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RIBBED DOUBLE PIPE HEAT EXCHANGER: ANALYTICAL ANALYSIS

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Abstract

This paper presents the findings obtained by modeling a Double Pipe Heat Exchanger (DPHE) equipped with repeated ribs from the inside for artificial roughing. An analytical procedure was developed to analyze the thermal and hydraulic performance of the DPHE with and without ribbing. The procedure was verified by comparing with experimental reported results and they are in good agreement. Several parameters were investigated in this study including the effect of ribs pitch to height ratios, P/e= 5, 10, 15, and 20, and ribs to hydraulic diameter ratios, e/D_h= 0.0595, 0.0765, and 0.107. These parameters were studied at various operating Reynolds number ranging from 2500 to 150000. Different installation configurations were investigated, too. An enhancement of 4 times in the heat transfer in terms of Stanton number was achieved at the expense of 38 times increase of pressure drop across the flow in terms of friction facto values.

Keywords: Double pipe heat exchangers, Heat transfer enhancement, Ribbing, Counter flow.

1. Introduction

The increasing cost of energy in the past years aroused the need for using more efficient energy systems. This in turn encouraged researches in the field of augmenting heat transfer in heat exchangers. Several techniques are recognized for the study of heat transfer enhancement; out of which, ribbing is found to be a powerful heat transfer enhancing tool. In this study, the effect of various parameters including rib pitch to height ratio (*P/e*) were studied at different Reynolds numbers and different installation configurations.

Nomenclatures

A	Total heat transfer area, m^2
A_f	Flow area, m^2
C_P	Specific heat at constant pressure, kJ/kg.K
D	Diameter, m
D_h	Hydraulic diameter, m
e	Rib height, m
e^+	Roughness Reynolds number
f	Friction factor for smooth case
f_r	Friction factor for ribbed case
He^+	Heat transfer function
h	Heat transfer Coefficient, W/m^2.K
k	Thermal Conductivity, W/m.K
L	Flow section length, m
m	Mass flow rate, kg/s
Nu	Nusselt Number
P	Pitch, m
Pr	Prandtl Number
Re	Reynolds Number
Re^+	Roughness function
r_i	Pipe inside radius, m
r_o	Pipe outside radius, m
St	Stanten Number
T	Temperature, K or ^{o}C

Greek Symbols

α	Flow angle of attack, degree
γ	Specific weight
η	Annulus efficiency index
μ	Dynamic viscosity, kg/m.s
ρ	Density, kg/m^3
Φ	Rib shape angle, degree

An early study of the effect of roughness on friction and velocity distribution was experimentally performed by Nikuaradse [1]. Webb et al. [2] in 1970 developed correlations for heat transfer and fiction factor for turbulent flow in tubes having repeated-rib. A generalized understanding of the Stanton number and friction characteristics of repeated ribs was developed in this study. The concept of efficiency index, η, was also introduced in the study, as the relative increase in friction necessary to achieve the desired heat transfer augmentation. An interpretation for the heat transfer and pressure drop behavior in the presence of tabulators was presented by Takase in 1996 [3].

Takase suggested that the presence of ribs in the flow section promotes turbulence at earlier stages of the flow where it increases the axial velocity due to the reduction in the channel cross section. The effect of pitch size was investigated by Yildiz et al. [4] in 1998 where they experimentally studied the effect of twisted strips on the heat transfer and pressure drop in double pipe heat exchangers with both parallel and counter flow. They have used galvanized iron twisted strip of 2 mm thick, 60 mm width, and 100 mm, and 170 mm pitch. They found that the Nusselt number could increase by up to 100% with a cost f about 130% increase in pressure drop for the tube with twisted strips; and that further improvements in heat transfer may be acquired by increasing pitch size.

