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AUGMENTATION OF RIBS TURBULATORS HEIGHT ON THE HYDROTHERMAL PERFORMANCE OF DOUBLE PIPE HEAT EXCHANGER

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Abstract

Thermal performance of double pipe heat exchanger can be enhanced by imposed turbulence in the annular flow using artificial roughening. This paper presents experimental results on enhancing the heat transfer by artificial roughening using energy promoters installed on the inner surface of the cold flow annulus. An experimental test rig was fabricated having 2.0 m long annular flow test section with 76.2 mm and 34.2 mm outside and inside diameters, respectively. The energy promoters have ribs shape with rectangular cross section. Two cases of rib's pitch to height ratios, equal to 10 and 15 and three height to hydraulic diameter, equal to 0.0595, 0.083, and 0.107 have been studied. The investigations were carried out at various flow rates within Reynolds number range of 2900 to 21000 in the cold annulus. For each roughening case, the thermal and hydraulic performances were evaluated by determining Stanton number and the associated pressure drop, respectively. The experimental results showed that enhancement in the heat transfer was combined with a penalty in the pressure drop due to the increase in the friction factor values. The combined hydrothermal enhancement results of the DPHE, in terms of the performance index, indicate that the small height ribs to hydraulic diameter of 0.0595, augmented higher than the large height ribs to hydraulic diameter of 0.107. Hence, it is recommended to use ribs installed on the inner surface of the annulus ribs to hydraulic diameter in the range of 0.06 ± 0.005. Also, it is recommended to investigate further parameters to explore further on the influencing of the ribs on the hydrothermal performance of the DPHE.

Keywords: Annular flow, Artificial roughening, Double pipe heat exchanger, Enhanced heat transfer, Ribs insert.

Nomenclature

A	Sectional area of the flow passage, m^2
Cp	Specific heat, kJ/kg·K
D	Diameter, m
D_h	Hydraulic diameter, m
e	Rib height, m
e^+	Roughness Reynolds number
f	Friction factor
f_o	Un-ribbed friction factor
f_r	Ribbed friction factor
h	Coefficient of heat transfer, W/m^2·K
I_p	Performance Indicator
l	Length of the test section, m
$\dot{m}$	Mass flow rate, kg/s
p	Rips pitch, m, separation distance between ribs
P, ΔP	Pressure, pressure difference, N/m^2
Q	Flow rate, m^3/s
T	Temperature, ^{o}C or K
U	Mean velocity of the flow, m/s

Greek Symbols

ε	Surface roughness, m
μ	Viscosity, kg/s.m
ρ	Density, kg/m^3

Dimensionless numbers

Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
St	Stanton number

1. Introduction

Double pipe heat exchangers (DPHE) are widely used devices in numerous industrial process applications like food industry, HVAC, chemical industries, refineries, etc. The common DPHEs comprise two concentric pipes forming outer annular flow and inner pipe flow. When the DPHE integrated within a thermal system, its performance is a major contributor to the overall system performance. For that, the thermal field researchers have widely proposed and investigated experimentally and numerically the performance enhancement techniques of the DPHE. The thermal enhancement techniques of the DPHE may be passive or active. In the passive techniques, no need for external energy consumption to move or rotate parts of the DPHE, as in the case of the active methods. The passive enhancing techniques may be achieved via artificial surface roughening, extended surfaces, surface coating, and insertion of turbulators or swirl generator.

Numerous investigation results on the effect of insertions, like twisted tapes and coiled wire insertion in the DPHE, have been reported. Related parameters of coiled wires like coil pitch, coil wire thickness, and parameters like twist ratio and tape thickness were studied extensively. The augmentations of each parameter on the heat transfer and pressure drop were investigated and reported by many researchers. Garcia et al. [1] carried experimental study on enhancing the heat transfer with the wire coil inserts in laminar, transition and turbulent regions at various Prandtl numbers. Naphon [2] studied the pressure drop in annulus due to the coil-wire insert. Shoji et al. [3], Gunes et al. [4], Eiamsa-ard et al. [5] and Akhavan-Behabadi et al. [6] reported pressure drop and heat transfer enhancement results at various flow geometries with presence of coiled-wires inserts. Choudhari and Taji [7] have, experimentally, studied the effect of material type of coiled wires on the heat transfer and associated pressure drop in DPHE. Gaikwad and Mali [8] investigated the twisted wire brush inserts in the inner pipe of the DPHE.

