Enhancement of heat transfer in a circular wavy-surfaced tube with a helical-tape insert

S. Eiamsa-ard and P. Promvonge

Abstract— *The purpose of this study is to investigate the heat transfer and pressure drop characteristics in a circular wavy-surfaced tube with a helical-tape insert. In the experiment, the turbulence flow near the tube wall is produced by using wavy-surfaced wall while the swirling flow is generated by inserting the helical-tape along the core region. Mean Nusselt numbers and pressure drops for flows ranging from Re = 3000 to 9200 in the tube with helical tape inserts and uniform wall heat flux were experimentally studied. The experimental data obtained are compared with those obtained from plain tubes of available data in the literature. The experimental result indicates that augmented heat transfer is considerably better than the plain tube. The Nusselt numbers for the tube with wavy- surfaced wall are found to be 1.9 to 2.0 times the plain tube value while for the tube combined with wavy-surfaced wall and a helical-tape insert to be 2.48 to 2.67 times and pressure drops are seen to be 9.3 to 22.3 times the plain tube. Moreover, the wavy-surfaced tube combined with a helical-tape insert gives higher heat transfer rate and pressure drop than the wavy-surfaced tube alone around 23 to 35% and 98 to 125%, respectively.*

Keywords— **heat transfer, helical-tape, turbulence flow, wavy-surface wall, swirl flow, turbulence flow, pressure drop.**

1. INTRODUCTION

The process of improving convective heat transfer in tubes of a heat exchanger has been widely investigated, especially in passive technique. The principle of the passive technique involved in either surface treatment, such as coated surface, rough surface and extended surface or flow manipulation such as swirl flow and putting additive into the flow. One of the most favorable passive techniques is a twisted-tape inserts because they are inexpensive and can be easily employed to the existing system. From the past research, Royds [1] was the first to prove the useful effects of turbulence flow generators on heat transfer in 1921 with many experiments and types of turbulators. Kreith and Margolis [2]-[3] proposed that heat transfer cab be enhanced by introducing swirl flow in the heat exchanger with tangential injection of the fluid at various locations along the tube axis. Marner and Bergles [4]-[7] have reported experimental data for laminar flows of ethylene glycol and polybutene 20 with a twisted-tape (y=5.39) in an isothermal tube. Their experimental data over a wide Prandtl number range (1260–8130) are of immense value in the twisted-tape-generated swirl flow heat transfer literature. They found that in very viscous liquid flows, swirl flows do not set in and the heat transfer enhancement is simply due to the duct partitioning. The twisted tape induces the flow to be turbulence and swirl. These cause a thinner boundary layer and longer residual time of the flow which consequently increase in heat transfer coefficient. However, increasing in pressure drop is the penalty of the twisted tape technique. To carry out this research on the straight tape twisted in geometry form of helical tape with similar geometry of the screw tape, the helical tape insert and the twisted-tape insert generate the swirling flow in the circular tube and both of them posses the different characteristics of flow. For the helical tape, the swirling flow goes in single way direction (a screw motion), while the twisted-tape shows the swirling flow in two ways direction simultaneously. Because of lower pressure drop, twisted tape insert is, in general, more popular than the helical tape despite higher heat transfer rate. However, at low values of Reynolds number the pressure drops for using both tapes are not much different. In a solar water heater system, helical tape insert can be well applied due to low Reynolds number in the system. This helical tape can help to promote higher heat transfer exchange rate than the use of twisted-tape because of shorter pitch length which leads to stronger swirling flow and long residence time in the tube. Thus, the aim of the present work is to reduce the pressure drop occurring from using the tape insert in the tube which benefits heat transfer rate. In this paper the influences of (1) circular tube with wavy-surface walls and (2) combination between tube with wavy-surface walls and helical-tape inserted at the core tube, on enhancement heat transfer rate were experimental investigated. All of the experiments were carried out at the same inlet condition with the Reynolds number of the inner tube, Re = 3000 – 9200.

