Study on the Heat Transfer and Pressure Drop of the Horizontal Corrugated Tubes

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Abstract

In this study, the results of the heat transfer and pressure drop characteristics in the horizontal double pipes with helical ribs are presented. Nine test sections with different characteristic parameters of: helical rib height-to-diameter, χ/d_i = 0.12, 0.15, 0.19 and helical rib pitch-to-diameter, p/d_i = 1.05, 0.78, 0.63 are tested. Cold and hot water are used as working fluids in shell side and tube side, respectively. Water mass flow rates are between 0.01 and 0.10 kg/s. The inlet cold and hot water temperatures are between 15 and 20°C, and between 40 and 50°C, respectively. Effects of inlet conditions of both working fluids on the heat transfer and pressure drop are discussed. The results obtained from the corrugated tube are compared with those from the smooth tube. It is found that the helical rib has significant effect on the heat transfer and pressure drop augmentations.

Keywords: Heat transfer; friction factor; corrugated tube

Introduction

In general, the heat transfer enhancement techniques can be divided into two groups: active and passive techniques. Tubes with helical ribs have been used as one of the passive heat transfer enhancement techniques and are the most widely used tubes in several heat transfer applications for example, heat recovery processes, air conditioning and refrigeration systems, chemical reactors. Asako et al. [1] numerically studied the heat transfer and pressure drop characteristics in a corrugated duct with rounded corners. Three corrugation tube angles and four aspect ratios were considered. Obot et al. [2] experimentally studied the heat transfer and pressure drop characteristics of the spirally fluted tubes in laminar transitional and turbulent flow. The friction factor obtained from the spirally fluted tube was generally higher than that from a smooth tube. Kang et al. [3] proposed the flooding correlation as a function of the inclination angle for a fluted tube with a twisted tape insert. Water-ethyl alcohol solution and air were used working fluids. The measured data from this study were compared with those from smooth tubes from the literature. Wang et al. [4] introduced the carbon steel spirally fluted tube for replacing the copper smooth tube normally used in the high pressure preheaters. The total heat transfer coefficient obtained from the carbon steel spirally fluted tube was 10-17% higher than that of the carbon steel smooth tube. Dong et al. [5] studied the turbulent friction and heat transfer characteristics of four spirally corrugated tubes with various geometrical parameters. The spirally corrugated ribs have significant effect on the enhancement of heat transfer but not as large as the friction increases. Barba et al. [6] presented the experimental results of the steady state heat transfer and pressure drop in a corrugated tube of Ethylene glycol. Based on the data gathering during this work, correlations of Nusselt number and friction factor were proposed. Rousseau et al. [7] described the development of a simulation model for the design of fluted tube water heating condensers. Vicente et al. [8, 9] experimentally studied the mixed convection heat transfer and isothermal pressure drop in the corrugated tubes for laminar, transition, and turbulent flows. At high Reyleigh number, Nusselt number obtained from these tubes are 30% higher than those from the smooth tube. The friction factor of the corrugated tube was between 5 and 25% higher than those of the smooth tube.

This study investigates the heat transfer characteristics and pressure drop of the horizontal corrugated pipes with diameter < 10 mm. The effects of various relevant parameters on the heat transfer and pressure drop characteristics are also investigated.

Experimental Apparatus and Method

Figure 1 shows a schematic diagram of the experimental apparatus. The experimental set up is composed of a test section, refrigerant loop, hot water loop, cold water loop and data acquisition system. The test section and the connections of the piping system are designed such that parts can be changed or repaired easily. The close-loops of hot and cold water consist of the 0.5 m^3 storage tanks, an electric heater controlled by adjusting the voltage, and a cooling coil immerged inside a storage tank. R22 is used as the refrigerant for chilling the water. The hot water is adjusted to the desired level and controlled by temperature controller. After the temperature of the cold and hot water are adjusted to achieve the desired level, the water of each loop is pumped out of the storage tank, and is passed through a flow meter, test section, and returned to the storage tank. The flow rates of the water are controlled by adjusting the valve and measured by the flow meters with the accuracy of ±0.2% of full scale. The test section made from the straight copper tube consists of the outer tube and inner tube with the length of 2000 mm. The inner diameter and outer diameter of the inner tube are 8.10 and 9.54 mm. respectively. The helical ribs are fabricated by cold rolling a sharp edged wheel on the outer surface of the copper tube. Nine type-T copper-constantan thermocouples with an accuracy of ±0.1% of full scale are installed to measure the hot water, tube wall, and cold water temperatures at the inlet, middle and outlet sections as shown in Fig. 2. The differential pressure transducer with the accuracy of ±0.02% of full scale is employed to measure the pressure drop across the test section. The dimensions of the test section are listed in Table 1.