Addition of nano particles to fluids, to enhance their thermal properties, is the state of the art technique to enhance the heat transfer in flowing fluids. A well coverage of the technique was presented in the review paper by Hussein et al. [9]. The paper discussed and compared the heat transfer enhancement and the pressure drop results that carried out so for by other researchers. They concluded that the nanothermal enhancement is advantageous upon the other techniques, where the pressure reduction is minimal compared to the surface roughening techniques.

The surface roughening is also influencing the thermal performance in convection heat transfer processes. The early study on surface roughening was experimentally performed by Nikuradse [10], who correlated the velocity distribution and friction to the surface roughness. On the roughening by dimpled, Park et al. [11], Hwang et al. [12], and Preibisch and Buschmann [13] are among researchers who studied the resulting heat transfer enhancement and frictional effects in heat exchangers. Al-Kayiem and Al-Habeeb [14] reported experimental results on the hydrothermal performance enhancement of DPHE using ribs fixed on the inner wall of the annulus. The reported measurement results focused on the effect of the ribs solidity in the annulus by changing the pitch between the ribs. Measurement results for pitch to height ratio, p/e of 10 and 15, and rib height to hydraulic diameter ratio, $e/D_h = 0.107$ showed performance enhancement of 1.3 to 1.8 in terms of efficiency index.

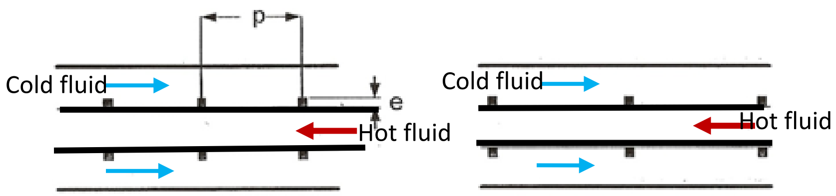
In his paper in 2008, Ozceyhan et al. [15] investigated numerically the heat transfer enhancement in a tube using circular rings separated from the wall. They validated the simulation by comparing their results with the experimental results of Eiamsa-ard and Promvonge [16]. This study differs from other studies in the field of insertion, where the ribs haven’t attached to the wall so that heat transfer enhancement is solely due to disturbing of the laminar sub layer. The study was carried out using FLUENT code and the results from this study show that heat transfer enhancement increased with the pitch of the ribs. A CFD simulation results on the effect of artificial roughening of DPHE by repeated ribs was reported by Al-Kayiem and El-Rahman [17]. Various configurations were simulated for ribs installed on the outer surface of the annulus. The validated simulation results demonstrated that ribbing enhances the heat transfer by more than 3 times at penalty of increasing pressure drop of more than 18 times.

The energy promoters, in terms of ribs as artificial roughening technique, are effective tools to enhance the heat transfer and improve the heat transfer in the heat exchangers. For the best knowledge of the authors, there is no work has been reported on experimental investigation on the ribs height augmentation on the performance of the DPHE. However, there is a need for detailed investigation on the influencing of the ribs height and the ribs pitch on the combined effect of thermal enhancement and pressure drop in DPHEs.

The objective of this paper is to present and discuss the effect of the ribs height on the hydrothermal enhancement of DPHE through experimental investigations. The parameters considered in the study are including two pitches to height ratios (*p/e* =10, and 15), three rib's height to hydraulic diameter (e/D_h = 0.0595, 0.083 and 0.107), and annular cold flow within a range of Reynolds number, Re_c from 2900 to 21000. An experimental setup equipped with measuring instrumentations has been designed and fabricated comprising hot and cold circulation flow loop and 3 m long test section of DPHE.

2. Problem Identification

DPHE is industrial thermal equipment constructed from hot flow in inner pipe and cold flow in an annulus surrounding the inner pipe. Heat transfer takes place as a result of the temperature difference between the hot fluid in the inner pipe and the cold flow in the annulus. The present work investigates the augmentation of height of ribs, installed on the inner surface of the annulus, on the DPHE performance. The ribs are rings with rectangular cross section, as shown in Fig. 1. Two cases of ribs solidity in terms of pitch, *p* to rib height, *e* have been investigated. In case A, *p/e* = 10 and in case B, *p/e* = 15. In each case, three different ribs heights have been used and specified in terms of rib height to annulus hydraulic diameter, e/D_h = 0.0595, 0.083 and 0.107. Summary of the cases is shown in Table 1.



Cases: A1, A2, A3 **Cases: B1, B2, B3**

Fig. 1. The ribbing cases.

Table 1. The tested cases of ribs.