2. EXPERIMENTAL SET-UP

Materials

The experiments were carried out in an open-loop experimental facility as shown in Fig. 1. The loop consisted of a 7.5 kW blower, orifice meter to measure the flow rate, and the heat transfer test section. The copper test tube has a length of L = 1250 mm, with 47.5 mm inner diameter (D_i), 50.5 mm outer diameter (D_o), and 1.5 mm copper tube thickness (t) as depicted in Fig. 2. The tube was heated by continually winding flexible electrical wire provided a uniform heat flux boundary condition. The electrical output power was controlled by a variac transformer to obtain a constant heat flux along the entire length of the test section and by keeping the current less than 3 amps. The outer surface of the test tube was well insulated to minimize convective heat loss to surroundings, and necessary precautions were taken to prevent leakages from the system. The inner and outer temperatures of the bulk air were measured at certain points with a multi-channel temperature measurement unit in conjunction with the Chromel-constantan thermocouples as can be seen in Fig. 2. Fifteen thermocouples were tapped on the local wall of the tube and the thermocouples were placed round the tube to measure the circumferential temperature variation, which was found to be negligible. The mean local wall temperature was determined by means of calculations based on the reading of Chromel-constantan thermocouples. Fig. 2(a) represented the circular tube with wavy-surfaced wall arrangement used in the present experiment. The wavy-surfaced wall was made of Aluminum with l = 95 mm (2.0D) in length and its center diameters were 46 mm and 28 mm, respectively. Fig. 2(b) represented the wavy-surfaced tube combined with a helical tape insert used in this test. In the experiments, the geometric conditions of the helical tape inserted were kept

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constant. The helical tape was made of stainless steel and has the geometric dimensions of W = 17 mm (0.95D), d = 5 mm (0.26D), P = 18 mm (0.95D), t = 1 mm (0.05D), respectively. In the test run, helical tapes were inserted in the core tube as shown in Fig. 2(b).