Experiments were conducted with various inlet temperatures and flow rates of hot water and cold water entering the test section. In the experiments, the hot water flow rate was increased in small increments while the cold water flow rate, inlet cold water and hot water temperatures were kept constant. The inlet hot and cold water temperatures were adjusted to achieve the desired level by using electric heaters controlled by temperature controllers. Before any data were recorded, the system was allowed to approach the steady state. Data collection was carried out using a data acquisition system having a capacity of 40 channels.

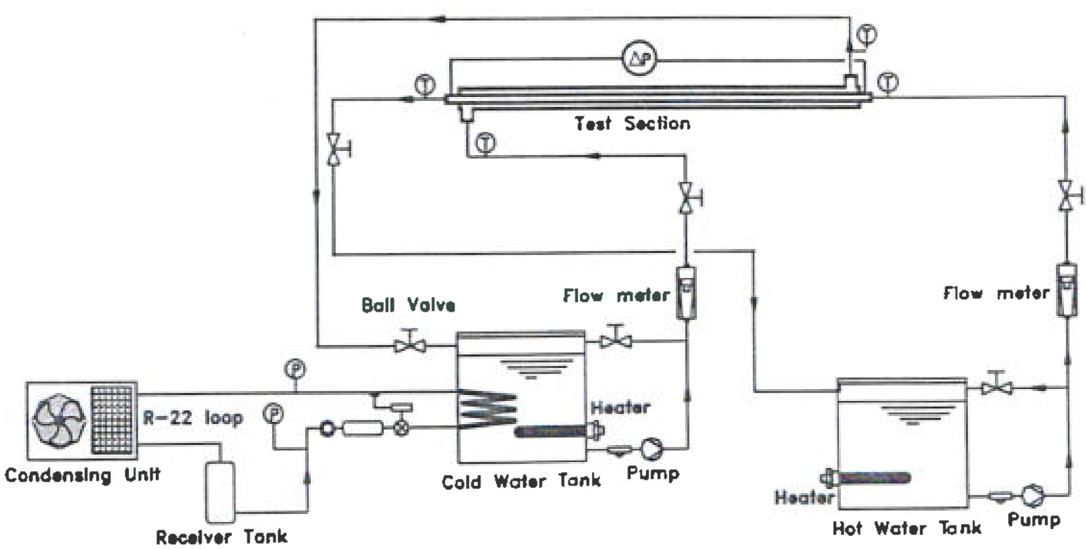

Figure 1 Schematic diagram of experimental apparatus

Table 1 Dimensions of the test section

Parameters	Dimensions
Outer diameter of outer tube, mm	28.30
Inner diameter of outer tube, mm	26.35
Outer diameter of inner tube, mm	9.54
Inner diameter of inner tube, mm	8.10
Length of test section, mm	2000.00
Pitches of helical rib, mm	8.50, 6.35, 5.08
Helical angle, °	45
Depths of helical rib, mm	1.00, 1.25, 1.50