Ribbing case	label	*p/e*	e/D_h
Case A	A1	10	0.0595
	A2		0.083
	A3		0.107
Case B	B1	15	0.0595
	B2		0.083
	B3		0.107

3. Experimental Implementations

An experimental test rig, equipped with a set of measuring instrumentations, has been designed, fabricated and justified. The experimental set up enables measurements of the thermal and hydraulic variables, pressures, temperatures, and flow rates that can be used to estimate Re, Nusselt number (Nu), Stanton number

(St) and the friction factor, *f*. The case of unribbed annulus is identified by the subscript, $(\ )_o$ while the case of ribbed annulus is identified by the subscript,$(\ )_r$.

3.1. Experimental setup

The experimental set up, shown in Fig. 2, is a flow loop comprises of test section of DPHE, hot and cold water circulation circuits, heating tanks, and measuring instruments. 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 litre capacity) and pumped to the annulus using 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 ^oC using adjustable thermostat. Both, the hot and cold water circulations were controlled by gate valves.

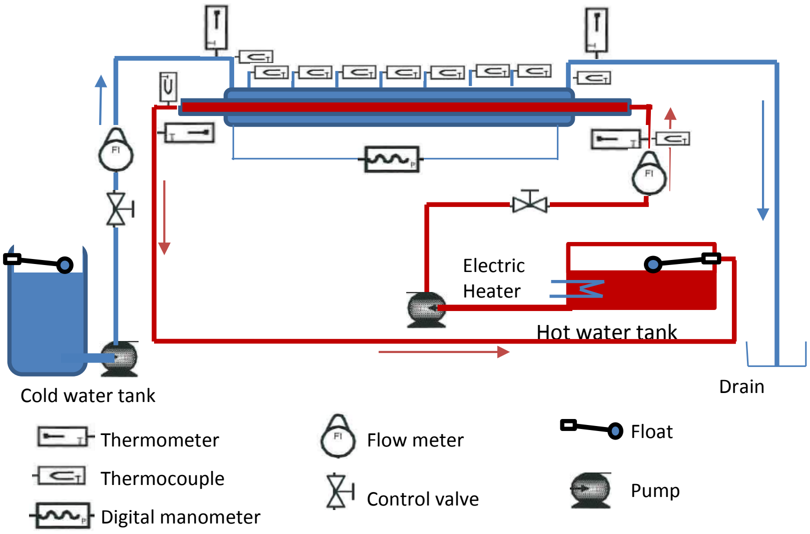


Fig. 2. Schematic of the experimental setup.

The test section, shown schematically in Fig. 3, is a 3000 mm DPHE. It is made of commercial galvanized steel (roughness, ε = 0.15 mm) with outer pipe has 76.2 mm ID and 89.3 mm OD and internal pipe has 25.4 mm ID and 34.2 mm OD. The stabilized zone of the annular flow, where the ribs were installed, is 2000 mm.

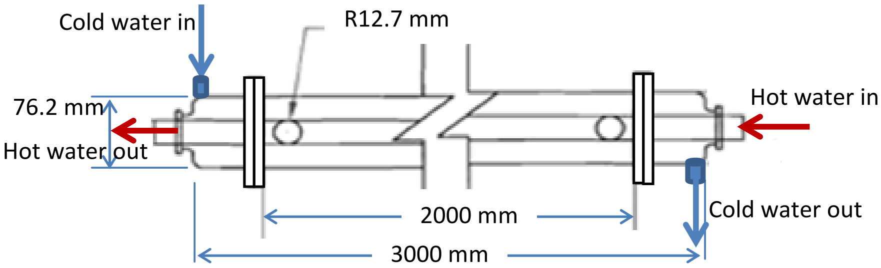


Fig. 3. Outlines of the test section of the DPHE.

3.2. The measuring instruments

For the inlet and outlet temperatures, a -10.0 to 100.0 °C glass stem thermometers have been used to measure the hot and cold water temperatures at inlets and outlets. Thermocouples, type T, have been used to measure the pipes surfaces temperatures. Each thermocouple is calibrated prior to use. All thermocouple wires were connected to a digital selector/reader have an accuracy of 0.5 °C. In some points, a fluctuation in the temperature reading is experienced. Hence the mean of the highest and lowest readings is considered.

Two variable area rotameters type GEC Elliot, with ranges of 0.0 to 100.0 LPM and 0.0 to 50.0 l/min, were used to measure the flow rates of the hot and cold water, respectively. For the cold water, a variable area rotameter ranged from 0.0 to 100.0 l/min was used, while another variable area rotameter with 0.0 to 50.0 l/m range was used for the hot water flow measurement. Both have been calibrated before starting the measurements.