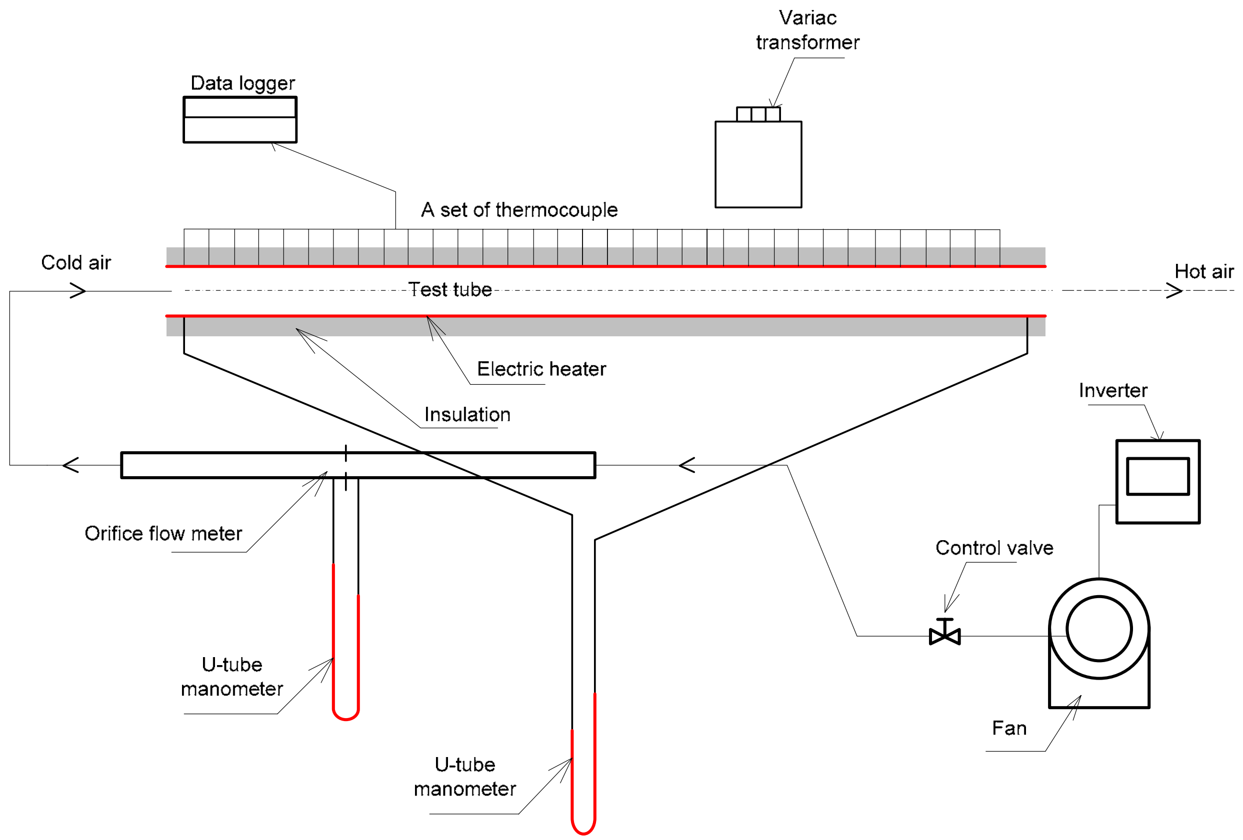
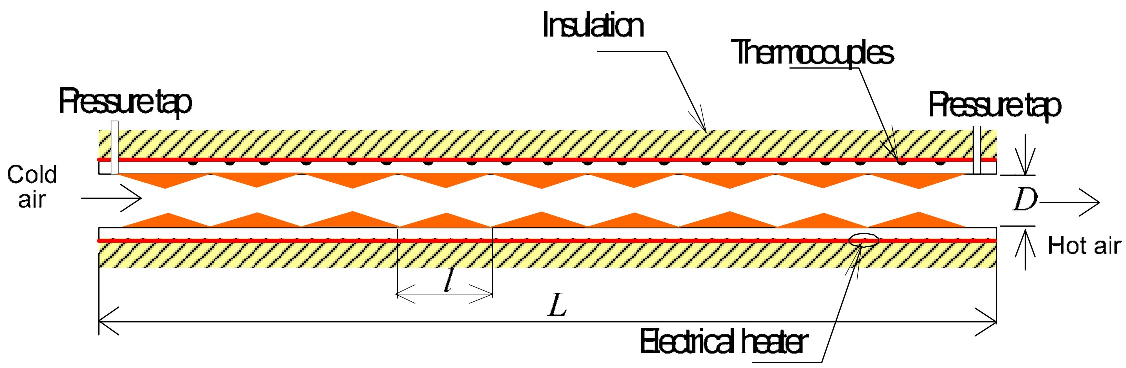
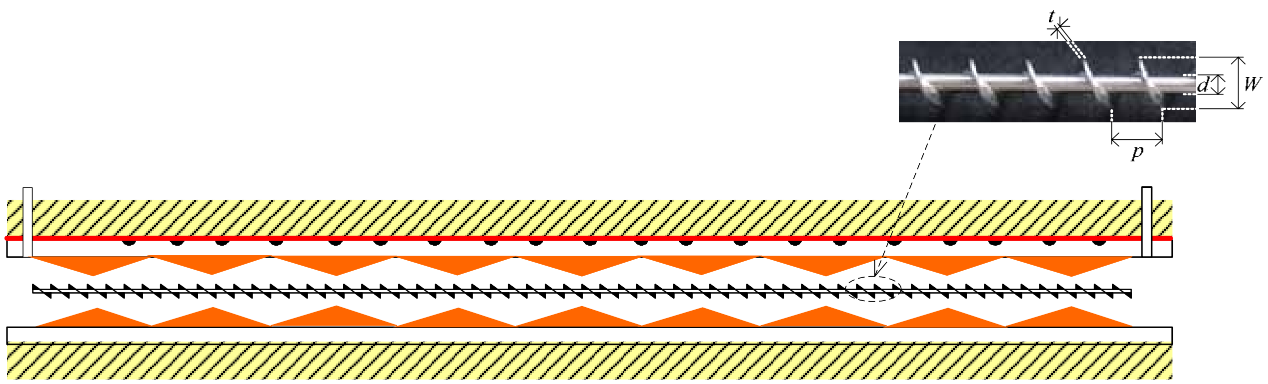


Fig. 1. Experimental apparatus.



(a) a circular wavy-surfaced tube wall



(b) a circular wavy-surfaced tube combined with a helical-tape

Fig. 2. Test tube.