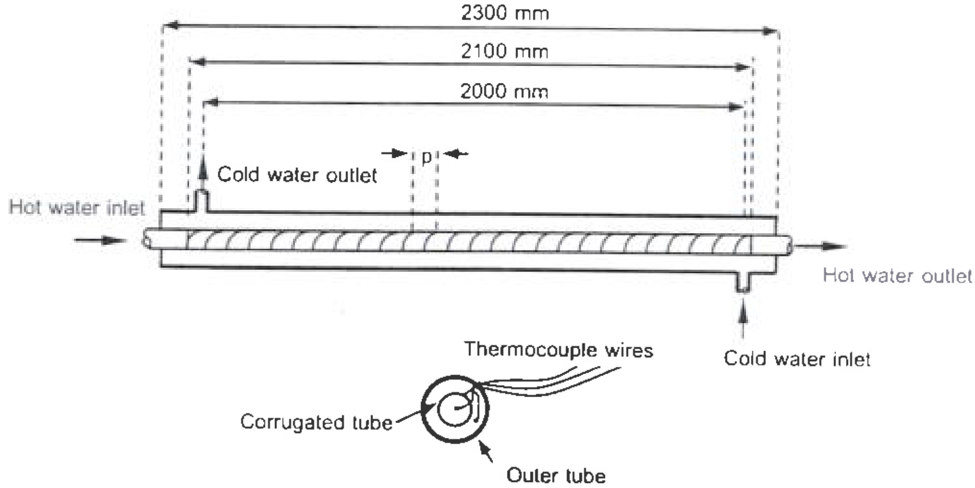

Figure 2 Schematic diagram of the test section

Data Reduction

In the following equations have been employed to calculate the heat transfer characteristics from the measured data. The data reduction of the measured results is summarized in the following procedures:

Heat transferred to the cold water in the test section, $Q_{w,c}$, can be calculated from

$$Q_{w,c} = m_{w,c} C_{p,w} \left(T_{w,c,out} - T_{w,c,in}\right) \quad (1)$$

where $m_{w,c}$ is the mass flow rate of cold water, $C_{p,w}$ is the specific heat of water, $T_{w,c,in}$ and $T_{w,c,out}$ are the inlet and outlet cold water temperatures, respectively.

Heat transferred from the hot water, $Q_{w,h}$, can be calculated from

$$Q_{w,h} = m_{w,h} C_{p,w} \left(T_{w,h,in} - T_{w,h,out}\right) \quad (2)$$

where $m_{w,h}$ is the hot water mass flow rate, $T_{w,h,in}$ and $T_{w,h,out}$ are the inlet and outlet hot water temperatures, respectively.

The average heat transfer rate, Q_{ave}, used in the calculation is determined from the hot water-side and cold water-side as follows:

$$Q_{ave} = \frac{Q_{w,c} + Q_{w,h}}{2} \quad (3)$$

The tube-side heat transfer coefficient, h_i, can be calculated from the average heat transfer rate obtained from

$$Q_{ave} = h_i A_i \left(T_{s,ave} - T_{w,ave}\right) \quad (4)$$

where $T_{s,ave}$ is the average wall temperature, and $T_{w,ave}$ is the average water temperature, and A_i is the inside surface area of tube.

The overall heat transfer coefficient, U_i, can be determined from

$$Q_{ave} = U_i A_i \Delta T_{LMTD} \tag{5}$$

where ΔT_{LMTD} is the logarithmic-mean temperature difference.

Friction factor for tube with helical rib, f_{hc}, can be calculated from

$$f_{hr} = \frac{\Delta P}{\left(\rho u^2/2\right)\left(L/d_i\right)} \tag{6}$$

where ΔP is the pressure drop across the test section, ρ is the density of water, d_i is the inner diameter of tube, u is the velocity of water, and L is the length of tube.

Results and Discussion

In the following section, the results of the heat transfer and pressure drop will be presented. A number of graphs can be drawn from the output of the present study but, because of the space limitation, only typical results are shown. Fig. 3 shows the variation of the average heat transfer rate with tube-side Reynolds number for the different inlet hot and cold water temperatures. As shown, at the specific temperatures of cold and hot water entering the test section, the heat transfer rate increases with increasing tube-side Reynolds number. However, this effect tends to diminish as Reynolds number increases. For a given tube-side Reynolds number, the heat transfer rate at higher inlet hot water temperature is higher than that at lower ones. This is because the heat transfer rate depends on the temperature difference of both working fluids. Fig. 4 also shows effect of inlet cold water temperature on the heat transfer rate. It can be clearly seen that the heat transfer rate tends to increase as the inlet cold water temperature decreases. The reason for this can be explained similarly as mentioned above. The results can be shown in another form as in Fig. 4 and the same explanation as for Fig. 3 can be given. The heat transfer rates obtained from the corrugated tube are higher than those from the smooth tube. This is because the helical ribs are significant effect on the mixing of fluid in the boundary layer and the turbulent intensity of fluid flow.

