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Modulated heat transfer tube with mesh cylinder inserted☆

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ABSTRACT

The concept of flow field modulation was proposed to enhance convective heat transfer in tubes. A mesh cylinder is suspended in the tube, dividing the cross section into an annular region and a core region. When the fluid flows over the mesh screen, a small portion of flow penetrates into the core region through mesh pores, while most of the fluid is within the annular region, leading to larger velocity gradient near the wall than that for the bare tube without mesh cylinder, this large velocity gradient can result in significant heat transfer enhancement. In this study experiments were performed at constant heat flux boundary conditions with water as the working fluid. Reynolds numbers vary from 2109 to 20,175, covering the transition and turbulent flow regimes. Experimental results showed that the heat transfer was enhanced over the whole length of tube, with the enhancement ratios from 1.21 to 1.84, and the largest enhancement ratio occurred in the transition flow regime. The mechanism for heat transfer enhancement could be attributed to: (1) The multi-scale characteristics of the heat transfer tube; (2) The modulated flow field with larger velocity and velocity gradient near the wall; and (3) The enhanced flow turbulence intensity.

1. Introduction

Heat exchangers have wide applications in various industry sectors. The design of heat exchangers is complicated, as it needs accurate analysis on heat transfer rate and pressure drop for long-term reliable and economic operation [1]. The challenge for design of heat exchangers is to make it compact and maintain high heat transfer rate with minimum pumping power. Various heat transfer enhancement techniques have been proposed and applied in industries.

In recent years, in order to relieve the energy shortage and environmental pollutions, the energy utilization efficiency is trying to be increased for fossil energy systems. Meanwhile, a large quantity of renewable energy such as solar energy, ocean energy, etc. has been put into use. In energy conversion and power generation systems with low grade energy and renewable energy resources, miniaturization of heat exchangers can reduce the investment cost and increase the system efficiencies. For example, a heat exchanger for an ocean thermal energy conversion (OTEC) plant requires heat transfer surface area at the order of 10^4 m^2/MW [1]. In summary, high heat transfer coefficients can achieve low and uniform temperature differences in heat exchangers, increasing the exergy efficiency of the component and system.

Besides, the thermal resistance can be increased due to fouling after the long-term operation of heat exchangers, the fouling is even more serious in heat exchangers in marine applications and chemical industries. For heat exchangers with fluids of low thermal conductivity (gases and oils), the heat transfer needs to be enhanced, and it can be realized by introducing disturbance in the fluid flow (breaking the viscous and thermal boundary layers).

Liu and Sakr [2] performed a comprehensive review on passive heat transfer enhancement in pipe heat exchangers. They reviewed experimental and numerical studies on heat transfer enhancement since 2004, by using twisted tape, wire coil, swirl flow generator, etc.

The twisted tape inserts are widely adopted to enhance the heat transfer efficiency and they perform better in laminar flow regime than in turbulent flow regime [3–8]. Eiamsa-Ard et al. [3] investigated the heat transfer characteristics of turbulent flow in circular tubes with twisted tape inserts using air as the working fluid. In their work, the heat transfer performance is better with a short tape insert in entrance, compared with a long tape inserted in the tube. Guo et al. [4] conducted numerical investigation on the heat transfer behaviors in the tubes with center-cleared twisted tape or short-width twisted tape insert. Their results indicated that the flow resistance was reduced compared with the conventional tape insert. Naphon [5] experimentally studied the heat exchangers with twisted tapes inserted in the tube bundle. Correlations of flow resistance and heat transfer were obtained. Murugesan et al. [6] used V-cut twisted tape to enhance the convective heat transfer. The Nusselt numbers could be increased by increasing the depth ratios and decreasing the twist ratios and width ratios.

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Nomenclature

BT	bare tube
D_i	inner tube diameter, m
D_o	outer tube diameter, m
f	frictional factor
h_{in}	water inlet enthalpy, J/kg
h_{out}	water outlet enthalpy, J/kg
I	current, A
k_f	water thermal conductivity, W/(mK)
k_w	stainless steel thermal conductivity, W/(mK)
L_d	developing length of the modulated flow, m
L_f	flow length between the two pressure ports, m
L_h	heating length, m
m	mass flow rate, kg/s
MHTT	modulated heat transfer tube
Nu	Nusselt number
$\Delta P_{f,m}$	measured frictional pressure drop, Pa
Pr	Prandtl number
q	heat flux on the inner wall surface, W/m^2
q_v	volume heating intensity within the wall thickness, W/m^3
Q	net heat received by water, W
Q_p	heating power, W
r	radial coordinate, m
Re	Reynolds number
ΔT	temperature difference between inlet and outlet, °C
T_b	cross-sectional average temperature, °C
T_f	water average temperature of the test section, °C
T_{in}	water inlet temperature, °C
T_{out}	water outlet temperature, °C
T_{wi}	inner wall temperature, °C
T_{wo}	outer wall temperature, °C
U	voltage, V
u	cross-sectional average velocity, m/s
x	axial coordinate, m