Method

In the apparatus setting above, the inlet bulk air at 25°C from a 7.5 kW blower was directed through the orifice meter and passed to the heat transfer test section. The air flow rate was measured by an orifice meter, built according to ASME standard. Manometric fluid was used in U-tube manometers with specific gravity (SG.) of 0.826 to ensure reasonably accurate measurement of the low pressure drop encountered at low Reynolds numbers. Also, the pressure drop of the heat transfer test tube and the snail were measured with inclined U-tube manometers. The volumetric air flow rates from the blower were adjusted by varying motor speed through the inverter, situated before the inlet of test tube. During the experiments, the bulk air was heated by an adjustable electrical heater wrapping along the test section. Both the inlet and outlet temperatures of the bulk air from the tube were measured by multi-channel Chromel-constantan thermocouples, calibrated within ±0.2°C deviation by thermostat before being used. It was necessary to measure the temperature at 15 stations altogether on the outer surface of the heat transfer test pipe for finding out the averaged Nusselt number. For each test run, it was necessary to record the data of temperature, volumetric flow rate and pressure drop of the bulk air at steady state conditions in which the inlet air temperature was maintained at 25°C. The various characteristics of the flow, the Nusselts number, and the Reynolds numbers were based on the average of tube wall temperature and outlet air temperature. The local wall temperature, inlet and outlet air temperature, the pressure drop across the test section and air flow velocity were measured for heat transfer of the heated tube with V-nozzles or snail entrance. The average Nusselt numbers were calculated and discussed where all fluid properties were determined at the overall bulk mean temperature.

3. DATA REDUCTION

In the present work, the air is used as working fluid and flowed through a uniform heat flux and insulation tube. The steady state of the heat transfer rate is assumed to be equal to the heat loss from the test section which can be expressed as:

$$Q_{air} = Q_{conv} \tag{1}$$

Where

$$Q_{air} = \dot{m}C_{pa}(T_o - T_i) = VI \tag{2}$$

The convection heat transfer from the test section can be written by:

$$Q_{conv} = hA(\tilde{T}_w - T_b) \tag{3}$$

whereas,

$$T_b = (T_o + T_i)/2 \tag{4}$$

and

$$\tilde{T}_w = \sum T_w / 15 \tag{5}$$

where T_w is the local wall temperature and evaluated at the outer wall surface of the inner tube. The averaged wall temperatures are calculated from 15 points, lined between the inlet and the exit of the test pipe. The averaged heat transfer coefficient, h and the mean Nusselt number, Nu are estimated as follows:

$$h = \dot{m}C_{p,a}(T_o - T_i)/A(\tilde{T}_w - T_b) \tag{6}$$

$$Nu = hD/k \tag{7}$$

The Reynolds number is given by

$$Re = UD/v \tag{8}$$

Friction factor, f can be written as:

$$f = \frac{\Delta P}{\left(\frac{L}{D}\right)\left(\rho\frac{U^2}{2}\right)} \tag{9}$$

in which U is mean velocity of the tube. All of thermo-physical properties of the air are determined at the overall bulk air temperature from Eq. (4).

4. RESULTS AND DISSCUSION

Effect of wavy-surfaced wall

The effect of using the wavy-surfaced tube wall on heat transfer characteristic is shown in Fig. 3. It is found that the tube fitted with the wavy-surfaced wall gives higher heat transfer rate than the plain tube. The maximum Nusselt number increased at about 202% when compared with those from correlations of the plain tube. It can be attributed that the use of the wavy-surfaced wall can cause the turbulence/reverse flow and pressure gradient in the radial direction. The boundary layer along the tube wall would be thinner with the increase of turbulent flow and pressure resulting in more heat flow through the fluid. Furthermore, the recirculation/reverse flow enhances the turbulence fluctuations, which lead to even better convection heat transfer. Thus, the higher Reynolds numbers the greater Nusselt number. The relationship between the pressure drop and Reynolds number for using the wavy-surfaced tube wall is presented in Fig. 4. In the figure, it is worth noting that pressure drop from the wavy-surfaced tube decreases at low Reynolds numbers due to weak turbulence/reverse flow but increases substantially at higher values of Reynolds number. The trend of pressure losses is similar for both the axial flow (plain tube) and the turbulence/reverse flow (tube with wavy-surfaced wall). The pressure loss for the tube with wavy-surfaced walls is substantially higher than that for the plain tube because of a higher surface area and the dissipation of dynamic pressure of the fluid at high viscosity loss near the tube wall. Moreover, the pressure loss has a high possibility to occur by the interaction of the pressure forces with inertial forces in the boundary layer. Also, the flow velocity is larger since the motion is not in an axial direction.