Fig. 5 shows the effect of cold water mass flow rate on the average heat transfer and inside heat transfer coefficient. It can be clearly seen from figure that the heat transfer rate increases with increasing cold water mass flow rate. This is because the heat transfer rate depends on the cooling capacity of cold water mass flow rate. However, these become closer at a lower water mass flow rate.

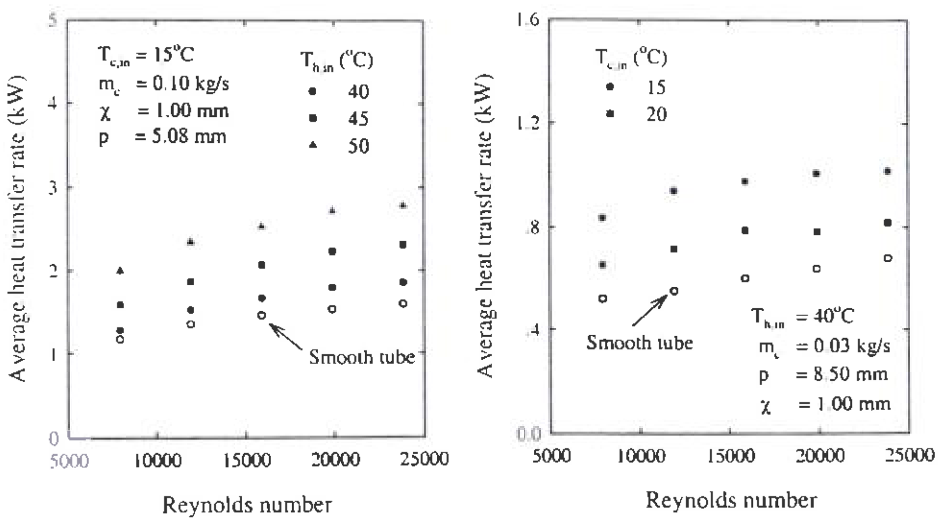

Figure 3 Variation of average heat transfer rate with hot water Reynolds number for different inlet hot and cold water temperatures

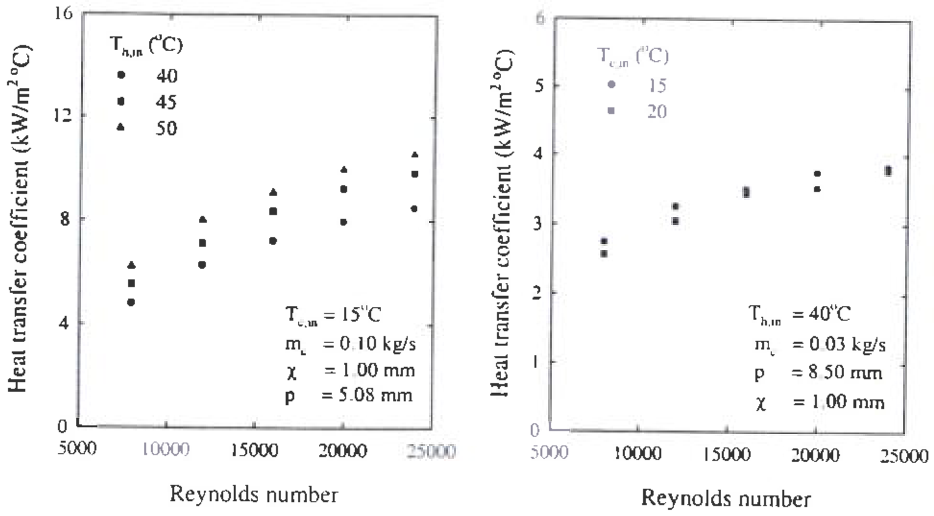

Figure 4 Variation of average tube side heat transfer coefficient with hot water Reynolds number for different inlet hot and cold water temperatures