Greek symbols

α	local heat transfer coefficient, W/(m^{2}K)
η	thermal efficiency
ρ_l	water density, kg/m^3
φ	heat transfer enhancement ratio

Subscript

ave	average
h	heating
i	inner
m	measurements
o	outer
p	predictions
v	volume
wi	inner tube wall
wo	outer tube wall
x	axial position

Experimental correlations were achieved in their work. Eiamsa-Ard and Promvonge [7] experimentally investigated the heat transfer and pressure drop behaviors of turbulent flow in tubes with the serrated twisted tape insert. Air was used as the working fluid. The experimental results showed that the comprehensive performance was better than that with the conventional tape insert. Eiamsa-Ard et al. [8] conducted the heat transfer experiments in circular tubes with the dual twisted tape insert, showing better performance than the single twisted tape insert.

Other several passive techniques such as ribs, conical nozzle, and conical ring, are generally more efficient in the turbulent flow regime than in the laminar flow regime [9–18]. Akhavan-Behabadi et al. [9] experimentally investigated the heat transfer behaviors in heat exchangers with the coiled wires inserted in the tube bundle. In their results, the Nusselt numbers could be increased by two to three times of those in the bare tube. Promvonge [10] studied the heat transfer and friction characteristics in horizontal tubes with the square coiled wires insert. The experimental results indicated that the heat transfer and pressure drop can be augmented significantly compared with the bare tube or conventional tubes with coiled wire insert. Muñoz-Esparza and Sanmiguel-Rojas [11] numerically studied the flow and heat transfer of laminar flow in tubes with coil insert using the finite volume method. Their numerical simulations were also verified by experiments. The experimental investigation of Li et al. [12] on the heat transfer enhancement in tubes with the discrete double inclined rib insert showed that the heat transfer enhancement ratios can reach 1–1.2, with the flow resistance increased by 70–150%. Promvonge [13] investigated the heat transfer characteristics in the tubes with conical ring insert experimentally. Kongkaitpaiboon et al. [14] found that the heat transfer coefficient of turbulent flow in the tubes with the perforated conical-ring insert could be increased by 137% through experimental investigation. Promvonge and Eiamsa-Ard [15] studied the heat transfer and pressure drop characteristics in tubes with the conical nozzle and/or swirl generator insert and the experimental correlations were given. Gül and Evin's experimental research [16] on the heat transfer in tubes with the helical swirl generator inserted in the tube entrance indicated that the local heat transfer coefficients could be increased by about 20%. Jen and Yan [17] numerically investigated the heat transfer behaviors in rectangular ducts with the porous media insert. Yang and Hwang [18] studied the heat transfer characteristics in tubes with the porous media insert by numerical simulations using the k-ε turbulent flow model.

In this study a new type of heat transfer tube with mesh cylinder inserts was proposed, which is totally different technology from those reported in early literature in that the mesh cylinder is made of hollow micro-membrane with interior empty instead of bulk porous media. The mesh cylinder consists of a flat mesh screen at the bottom and a circular mesh surface on the side, dividing the tube cross section into an annular region and a core region. When the fluid flows over the mesh screen, a small portion of flow penetrates into the core region through mesh pores, while most of the fluid is within the annular region, leading to large velocity and its gradient near the wall. Preliminary experimental studies were performed to verify the idea.

2. Experimental setup and test section

Fig. 1 shows the experimental setup. The deionized/degassed water was driven by a centrifugal pump and flowed through a valve, a mass flow meter, a test section and returned to an overflow tank, which was at the atmosphere pressure. The gravitational force drove the water flow downward to the water tank at the pump tail. A heat exchanger with cooling water was used to remove the heat from the system. An overflow tube made superfluous water flowing back to the water tank, ensuring a constant water level.

The vertically arranged stainless steel tube had an outer diameter of 16.20 mm and inner diameter of 13.80 mm with a length of 2.0 m. The tube was directly heated by power source with an alternative-current (AC) voltage. The heating length was 0.98 m with two copper electrode plates welded at both ends. An electric transformer was used to convert the 380 V AC voltage to a required low voltage. The current flowing through the test tube was large due to the low electric resistance of the test tube. This heating technique was widely used in heat transfer experiments previously [19].