Ribbed double pipe heat exchanger: experimental analysis

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Abstract

Convection heat transfer can be enhanced by imposed turbulence in the annular flow of a double pipe heat exchanger. This paper presents and discusses the results obtained from experimental measurement by the installation of turbulence promoters, having rib configuration, on the inner surface of the cold flow annulus of a counter flow double-pipe heat exchanger. The promoters have been selected with rib's height to hydraulic diameter, e/D_h equal to 0.107 and two pitch to height ratios, p/e equal to 10 and 15. The annular cold flow was investigated within Reynolds number range of 2000 to 20000. The measured data enabled us to estimate the friction factor, Reynolds number and Stanton number of each case in order to analyse the performance enhancement of the double pipe heat exchanger. The results showed that enhancement in the heat transfer, in terms of the Stanton number, was combined with a small penalty in the pressure drop, which was due to an increase in the friction factor values. Within the tested ranges of e/D_h and Re, the performance index indicated enhancement of about 1.3 to 1.8 at pitch to $p/e = 10$. It is recommended to investigate more cases of rib's heights and installation in the hot fluid flow side.
Keywords: double pipe heat exchanger, rib, enhanced heat transfer, artificial roughening, annular flow.

1 Introduction

Double pipe heat exchangers (DPHE) are devices that transfer thermal energy from hot fluid to cold fluid through metal surface. The common DPHEs comprise two concentric pipes forming outer annular flow and inner pipe flow.

WIT Transactions on Engineering Sciences, Vol 83,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/HT140011

The DPHEs are widely used device in numerous industrial process applications like the food industry, heating and ventilation, chemical industries, refineries, etc. The DPHE performance is a major contributor to the overall process performance. For that, researchers have widely studied the device and many enhancing techniques are proposed and investigated experimentally and numerically. The enhancement techniques of the DPHE may be passive or active. The active techniques may be through mechanical auxiliary elements, rotation of surfaces, mixing of fluids with mechanical and many other methods. In the passive techniques, there is no need for external energy consumption to move or rotate parts of the DPHE. The passive techniques may be achieved via artificial surface roughening, extended surfaces, surface coating, and insertion of turbulators or swirl generators.

Numerous researches have investigated the effect of twisted tapes and coiled wire insertion in the DPHE. Related parameters of coiled wires such as the coil pitch, coil wire thickness, and parameters of swirl generator like twist ratio and tape thickness were studied extensively. The augmentation of the each parameter on the heat transfer and pressure drop are reported by many researchers, e.g. Garcia *et al.* [1], Naphon [2], Shoji *et al.* [3], Gunes *et al.* [4], Eiamsa-ard *et al.* [5] and Akhawan-Behabadi *et al.* [6]. Choudhari and Taji [7] have experimentally studied the effect of material type of coiled wires on the heat transfer and in pressure drop in DPHE.

The early study on surface roughening was experimentally performed by Nikuradse [8] who correlated the velocity distribution and friction to the roughness. On the roughening by dimpled Park *et al.* [9], Hwang *et al.* [10], and Preibish and Buschmann [11] among researchers who studied the resulting heat transfer enhancement and frictional effects. Webb *et al.* [12] in 1970 developed correlations for heat transfer and fiction factor for turbulent flow in tubes having repeated-rib. Following that large numbers of investigations have been reported on the use of turbulators to enhance the heat transfer in thermal equipment. Al-Kayiem and Al-Habeeb [13], conducted numerical study on the effect of various ribbing configurations on the heat transfer of DPHE. They have numerically evaluated Stanton number and the friction coefficient of ribbed annulus using the correlations from literature. Presenting their PhD thesis, Ozceyhan *et al.* [14] have experimentally investigated the flow and heat transfer in rib inserted pipe. An analytical result on the effect of artificial roughening of DPHE by repeated ribs was reported by Al-Kayiem and El-Rahman [15]. However, for the best of the authors knowledge there is no work has been reported on experimental investigation on the ribs augmentation on the performance of the DPHE.

The objective of this paper is to present experimental investigation and results of ribs insertion in DPHE. Many parameters have been considered in the study including the rib's height to hydraulic diameter ($e/D_h = 0.107$), pitches to height ratios (*p/e = 10, and 15*), and annular cold flow within Reynolds number range of 2600 to 20000. In this investigation, the ribs effect was measured when the ribs are installed on the inner surface of the annulus.

2 Experimental implementations

The entire investigations are carried out experimentally. For that, an experimental test rig equipped with suitable measuring instrumentations is designed and fabricated. The experimental set up enables measurements of the thermal and hydraulic variables that can lead to prediction of Re, Nu, St and the friction factor, *f*.