A sensitive Micromanometer type wo-80 YAMOTO works, with 1.96 Pa, has been used to measure the pressure drop across the 2.0 m long test section, with puncture pressure 4000 mm H_2O. It has an accuracy of 0.2 mm H_2O, which quite enough for the present investigations.

4. Results and Discussion

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, and the friction factor, *f*.

4.1. Results of un-ribbed annulus

Justification of the measurement results for the pressure drop and the heat transfer is achieved by comparing the results of un-ribbed case with well-established correlations. The hydraulic characteristics have been determined in terms of the friction factor, f_o. The measured pressure drop across the test section is used to determine f_o from Darcy Eq. (1).

$$f_o = \frac{2\,\Delta P_{measured}}{\rho(l/D_h)\cdot(Q/A)^2_{annulus}}. \tag{1}$$

On other hand, to calculate f_o, the well-established Colebrook equation (Rennel and Hudsen [18]) is used since the flow is turbulent:

$$\frac{1}{\sqrt{f_o}} = -2\log[\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\cdot\sqrt{f_o}}] \tag{2}$$

where, ε is the surface roughness taken as 1.5×10^{-4} m. The equation is solved by iteration with first guess of $f_o = 0.01$.

The measured and the calculated friction factor results are presented in Fig. 4 as f_o versus log Re_c. The experimental and measurement trend is similar that the friction factor value is reducing as Re_c in the annulus is increasing. Both, the experimental and the theoretical values are in good agreement with Moody chart values for smooth pipe. The mean relative error between the measured and calculated is about 4.5%.

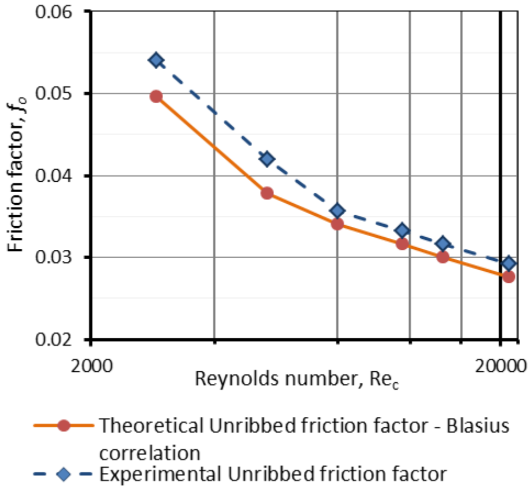


Fig. 4. Comparison of the predicted and measured friction factor in the annulus.

For justificating the thermal behaviour of the annulus, the experimental measurement results are compared with the well-known Dittus-Boelter correlation cited by Holman [19], as:

$$Nu_o = 0.023 Re_c^{0.8} Pr^{0.4} \tag{3}$$

And then calculate St_o from equation 4.

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

The theoretical valus of Nu_o and St_o are predicted from eqns. 3 and 4, respectively. The experimental values of Nu_o are based on the measurement of the gained heat, $Q_{gained} = \dot{m}\, C_p\, \Delta T_f$ and from that, the convection heat transfer is predicted from $hA(\overline{T}_s - \overline{T}_f)$, where $\overline{T}_s$ *and* $\overline{T}_f$ are the mean of the measured temparatures of the surface and the fluid. Then Nu_o, and St_o could easly be evaluated by their definitions as; Nu = $h.D_h/k_w$ and St = Nu/Re.Pr. For all cases of prediction by eqns. 2, 3, and 4, Reynolds number of the cold annulus, Re_c is based on the hydraulic diameter, D_h of the annulus as:

$$Re_c = \frac{\rho\, \overline{U}\, D_h}{\mu_w} = \frac{\rho (Q_c / A_{ann}) D_h}{\mu_w} \tag{5}$$

The thermal analysis results of the unribbed annulus, in terms of St_o number verses log Re_c number, are shown in Fig. 5. Results of the thermal behaviour for un-ribbed annulus have the same trend when predicted experimentally and theoretically. The predicted 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.