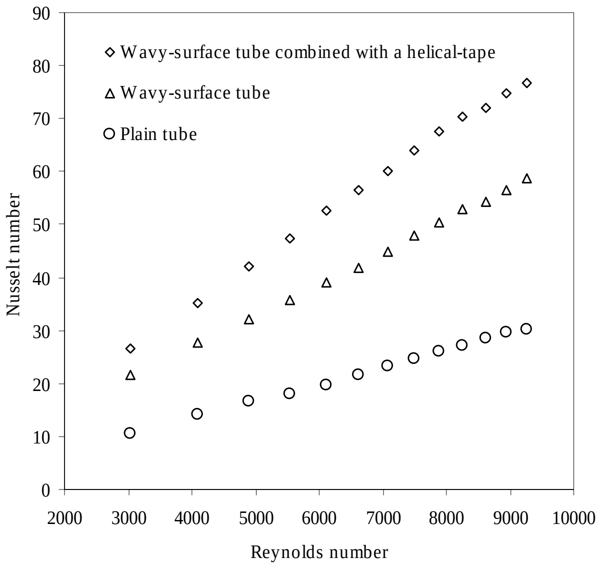


Fig. 3 Relationship between Nusselt number and Reynolds number.

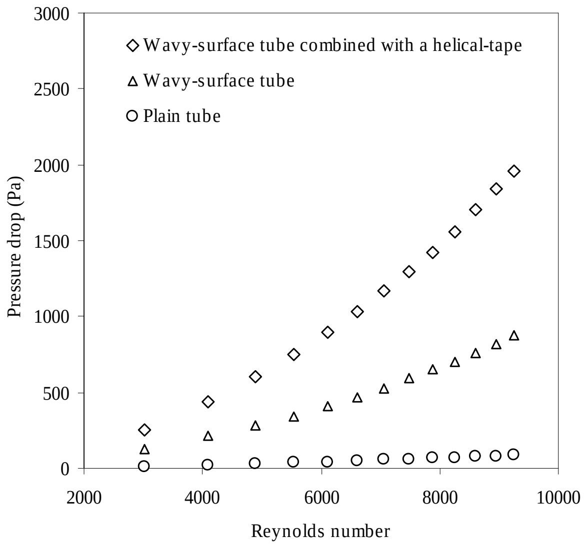


Fig. 4 Relationship between pressure drop and Reynolds number.

Effect of the tube with wavy-surfaced wall combined with a helical tape insert

In comparison between the circular wavy-surfaced tube with and without a helical tape, it can be seen that the tape yields higher heat transfer rate than that without a helical tape. This can be attributed to a flow mixing behavior between 2 streams from using the helical tape: swirling flow around the tape and the turbulence flow along the wavy-surfaced wall. This mixing gives rise to turbulence/swirl flow greater than that without a helical tape which has a turbulence flow only. In general, the average heat transfer rate for employing the wavy-surfaced tube with helical tape is found to be 23 to 35 % better than that for the wavy-surfaced tube without helical tape. The corresponding increase in mean Nusselt numbers in the heat exchanger is about 202 % to 267 % with and without a helical tape respectively. It is obvious that the use of the wavy-surfaced tube with a helical tape gives higher pressure drop than that of the wavy-surfaced tube without a helical tape due to larger contact surface areas. Besides, the presence of the wavy-surfaced tube with a helical tape reduces flow areas, resulting in a high speed rotating flow. This leads to the substantial pressure loss action of the fluid (hot air) between the helical tape surface and the inner wavy-surfaced tube wall higher than the case of the tube without a helical tape. From the results of the wavy-surfaced tube with a helical tape, pressure loss increases around 98 to 125 % in comparison with the wavy-surfaced tube without helical tape.

5. CONCLUSIONS

An experimental study has been performed on a helical-tape insert in a circular wavy-surfaced tube using hot air as the test fluid. The influence of the helical tape insert on the heat transfer and pressure drop characteristics has been demonstrated. The result shows that the increases in heat transfer and pressure drop are strongly influence by turbulence/swirling motion induced by the helical-tape and wavy-surfaced wall. As the Reynolds number increases, the turbulence/swirling flow is stronger which in turn results in an increase in the heat transfer and pressure drop. The maximum increases in heat transfer rate and pressure drop are found to be about 2.67 and 22.3 times the plain tube for the flow range studied.

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