2.1 Experimental set up

The experimental set up comprises flow circulation loop, test section of DPHE model and measuring instruments, as shown in fig 1. A model of DPHE is designed and fabricated from outer pipe with 76.2 mm ID and 89.3 mm OD and internal pipe with 25.4 mm ID and 34.2 OD. The length of the test section is 2000 mm.

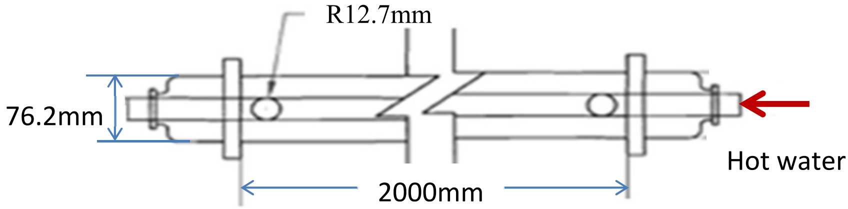

Figure 1: The test section of the DPHE model.

The flow loop is open type with forced circulation by pumping the hot and cold fluids in the inner pipe and the annular, respectively. The cooling water is supplied from constant head tank (220 letter capacity) and pumped to the annulus using a 5-hp pump. The hot water is pumped by 0.75-hp centrifugal pump through the inner pipe and returned back to the heating tank. The water is heated in the heating tank by three electrical heaters providing a total of 7 kW which insuring steady hot water at 80^{o}C using adjustable thermostat. Both, the hot and cold-water circulation are controlled by gate valves.

2.2 The measuring instruments

The instruments used for the temperature measurements are all calibrated according to the arrangement shown in fig 2. For the inlet and outlet temperatures, a glass stem thermometers are used, while thermocouples type T are used to measure the pipes surfaces temperatures. All thermocouple wires are connected to a digital selector/reader have accuracy of 1^{o}C. Two variable area rotameters are used to measure the hot and cold water flow rates. A sensitive micromanometer has 1.96 Pa accuracy is used to measure the pressure drop a cross the 2 m long test section.

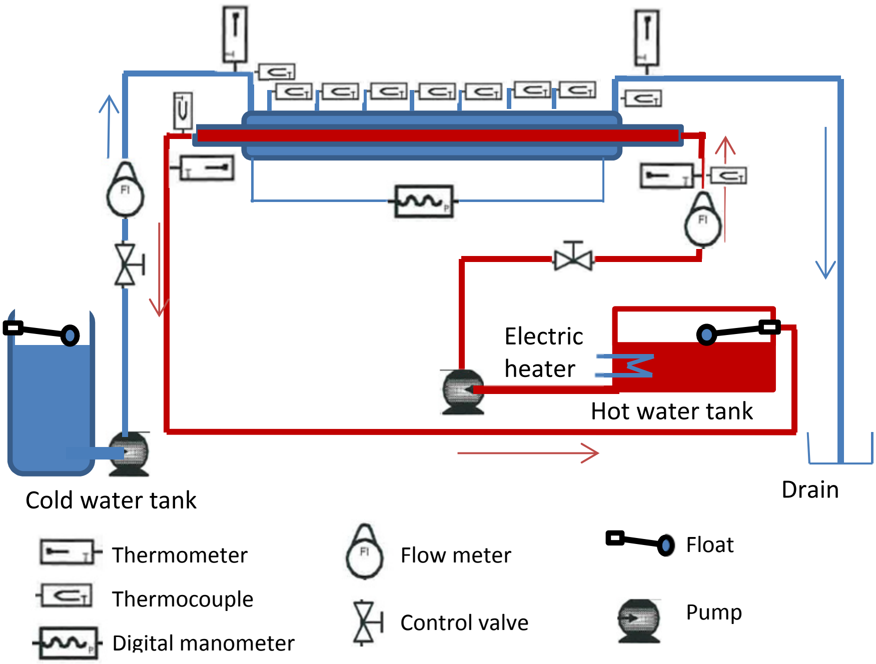

Figure 2: Schematic of the test rig.

3 Results and discussions

The measurement data include the inlet and outlet temperatures of the hot and cold fluids, the pressure difference across the annulus, the volume flow rates of the hot and cold fluids, and the pumping power. Those experimentally measured variables are allowing the prediction of the Nu, St, Re, numbers, and the friction factor, *f*.