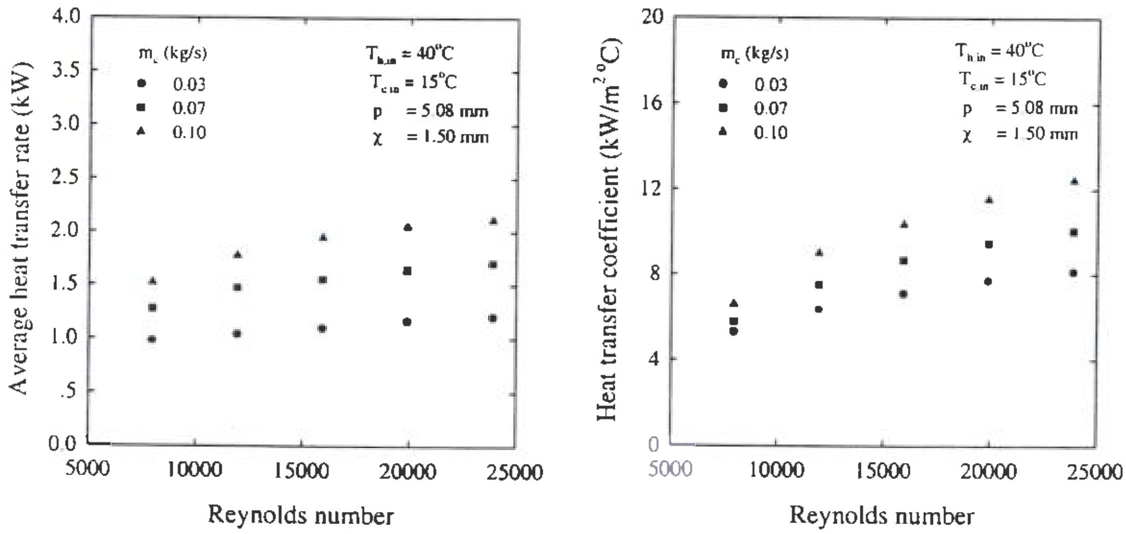

Figure 5 Variation of average heat transfer rate and heat transfer coefficient with hot water Reynolds number for different cold water mass flow rates

Figure 6 shows the variation of pressure drop with Reynolds number. In general, the flow through the tube with helical rib is quite complex. However, the pressure drop across the tube with helical rib is produced by: (1) drag forces exerted on the flow field by the helical rib, (2) flow blockage due to area reduction, (3) turbulence augmentation, and (4) rotational flow produced by the helical rib [8]. It can be clearly seen that the friction factor continues to increase with Reynolds number and rises quickly at a higher water mass flow rate. Inlet cold and hot water temperature have not significant effect on the pressure as shown in Fig. 6. The results can be shown in another form as in Fig. 7 and the same explanation as for Fig. 6 can be given. The friction factors obtained the corrugated tube are higher than those from the smooth tube. The reason for this can be explanation as mentioned above.