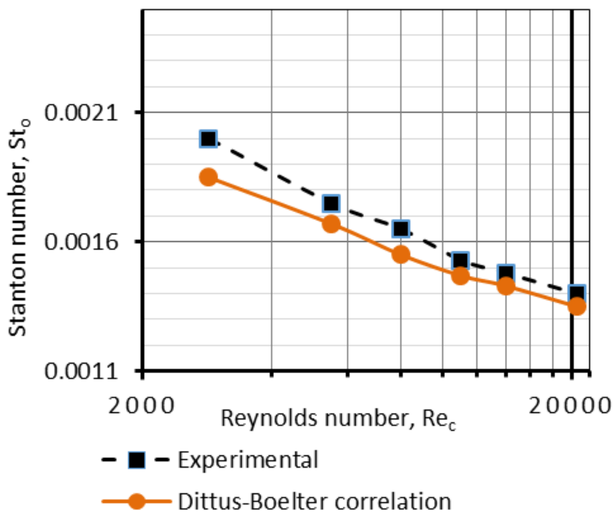


Fig. 5. Comparison between the measured and the calculated Stanton number in the unribbed annulus.

4.2. Results of the ribbed annulus

Two cases , A and B, of ribbing with different pitch to height ratios have been investigated. In each cases, the height to hydraulic diameter is investigated experimentally with three ribs heights, as e/D_h = 0.0595, 0.083 and 0.107. This section, presents and discuss the experimental results of the hydraulic performance, the thermal performance, and finally the combined thermal and hydraulic influene of the ribs on the annulus.

4.2.1. The hydroulic performance analysis

The experimental friction factor for the ribbed annulus, f_r is determined from the measured pressure difference and the mean velocity at various Re_c using eq. 1. The results for cases, A and B are presented in Figs. 6 and 7 respectively, as ribbed to un-ribbed ratio, f_r/f_o versus Re_c. The increase in the pressure losses due to the ribs 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. In bothe cases, the friction factor is incresed considerably compared to the unribbed case. As the flow rate increased, the influence of the ribs become more effective. The other issue that noticed from the results that ribs height is an effective parametr in increasing the resistance to the flow, which in turn, leading to higher pressure drop and higher pumping power. The mean difference of the friction ratio between the low height and the medium height is about 28% over the entire range of Re. By increasing e/D_h from 0.0595 to 0.83 causes increament in the friction ratio by 28%. By increasing e/D_h from 0.083 to 0.107, the friction ratio increase by 36%. This indicate that the increase of the friction factor due to increase in the ribs height is not linear.

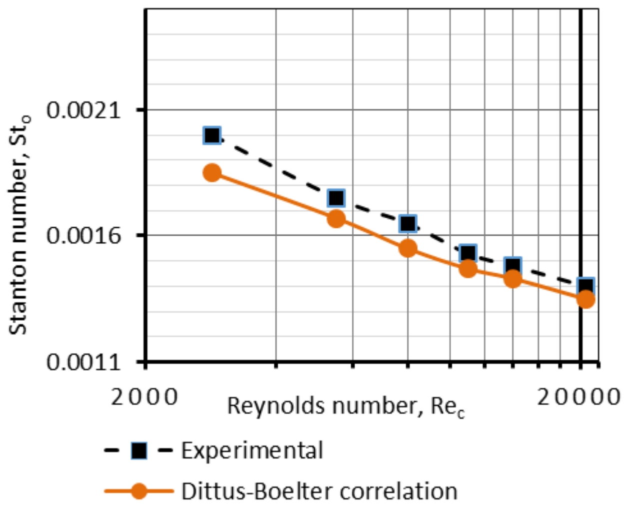


Fig. 6. The influence of the ribs height on the friction factor at *p/e* =10; i.e., case A.

Comparison between the results of case A and case B confirms the fact that the larger the number of ribs per unit length of the annulus, the higher is the agumentation of the ribs on the friction factor and the pressure drop. However, to analyse the ribs height in case B, one can realize the same behaviour that the friction ratio increases as Re increase. The other similar behaviour is the higher friction ratio at higher ribs height.

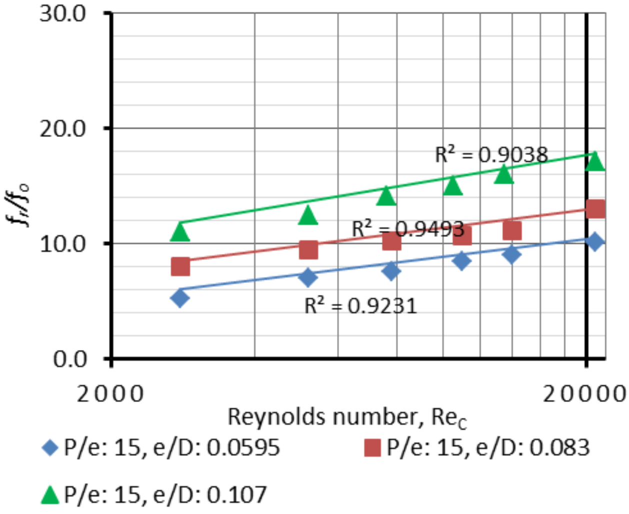


Fig. 7. The influence of the ribs on the friction factor at *p/e* = 15; i.e., case B.