3.1 Results of un-ribbed annulus

The hydraulic characteristics, through the friction factor determination, and thermal characteristics through heat transfer determination, are carried out by comparing with the well-established correlations in the literature. Fig 3 shows the friction factor verses Reynolds number of the cold fluid in the annulus, as measured experimentally and predicted using Blasius correlation and McAdams correlation for turbulent flow.

Friction factor for the un-ribbed case, f_o is evaluated experimentally and theoretically as follows:

- From the experimental measurements of Δp:

$$f_o = \frac{\Delta p}{4 \frac{L}{D_{hydr}} \left(\frac{\rho u^2}{2} \right)} \tag{1}$$

- f_o Predicted theoretically by the Blasius correlation [16]:

$$f_o = 0.0791 \times \mathrm{Re}_c^{-0.25} \qquad \mathrm{Re}_c \leq 10^5 \tag{2}$$

- And, also predicted theoretically by the McAdams correlation [17]:

$$f_o = 0.0014 + 0.125 \times \mathrm{Re}_c^{-0.32} \qquad 4 \times 10^4 \leq \mathrm{Re}_c \leq 10^6 \tag{3}$$

As one can notice from fig 3, the experimental results are in good agreement with both correlations. The maximum deviations of the predicted friction factor results are 3% and 6% by Blasius and McAdams, respectively compared to the experimental measurement results.

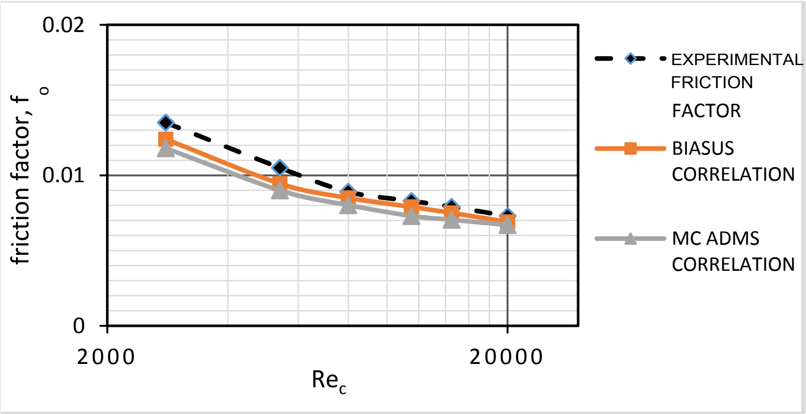

Figure 3: Comparison of the predicted and measured friction factor in the annulus.

For justification of the thermal behaviour of the annulus, the measurement results are compared with Webb [12] correlation. The measurement results are based on the measured gained heat, $\dot{m}\, C_p\, \Delta T_f = hA(\bar{T}_s - \bar{T}_f)$. Measuring the temperature of the inner surface of the annulus and inlet and outlet temperatures of the fluid makes the prediction of the convection heat transfer, h achievable.

www.witpress.com, ISSN 1743-3533 (on-line)

Then Nu_o cauld easly be evaluated and as a consequence, St_o is predictable in the form:

$$St_o = \frac{Nu_o}{Re_c.Pr} \tag{4}$$

While the predicted results are by the Dittus-Boelter correlation [18] as:

$$Nu_o = 0.023 \times Re_c^{0.8} Pr^{0.4} \tag{5}$$

and by the Webb correlation [12] as:

$$Nu_o = \frac{\left(f_o/8\right) Re_c.Pr}{1.07 + 12.7\left(f_o/8\right)^{0.5}\left(Pr^{2/3} - 1\right)} \tag{6}$$

where

$$f_o = (0.79 \times \ln Re - 1.64)^{-2}$$

For all cases of prediction by eqn (2), (3), (5) and (6), and experimental evaluation by eqn (4), Re_c is:

$$Re_c = \frac{\rho U \overline{D}_{hydr}}{\mu} \tag{7}$$

The thermal analyses are presented in terms of St_o number verses Re_c number as shown in fig 4. Results for un-ribbed annulus are in good agreement with the experimental results. The predicted results by Webb correlation are over estimating St number values by about 3%, while results by Dittus-Boelter are under estimating St number by about 5%. However, the experimental data is considered to be justified by these limits of error in both, the hydraulic and thermal aspects.

