreased. When $L/d = 6.2$, the heat transfer was augmented by 40%, and the hydraulic drag also increased by 70% on average. Other researches were carried out to study the thermal-hydraulic performance of the twisted elliptical tubes with different geometrics, working fluids and Reynolds numbers. Yang and Li [2] studied the heat transfer characteristics of fluid with different Prandtl number in laminar flow region in a twisted elliptical tube. Meng et al. [3] presented the numerical results of laminar flow in a twisted oval tube. There was a notable enhancement in convective heat transfer in a twisted elliptical tube with a low increment in flow resistance. The overall thermal-hydraulic performance was up to 2–4.

Besides, Yang et al. [4] conducted an experimental investigation on the heat transfer and flow characteristics of water flow in the twisted elliptical tubes in laminar, transition and turbulent regions. Correlations of the average Nusselt number and the friction factor were derived. It was discovered that the overall thermal-hydraulic performance was better in the laminar flow region because of the early transition from laminar to turbulence region in the twisted elliptical tube. Tan

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et al. [5] studied the turbulent flow in different aspect ratio and twist pitch length, demonstrating that the heat transfer coefficient and the friction factor increased as the aspect ratio increased and the twist pitch length decreased. Results showed that the thermal-hydraulic performance was better when the Prandtl number of the working fluid was greater.

Unlike thermodynamics, there is no physical property in heat transfer science to describe the efficiency of the heat transfer. To compare the efficiency of heat exchangers, researchers have tried to find the relationship between irreversibility produced in the process and the heat transfer performance of the heat exchanger. Bejan [6] applied the entropy analysis in thermodynamics to heat transfer processes. He indicated that the irreversibility was reflected in heat transfer across a temperature difference and the flow resistance and the achievement of the minimum entropy generation was the goal in a heat transfer process. The principle of minimum entropy generation is utilized by many researchers as an object function in optimizing heat exchangers. Shah and Skiepko [7] investigated 18 types of heat exchangers numerically. It was discovered that when the minimum entropy generation was achieved, the heat transfer performance could be at the maximum, median, or even minimum. Although the concept of the entropy generation provides a theoretical evaluation in convective heat transfer processes, there is the entropy generation paradox that cannot be explained by the minimum entropy generation principle.

Guo et al. [8] presented the concept of heat transfer potential capability as an electrical analogy in 2007. A new physical property and entransy were defined as heat transfer potential capability corresponding to electric potential energy in electricity as below

$$E_h = \int_0^T QdT. \tag{1}$$

Q is the heat content. For an object, Q is the heat capacity mC_pT, which is related to the temperature of the object. The entransy of an object can be defined as

$$E_h = \int_0^T QdT = \frac{1}{2}mC_pT^2 = \frac{1}{2}QT. \tag{2}$$

For a heat transfer process from a constant temperature heat source, the heat transfer Q is not related to the temperature of the heat source. The entransy of heat transfer can be defined as

$$E_h = \int_0^T QdT = QT \tag{3}$$

representing the transmission capacity of the heat transfer Q at the temperature T. The unit of entransy is $j{\cdot}\mathrm{K}$.

For a convective heat transfer process, the energy balance equation can be derived as

$$\rho\frac{Dh}{Dt} = -\nabla\cdot\dot{q}_h + \Phi + \dot{Q}_{\mathrm{int}}, \tag{4}$$

h is the enthalpy; $-\nabla\cdot\dot{q}_h$ is the heat flowing through the inlet and outlet; Φ is the dissipation produced by the viscosity; $\dot{Q}_{\mathrm{int}}$ is the internal heat.