In conclusion, the presence of the ribs in the inner surface of the annulus caused large increment in the friction factor and larger pressure drop compared to the unribbed annulus.

4.2.2. The thermal performance analysis

The results of the thermal enhancement due to the ribs installation are shown in Figs. 8 and 9 for the case A and B, respectively. The values of the St_r are obtainable using the same procedure of the un-ribbed case described in section 4.1. The results are presented in terms of Stanton number ratios of ribbed to un-ribbed cases, St_r/St_o versus Re_c. Over the entire range of Re_c of the annulus flow, the enhancement in case A is larger than the enhancement of case B. This indicates that higher number per unit length, augments in better larger thermal performance. More presence of ribs on the surface causes shorter flow attachement to the wall, i.e., the shorter pitch increases the number of disturbances and distroyment of the laminar sublayer near the wall. In terms of ribs height, the results of both cases, A and B show that larger thermal enhancment is achieved as the ribs hieght increases. In case of shorter pitch of ribbing, the contribution of the height becomes more effective. For example in case A, at Re_r = 2900, the value of St_s increases by about 4.2 times of the unribbed annulus for *e/D* = 0.107, while in case B, it icreases by 3.3 times for the same ribs heighs. This thermal enhancement has the same trend over the entire range of Re.

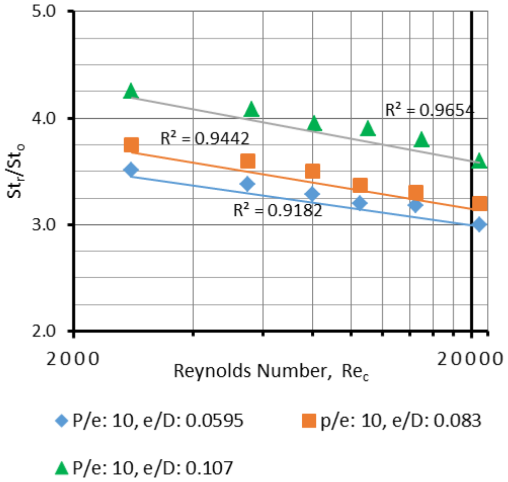


Fig. 8. The influence of the ribs on the heat transfer at *p/e* = 10.

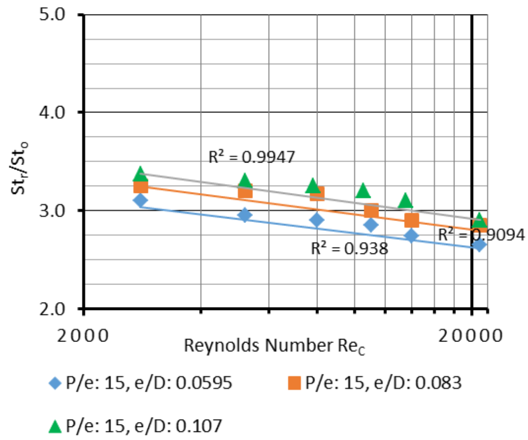


Fig. 9. The influence of the ribs on the heat transfer at *p/e* = 15.

4.2.3. Combined hydrothermal influencing by ribs

The thermal enhancement is not necessary an indication of increase in the DPHE performance. The insertion of the ribs in the flow field creates larger shear resistance near the wall causing higher frictional pressure drop. In such situation, on one hand, the DPHE performance is improving from the point of view of thermal process, and on the other hand is reducing from the point of view of hydraulic process. Combination of the hydrothermal influences due to the ribs installation should be counted simultaneously. This combined augmentation can be obtained by the Performance Indicator, $I_{p.}$, which is suggested in the present investigation, as:

$$I_p = \frac{\mathrm{St_r/St_o}}{\sqrt[3]{f_r / f_o}} \tag{6}$$

This index combines the influences of the thermal enhancement and the penalty of larger pressure drop. The results of the tested cases in the present work, A and B are presented in Figs. 10 and 11 respectively in terms of the Performance indicator versus the roughness Reynolds number, e^+ defined as

$$e^+ = \frac{e}{D_h} \cdot \mathrm{Re} \cdot \left(\frac{f_r}{2}\right)^{0.5} \tag{7}$$