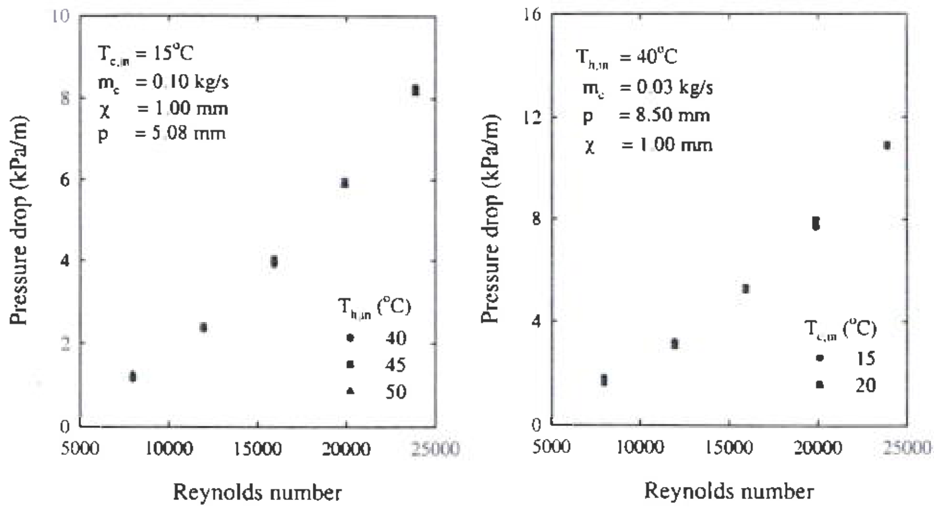

Figure 6 Variation of pressure drop with hot water Reynolds number for different inlet hot and cold water temperatures

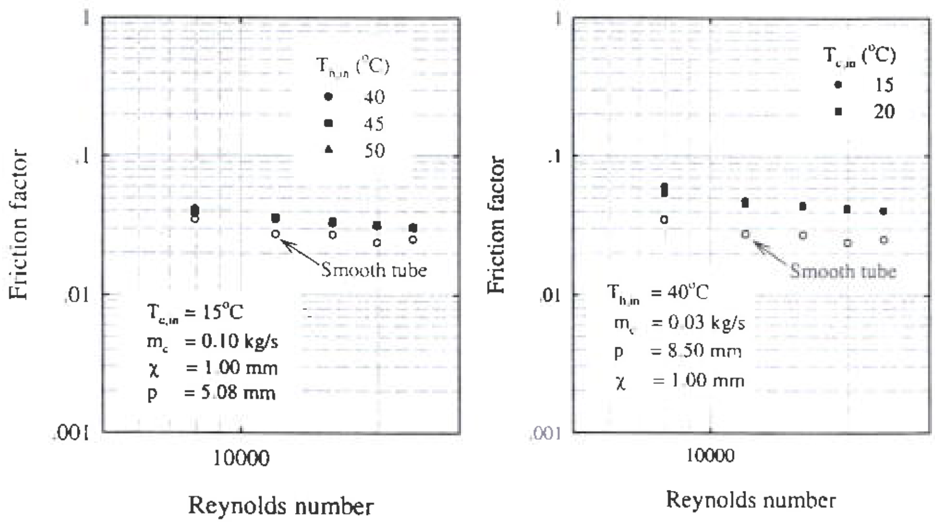

Figure 7 Variation of friction factor with hot water Reynolds number for different inlet hot and cold water temperatures

Conclusion

New experimental data on the heat transfer coefficient and friction factor characteristics of the horizontal tubes with helical rib are presented. The effects of inlet conditions and helical rib configuration on the heat transfer and pressure drop characteristics are also considered. The heat transfer coefficient and friction factor augmentations obtained from this study are compared with those from the tube without helical rib. The helical ribs have significant effect on the enhancement of heat transfer and pressure drop. This is because the helical rib has significant effect on the mixing of fluid in the boundary layer and increase turbulent intensity of the fluid flow. Therefore, the heat transfer rate and pressure drop tend to increase as compared with the tube without helical rib.

Nomenclatures

A	area
C_p	specific heat, kJ/(kg °C)
d	diameter, *m*
f	friction factor
h	heat transfer coefficient, kW/(m^2 °C)
k	thermal conductivity, kW/(m °C)

L	length, m
m	mass flow rate, kg/s
P	pressure, kPa
p	helical rib pitch, m
Pr	Prandtl number
Q	heat transfer rate, kW
Re	Reynolds number
T	temperature, °C
U	overall heat transfer coefficient, kW/(m^2 °C)
u	velocity, m/s
δ	tube thickness, m
ρ	density, kg/m^3
χ	helical rib depth, m

Subscripts

ave	average
c	cold
h	hot
he	helical rib
i	inside
in	inlet
o	outside
out	outlet
s	surface, wall
t	tube
tot	total
w	water

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