Also, for ideal incompressible flow that is

$$dh = C_pdT. \tag{5}$$

The entransy balance equation can be obtained by substituting Eq. (4) by Eq. (5) and multiplying by the temperature T, then we obtain

$$\rho C_pT\frac{DT}{Dt} = -\nabla\cdot(\dot{q}_hT) - \lambda(\nabla T)^2 + \Phi T + \dot{Q}_{\mathrm{int}}T. \tag{6}$$

The left term in Eq. (6) is the rate of entransy variation with time. $-\nabla\cdot(\dot{q}_hT)$ is the entransy transfer with heat flow; $\lambda(\nabla T)^2$ is the entransy dissipation in the irreversible process; ΦT is the entransy flow from Joule heat produced by the viscosity; $\dot{Q}_{\mathrm{int}}T$ is the entransy flow input from internal heat source. $k(\nabla T)^2$ represents the irreversibility of heat transfer processes, while ΦT represents the irreversibility of heat-work conversions. Because the irreversibility of heat transfer processes is relatively larger than ΦT that of heat-work conversions in heat exchangers, ΦT can be omitted to simplify. Therefore, the entransy dissipation rate can be defined as

$$\dot{e} = \lambda(\nabla T)^2 = -\dot{q}_h\cdot\nabla T. \tag{7}$$

The entransy dissipation rate can be a criterion of the reduction in heat transfer ability. In heat transfer optimization, there are two common goals: maximum heat transfer at a given temperature difference and minimum temperature difference at a given heat flux. From the definition of the entransy dissipation rate, larger entransy dissipation rate at a given temperature difference and smaller entransy dissipation rate at a given heat flux result in better heat transfer performance, referred to the entransy dissipation extremum principle. The entransy concept has been applied in many studies [9–12].

Chen et al. [13] compared the entransy dissipation theory with the entropy generation theory for the optimization of heat transfer. It was discovered that under same limitations, the optimization with minimum entropy generation resulted in the best heat-work conversion efficiency, while the optimization based on the entransy dissipation extremum principle resulted in the best convective heat transfer efficiency.

The thermal resistance is commonly utilized as a criterion of the performance in heat exchangers and it can be defined as

$$R = \frac{\Delta T}{\dot{Q}}. \tag{8}$$

In which is the temperature difference during the heat transfer process. However, the definition is limited to one dimension, therefore it is not suitable for complex heat transfer problems. Guo et al. [8] presented the thermal resistance based on the concept of entransy dissipation and it was defined as

$$R_h = \frac{\dot{e}}{\dot{Q}^2} = \frac{(\Delta T)^2}{\dot{e}} \tag{9}$$

with a unit $\mathrm{K}{\cdot}s/j$. When the heat transfer rate is fixed, less entransy dissipation leads to lower thermal resistance. When the temperature difference is fixed, the more entransy dissipation also leads to lower thermal resistance. It can be concluded that in a heat transfer problem with certain limitations, when the thermal resistance based on the entransy dissipation is minimum, the performance in heat transfer is the best. Compared with the original definition of the thermal resistance, the thermal resistance based on the entransy dissipation reveals the physical meaning of thermal resistance. It is related to the distribution of temperature, velocity, and the physical properties in the heat transfer area, such as the thermal conductivity. Therefore, it can be used in complex heat transfer problems and provide the direction of enhancing the heat transfer performance clearly.

In this study, the main purpose is to enhance the convective heat transfer efficiency of tube heat exchangers. Twisted elliptical tubes are investigated numerically and compared with the oval tube. Except the thermal resistance, field synergy angle, pressure drop and thermal performance factor are also used to describe the performance of the heat exchanger. Thermal resistance is defined based on the entransy dissipation which can be called equivalent thermal resistance and can be used as a criterion of the performance.

2. Field synergy principle

In heat exchanger problems, there exist the vector field because of the flowing working fluid and the temperature field. In 1998, Guo et al. [14] introduced the field synergy principle that explained the heat transfer mechanism by the synergy between the velocity vector and the temperature gradient. In addition, Yen et al. [15] applied the field synergy principle to hence improves the heat transfer coefficient. In 2018, Yu et al. [16] adopted the field synergy number and applies it to