The results of both cases, A and B show 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 supersedes the thermal enhancement. At lowest $e+$,(~15) the efficiency index is 1.75 for case A; and it is about 0.3 for case B,(e^+~ 48). The influencing of the ribs height is quite clear in both cases. Ribs with lower height, e/D_h = 0.0595, are considerably enhancing the overall performance of the DPHE compared to the case of ribs with high height, e/D_h = 0.107. This draws an important conclusion to use ribs with heights, e/D_h within a range of 0.06 ± 0.005.

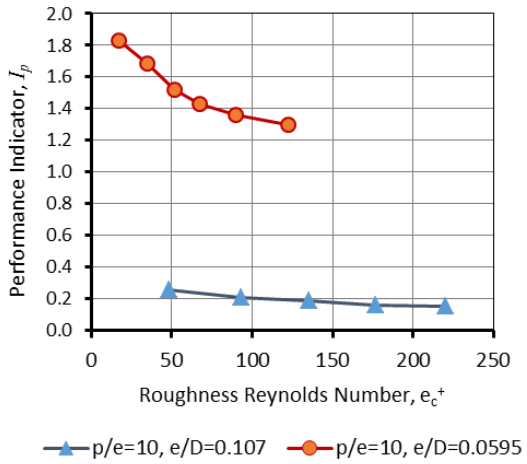


Fig. 10. The efficiency index of case A at various roughness Reynolds numbers, e_c^+.

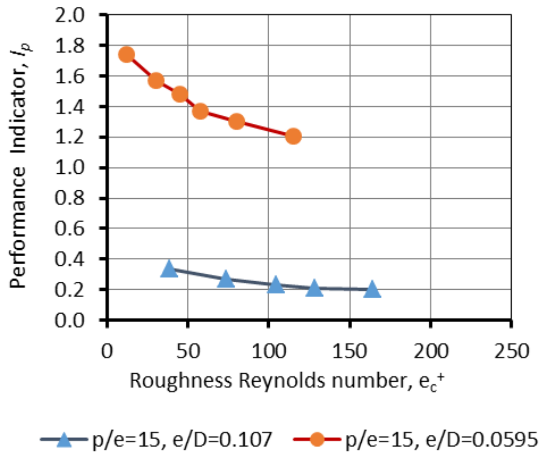


Fig. 11. The efficiency index of case B at various roughness Reynolds numbers, e_c^+.

4.3. Uncertainty analysis

The goodness of the experimental results may be judged by various methods. In the present work, the calibration of the instruments and the coefficient of determination have been adopted to evaluate the experimental uncertainties.

4.3.1. Calibration of the instruments

A known volume container and stop watch have been used to count the filling time, and simultaneously the reading of the rotameters was recorded. Various flows have been rated to obtain the calibration curve as rotameters reading versus the volume-to-time record. The procedure has been repeated three times and the mean values were considered. The calibration equation and the coefficient of determination are shown in Fig. 12.

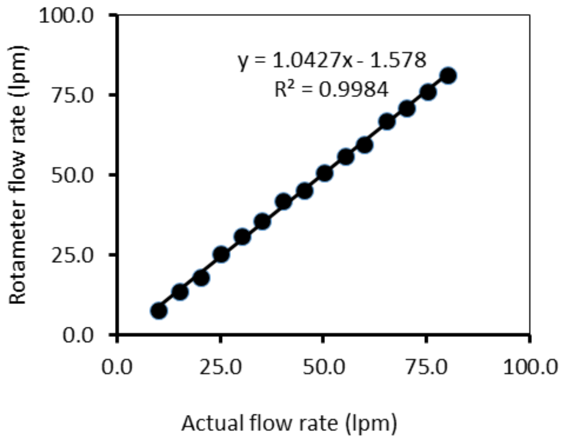


Fig. 12. Calibration results of flow rate rotameter.

The thermocouple wires were connected to a digital reader selector. Hence, the calibration of the thermocouples included the selector automatically. The calibration was carried out using the traditional method of heating of crashed ice in water up to the boiling point. To count for the hysteresis, the procedure was carried out in two ways by heating up to 100 ^{o}C and then cooling by added cold ice/water till zero ^{o}C. The actual readings were recorded from stem thermometer, while the thermocouple reading was recorded from the digital reader. Sample of thermocouple calibration results is shown in Fig. 13. No one of the thermocouples has coefficient of determination less than 0.98. The final results of each thermocouple calibration were introduced in the computer program which predicts the experimental heat transfer parameters.

