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Effects of characteristic parameters on heat transfer enhancement of repeated ring-type ribs in circular tubes

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ABSTRACT

Heat transfer enhancement of repeated ring-type ribs in circular tubes was experimentally investigated. Air, water and ethylene glycol–water solution (33.3% EG by vol.) were used as the working fluids. The rib height-to-tube inner diameter ratio (e/d) and rib pitch-to-tube inner diameter ratio (p/d) were arranged in the range of 0.025–0.069 and 0.29–5.8 respectively. The Reynolds number (Re) was in the range of 3601–26025 and the Prandtl number (Pr) was in the range of 0.7–15.6. Empirical equations for the Nusselt number (Nu) and Darcy friction factor (f) are proposed. The Nu value increases with the e/d value and it decreases with an increase of the p/d value. In addition, the Nu value increases with the Re value and it is proportional to the 0.45 power of the Pr value. The Nu enhancement index and mechanical energy consumption index were used to compare the heat transfer enhancing tubes to a smooth tube. At $e/d \leqslant 0.043$, for achieving an effective heat transfer enhancement, the p/d value needs to be smaller than 4.35; at $e/d \geqslant 0.069$, for avoiding a large pressure drop, the p/d value should be larger than 1.45.

1. Introduction

Circular tubes are widely used for fabricating shell-and-tube heat exchangers in industry. Heat transfer performance of these heat exchangers is highly dependent on the internal and external convection heat transfer coefficients of the tubes. Effectively increasing the convection heat transfer coefficients not only reduces the heat exchanger size, but also cuts down the manufacturing cost. The convection heat transfer coefficients can be raised by applying various heat transfer enhancement techniques. In air-conditioning and refrigeration applications, the increase in convection heat transfer coefficient on the inner side of the circular tubes is especially useful for upgrading the performance of medium/large-size chillers with shell-and-tube evaporators and condensers. In these evaporators and condensers, by substituting smooth circular tubes with heat transfer enhancing tubes, the evaporating temperature of the refrigerant can be raised and the condensing temperature can be reduced. Consequently, the power consumption of the compressor is decreased and an upgrade of the system performance is achieved.

In the past few decades, numerous heat transfer enhancement techniques for tubes and ducts have been proposed. Comprehensive assessments of these techniques are available in the literature [1–3]. Webb et al. [4] investigated heat transfer and fluid friction for fully developed turbulent flow in tubes with transverse ribs. Webb and Ramadhyani [5] analyzed flow field in a parallel-plate channel with staggered ribs. Sparrow et al. [6] showed that heat transfer enhancement of a slat-like blockage in a circular tube is effective within a distance of 10 tube diameters downstream of the blockage. Gee and Webb [7] measured heat transfer data in circular tubes with helical ribs. Sethumadhavan and Raja Rao [8] proposed optimum rib helical angles for helical-wire-coil-inserted circular tubes. Uttarwar and Raja Rao [9] showed that, for helical-wire-coil-inserted circular tubes, heat transfer enhancement at low Reynolds numbers is more pronounced than that at high Reynolds numbers. Royal and Bergles [10] compared condensation heat transfer in tubes with twisted-tape inserts to that with internal fins. Goto et al. [11,12] examined condensation and evaporation heat transfer augmentations in internally grooved tubes. Fernandez and Poulter [13] proposed a flag-type insert for enhancing heat transfer in circular tubes. Wang et al. [14] measured heat transfer data in a channel with metallic-filament inserts. Junkhan et al. [15] investigated the effect of turbulators on the heat transfer for circular tubes in fire tube boilers. Molki and Bhamidipati [16] explored heat transfer enhancement due to Corona wind effect in circular tubes. Zhou [17] showed heat transfer enhancement of nano-particle fluid exerted with acoustic oscillation. Rabienataj Darzi et al. [18] measured heat transfer and fluid friction data for nano-particle fluid in

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Nomenclature

c_p	specific heat, J/kg-K
d	tube inner diameter, m
d_o	tube outer diameter, m
e	rib height, m
f	Darcy friction factor
h_i	average internal convection heat transfer coefficient, W/m^2-K
h_o	average external convection heat transfer coefficient, W/m^2-K
k	fluid thermal conductivity, W/m-K
k_c	tube-wall thermal conductivity, W/m-K
L	tube length, m
$\dot{m}$	mass flowrate, kg/s
m	slope
Nu	average Nusselt number, hd/k
p	rib pitch, m
ΔP	pressure drop, mm-H_2O or kg/m-s^2
Pr	Prandtl number, $\mu c_p/k$
r_a	groove arc radius, m
r_1	Nu enhancement index
r_2	mechanical energy consumption index
Re	Reynolds number, $\rho Ud/\mu$
T	fluid temperature, °C
$T_{m,inner}$	mean fluid temperature in tube, °C
$T_{m,outer}$	mean fluid temperature in annulus, °C
T_w	tube wall temperature, °C
U	mean fluid velocity, m/s
$\dot{V}$	volumetric flowrate, L/min
Greek symbols	
μ	dynamic viscosity, kg/m-s
ρ	density, kg/m^3
Subscripts	
b	bulk
i	inlet
o	outlet or smooth tube
w	wall