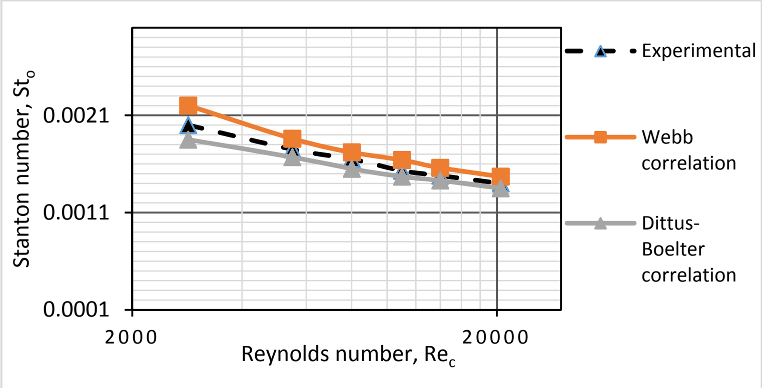

Figure 4: Comparison of predicted and measured Stanton number in the annulus.

Reynolds number, Re_c in the annulus used in eqn (2) is based on the hydraulic diameter, D_{hydr} of the annulus, through which the cold fluid is flowing.

3.2 Results of the ribbed annulus

Two cases of ribbing with different pitch to height ration are investigated, as shown in fig 5 and table 1. In both cases, the height to hydraulic diameter, e/D_h is fixed at 0.107.

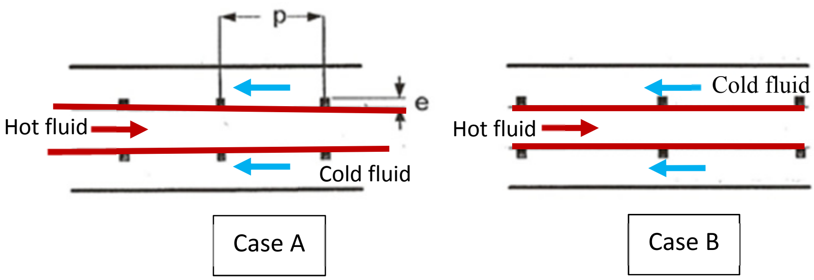

Figure 5: The ribbing cases.

Table 1: The tested cases of ribs.

Ribbing case	e/D_h	p/e
Case A	0.107	10
Case B	0.107	15

The experimental friction factor for the ribbed annulus is determined from the measured pressure difference and the mean velocity at various Re using eqn (1). The results for the two cases, A and B are presented in fig 6 as ribbed to un-ribbed annulus. The increase in the pressure losses due to the rib installation with P/e = 10 is higher than the case of P/e = 15. This is due to the higher resistance of ribs to the flow and the increase in the shear forces acting on the flow.

The results of the thermal enhancement due to the ribs installation are shown in fig 7 for the cases of P/e equal to 10 and 15. The values of the St_r are obtainable using the same procedure of the un-ribbed case. The results are demonstrated in terms of Stanton number ratios of ribbed to un-ribbed cases, St_r/St_o. Over the entire range of Re of the annulus flow, the enhancement in case A is larger than the enhancement of case B. This indicates that as the ribs are installed with higher number per unit length, better augmentation on the thermal performance is achievable. However, this is not necessary an indication of overall increase in the DPHE performance. Combination of the hydrothermal influences will provide better idea, and this is obtainable by adoption of the efficiency index, η.

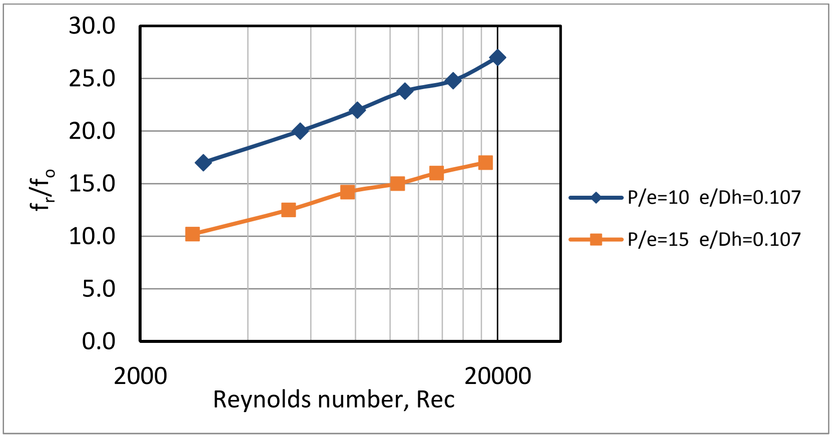

Figure 6: The influence of the ribs on the friction factor at *P/e* = 10 and 15.