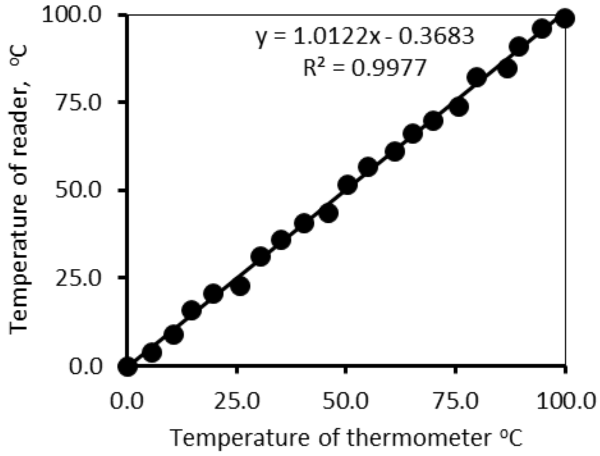


Fig. 13. Calibration results of thermocouple wire.

4.3.2. Coefficient of determination (R^2)

This coefficient is equivalent to the ratio of the regression sum of error squares (SES) to the total sum of squares (SST), which explains the proportion of variance accounted for in the dependent variable. It evaluates the goodness of the data in terms of variances. Various authors (e.g., Doymaz [20] Suherman et al. [21] and Singh and Pandey [22]) used the coefficient of determination, R^2 to evaluate their experimental data. The SES and the SST can be calculated from the following formulae:

Regression sum of squares:

$$\text{SES} = \sum_{i=1}^{N}\left[Y_i^{\wedge} - \bar{Y}\right]^2 \tag{8}$$

The total sum of squares:

$$\text{SST} = \sum_{i=1}^{N}[Y_i - \bar{Y}]^2 \tag{9}$$

Subsequently, the coefficient of determination, R^2 can be calculated as:

$$R^2 = 1 - \frac{\text{SES}}{\text{SST}} \tag{10}$$

where, Y_i is an experimental data point, $\overline{Y}$ is the mean value of Y_i, $Y_i^{\wedge}$ is the estimated value of Y_i, N is number of data points, experimental data, respectively.

As the value of R^2 approaches unity, it is an indication for low experimental uncertainty. The R^2 values obtained for the various experimental parameters used in the present work are tabulated in Table 2. All the coefficients of determination are higher than 0.9 which insure the low vagueness of the results.

Table 2. The coefficient of determination of regression, R^2.

Dependent versus independent parameter	Experimental case		R^2 value
	p/e	e/D_h	
f_r/f_o versus Re_c	10	0.0595	0.921
		0.083	0.906
		0.107	0.926
	15	0.0595	0.923
		0.083	0.950
		0.107	0.904
St_r/St_o versus Re_c	10	0.0595	0.918
		0.083	0.944
		0.107	0.965
	15	0.0595	0.938
		0.083	0.909
		0.107	0.995

5. Conclusions

Experimental investigations of un-ribbed and ribbed annulus have been carried out using ribs on the inner side of the annulus with e/D_h = 0.0595, 0.083 and 0.107. Two rib pitch to height ratios have been considered as p/e = 10 and 15. The experimental setup and the measurement procedure are verified by comparing the measurement results with the well-established correlations for the forced convection heat transfer and friction losses. The following conclusions are made from the experimental measurements:

- The pitch between the ribs is an effective parameter in the hydrodynamic performance of the DPHE.
- The smaller is the pitch the higher is the pressure drop, and the enhanced heat transfer.
- By increasing e/D from 0.0595 to 0.83, the friction ratio is increased by 28%.
- By increasing e/D from 0.083 to 0.107, the friction ratio is increased by 36%.
- At p/e = 10, the value of St_s increases by about 4.2 times of the unribbed annulus for e/D = 0.107, while at p/e = 15, it icreases by 3.3 times for the same ribs heighs. This thermal enhancement has the same trend over the entire range of Re.
- The combined hydrothermal enhancement of the DPHE, in terms of the eficiency index, indicates that the small height ribs, e/D = 0.0595 ugumented higher than the large height ribs, e/D = 0.107. Hence, it is recommended to use ribs with heights around e/D_h in the range of 0.06 ± 0.005.

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

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