helically corrugated tube. Zimparov [19] investigated heat transfer in corrugated tubes inserted with a twisted tape. Won and Ligrani [20] compared heat transfer in a channel with parallel-rib turbulators to that with crossed-rib turbulators. Singh et al. [21] proposed a set of heat transfer and fluid friction factor correlations for multiple arc shape roughness elements in a rectangular duct. San and Huang [22] investigated heat transfer and fluid friction for air flow in circular tubes with repeated ribs. Rainieri et al. [23] measured heat transfer data for highly viscous fluid in coiled corrugated tubes. Bas and Ozceyhan [24] investigated heat transfer enhancement of twisted tape inserts in a circular tube. Garcia et al. [25] compared heat transfer performance of corrugated tubes to those of dimple tubes and wire-coil-inserted tubes. Tan et al. [26] showed heat transfer characteristics of twisted oval tubes. Promvonge et al. [27] measured heat transfer and pressure drop data for a corrugated tube with double twisted tape inserts. Rainieri et al. [28] showed that installing wire coil in corrugated tubes can further enhance the heat transfer. Naphon and Suchana [29] measured heat transfer and pressure drop data for flow in a concentric tube inserted with twisted wire brushes. Kim et al. [30] proposed an optimum design for transverse ribs in circular tubes. Zhang et al. [31] investigated heat transfer enhancement of helical blade rotors in a tube. Saha [32] investigated heat transfer performance for a highly viscous flow in square and rectangular tubes with transverse ribs and coiled-wire insert. Naphon et al. [33] and Ravigururajan and Bergles [34] proposed heat transfer and fluid friction equations for tubes with helical rib.

As indicated in the above, there are many techniques that can be used to enhance the in-tube convection heat transfer. Based on an overall evaluation on heat transfer enhancement, reliability and manufacturing cost, repeated ribs appear to be superior to the others. In this work, thirteen heat transfer enhancing tubes with repeated ribs (Figs. 1 and 2) were fabricated through a rolling process. The inner and outer diameters of the tubes are 13.8 mm and 15.8 mm respectively. The tube length is 1.08 m. After the rolling process, the inner and outer surfaces of the tubes form repeated ring-type ribs and grooves respectively. The arc diameter of the grooves is 2 mm which makes the groove arc diameter-to-tube inner diameter ratio of the test tubes be 0.145. The test tubes are different in rib pitch (p) and rib height (e). This provides the experiment with the rib pitch-to-tube inner diameter ratio (p/d) in the range of 0.29–5.8 and the rib height-to-tube inner diameter ratio (e/d) in the range of 0.025–0.069. The objective of this work is to establish heat transfer and fluid friction data for the heat transfer enhancing tubes. In addition, from the obtained data, it also intends to acquire appropriate e/d and p/d values for achieving an effective and efficient heat transfer enhancement. In the experiment, the Reynolds number (Re) was arranged in the range of 3601–26025.

2. Experimental setup and apparatus

One smooth tube and thirteen heat transfer enhancing tubes with different e/d and p/d values were tested. The specification of these tubes is listed in Table 1.

The experimental apparatus is shown in Fig. 3. In each set of the measurement, a test tube was installed inside another tube with inner diameter of 36 mm. The two tubes formed a double-pipe device. A boiler was used to generate steam for heating the outer surface of the test tube. Before entering the annulus of the double-pipe device, the steam was arranged to pass through a coiled copper tube which was placed in a tank filled with water. The length, wall thickness and outer diameter of the coiled tube are 5.8 m, 1 mm and 19.05 mm respectively. As the steam passed through the coiler copper tube, within a few minutes, the water in the tank started to boil and eventually maintained at a temperature close to 100 °C. Due to the heat transfer between the boiling water in the tank and the steam in the coiled tube, a stable temperature of the steam (~100 °C) entering the annulus was achieved.

Three different fluids (air, water and ethylene glycol–water solution with 33.3% EG by volume) were individually used as the working fluid in the test tube. For different fluids, a slight

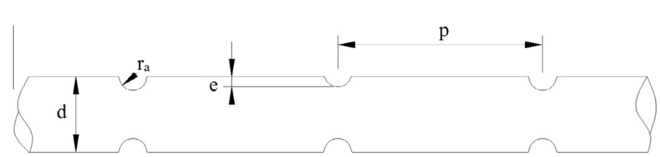

Fig. 1. Schematic of test tube.