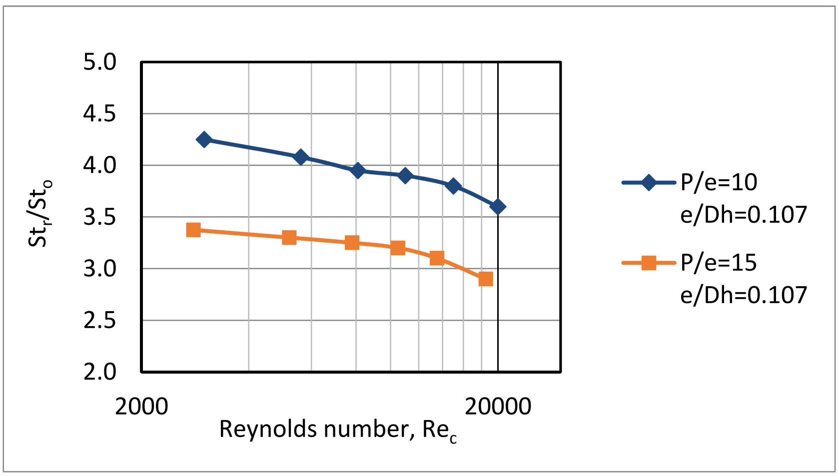

Figure 7: The influence of the ribs on the heat transfer at P/e = 10 and 15.

The new trend of enhancement of heat transfer by regular ribs roughening is characterized by the efficiency index; η. Gee and Webb [19] suggested that this index is given by:

$$\eta = \frac{\left[\dfrac{\mathrm{St_r}}{\mathrm{St_o}}\right]}{\left[\dfrac{f_r}{f_\mathrm{o}}\right]} \tag{8}$$

This index combines the influences of the thermal enhancement and the penalty of larger pressure drop. For the tested cases, the results are presented in fig 8. It shows that the efficiency of the ribbed DPHE is reducing as the roughness Reynolds number, e+ increases. This indicates that the ribs influence on the pressure losses is higher than the thermal enhancement. At lowest e+, the efficiency index is 0.26 and 0.325 for case A and case B, respectively. At high e+, the efficiency index reduces to 0.14 and 0.175, for cases A and B, respectively. The rib in case of *p/e* = 10 shows higher efficiency compared to the case of *p/e* = 15.

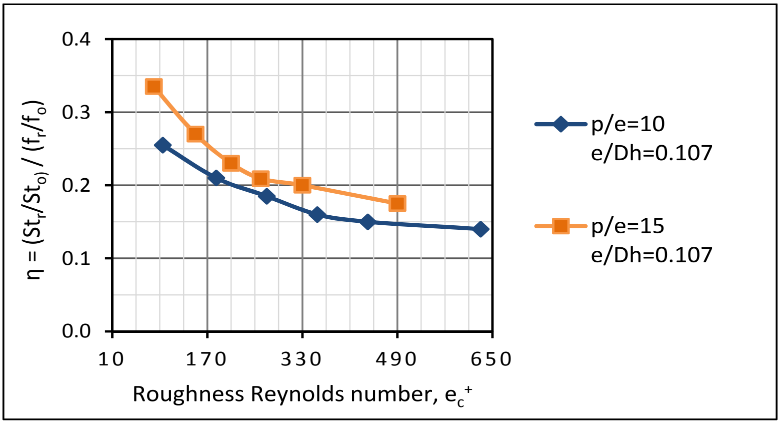

Figure 8: The efficiency index at *p/e* = 10 and 15, at various Roughness Reynolds number, e_c^+.

4 Conclusions

Experimental investigations of un-ribbed and ribbed annulus have carried out using ribs on the inner side of the annulus with e/D_h = 0.107. Two rib pitch to height were considered as *p/e* = 10 and 15. The experimental set and measurement procedure were verified by comparing the results with the well-established correlations for the forced convection heat transfer and friction factor estimations. The followings conclusions are made from the experimental measurements:

- The ribs with *p/e* = 10 enhanced the heat transfer in terms of Stanton number by 3.6 and 4.26 at Re = 3000 and 20000, respectively.
- The ribs with *p/e* = 15 enhanced the heat transfer in terms of Stanton number by 2.95 and 3.4 at Re = 2800 and 18500, respectively.
- The thermal enhancement is combined with increase in the pressure drop. In terms of efficiency index, the tested DPHE showed that larger number of ribs per unit length of the annulus resulted in slightly lower efficiency index.

It is recommended to investigate more rib cases, and also, to predict the pumping power in each case to realize the gained benefit from the thermal enhancement and penalty paid for higher pumping power.

Acknowledgements

The authors acknowledge Universiti Teknologi PETRONAS (UTP) for the financial support to produce and present the paper. Also, appreciations are due to the Ministry of Industry in Iraq for providing the research grant.

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