In 1999, Al-Habeeb, [5], studied experimentally the effect of ribbing on the parallel flow of double pipe heat exchangers. Reynolds number used was in the range of (2500-20000) for the annulus flow. Results showed that when the hot flow is inside the pipe, heat transfer enhancement of 4.26 times was achieved with 26.8 times pressure drop in terms of friction factor value.

In 2008, Al-Kayiem and Al-Habeeb [6], conducted a 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. Results of the study revealed good agreement between their numerical correlations results and experimental results of [5].

The main objective of this work is to develop and verify an analytical procedure which is valid to model the heat transfer and pressure drop behavior in ribbed double pipe heat exchangers.

The methodology of developing the analytical procedure consists of gathering a set of empirical equations and correlations recommended by other researchers. These equations and correlations were then compiled in a MATLAB code. The model results were compared against experimental results for validation purpose. This study accounts for the specific flow case wherein cold water flows in the annulus counter to the hot water flowing inside the pipe. Ribs are also taken to be on the annulus side of the DPHE. The study investigated different ribbing configuration with respect to pitch size (P) and rib height (e). Figure 1 below shows an example of the ribbing configurations.

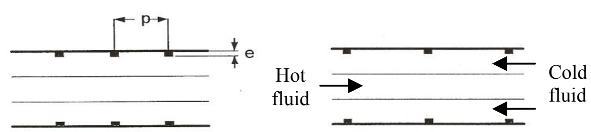

Fig. 1. Convention for Pitch and Rib Height, and the Directions of the Fluids.

2. Analytical Modelling

Figure 2 shows a schematic diagram of the DPHE under investigation (all dimensions are in mm)

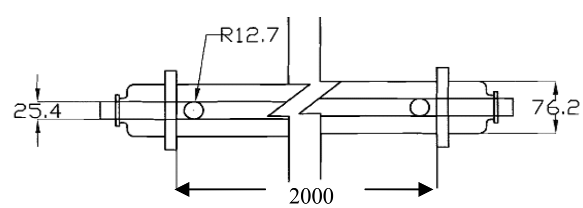

Fig. 2. Schematic Diagram of the Investigated DPHE.

2.1. Friction factor for smooth cases

Two correlations [7] were selected to evaluate the friction factor as follows:

Blasius correlation (Reynolds numbers $4\times10^3 \le \mathrm{Re} \le 10^6$)

$$f = 0.0791\mathrm{Re}^{-0.25} \tag{1}$$

Drew, Koo and McAdams correlation (Reynolds numbers $4\times10^4 \le \mathrm{Re} \le 10^6$)

$$f = 0.0014 + 0.125\mathrm{Re}^{-0.32} \tag{2}$$

The previous correlations evaluate the friction factor as a function of Reynolds number only.

2.2. Convective heat transfer for smooth cases

The coefficient of convective heat transfer, h, is a function of several variables including geometry of the flow, surface roughness, flow velocity and the viscosity.

Dittus and Boelter [8] recommended the following correlation:

$$\mathrm{Nu} = \frac{h \cdot D}{k} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n} \tag{3}$$

where the exponent, n, has values of 0.4 for heating and 0.3 for cooling.

Stanton, Reynolds, Nusselt and Prandtl numbers are evaluated using the following fundamental formulae respectively:

$$\mathrm{St} = \frac{h}{\rho u c} \tag{4}$$

$$\mathrm{Re} = \frac{\rho u D}{\mu} \tag{5}$$

$$\mathrm{Nu} = \frac{hD}{k} \tag{6}$$

$$\mathrm{Pr} = \frac{c_p \mu}{k} \tag{7}$$

Substituting the diameter with the hydraulic diameter (D_h) and rearranging the four equations, Stanton number for smooth annulus can be given as follows:

$$\mathrm{St} = \frac{\mathrm{Nu}}{\mathrm{Re} \cdot \mathrm{Pr}} \tag{8}$$

2.3. Friction factor for ribbed annulus cases

By combining the velocity defect law for pipe flow with the law of the wall, Nikuradse [1], developed the "friction similarity law" for sand grain roughness. This can be assumed to hold for the entire cross section of the flow. To satisfy the ribbed annulus flow, the average surface roughness, ε, is replaced by the rib height, e. The Roughness function, Re^+ is obtained as:

$$\mathrm{Re}^+\left(e^+\right) = \left(\frac{2}{f_r}\right)^{0.5} + 2.5\ln\left(\frac{2e}{D_h}\right) + 3.75 \tag{9}$$

where, the roughness Reynolds number, e^+ is:

$$e^+ = \frac{e}{D_h} \cdot \text{Re} \cdot \left(\frac{f_r}{2}\right)^{0.5} \tag{10}$$

Han [9] recommended a correlation for the friction factor for turbulent flow between parallel plates with repeated-rib roughness by taking into account the geometrically non similar roughness parameters of P/e, rib shape, Φ and the angle of attack, α, as:

$$\text{Re}^+\left(e^+\right) = 4.9\left(\frac{e^+}{35}\right)^m \left(\frac{10}{\left(p/e\right)}\right)^{-n} \left(\frac{\phi}{90^{\circ}}\right)^{-1} \left(\frac{\alpha}{45^{\circ}}\right)^{-0.57} \tag{11}$$

where the exponents m and n are given as follows:

$m = -0.4$ if $e^+ < 35$

$m = 0$ if $e^+ \geq 35$

$n = -0.13$ if $P/e < 10$

$n = 0.53\left(\frac{\alpha}{90^o}\right)^{0.71}$ if $P/e \geq 10$

Equations (9)-(11) were solved iteratively by using initial guess of $e^+ = 1$ and substituting into Eq. (9). Re^+ is substituted from Eq. (11). Iterations were performed until residues fell below 0.001.

2.4. Heat transfer of ribbed annulus case

Han et al. [9] and Webb et al. [10] proposed a formula that applies the heat and momentum transfer analogy known as ”Heat Transfer Similarity Law” as follows:

$$\frac{\left(\frac{f_r}{2\text{St}}\right) - 1}{\left(\frac{f_r}{2}\right)^{0.5}} + \text{Re}^+ = \text{He}^+\left(e^+, \text{Pr}\right) \tag{12}$$

where He^+, Re^+ and f_r are known. f_r is calculated as in Subsection 2.3, then Stanton number in the ribbed flow could be evaluated as:

$$\text{St}_r = \frac{f_r}{\left(\text{He}^+ - \text{Re}^+\right)\left(2f_r\right)^{0.5} + 2} \tag{13}$$

Values of He^+ can be found using the following correlation which is recommended by Webb et al. [10]

$$\text{He}^+ = 4.5\left(e^+\right)^{0.28}\left(\text{Pr}\right)^{0.57} \tag{14}$$

3. Results and Discussion

The results are discussed in this section beginning with the smooth case results which illustrates the normal heat transfer and pressure drop behavior at different Reynolds numbers. It is then followed by separate discussions for the effect of the rib height and the pitch distance respectively. A comparison with the effect of the rib height as obtained experimentally is also presented under the effect of the rib height section. The ribbing configurations investigated are summarized in Table 1 below:

Table 1. The Investigated Cases of Repeated Ribbing.

Annulus	*e*	e/D_h	*P/e*
Case1	0.0025	0.0595	5, 10,15, 20
Case2	0.0032	0.0765	5, 10, 15, 20
Case3	0.0045	0.17	5, 10, 15, 20

3.1. Non-ribbed case

It can be noted on Fig. 3 that generally, Mc Adams correlation reveals higher values for the friction factor. However, at mid range of Reynolds number 10^4 to 6×10^4, the friction factor values calculated both by Mc Adams and Blasius correlations tend to become identical. The friction factor trend portrayed by the two mentioned correlation shows that as Reynolds number increases the friction factor decrease and the pressure drop as a consequent.

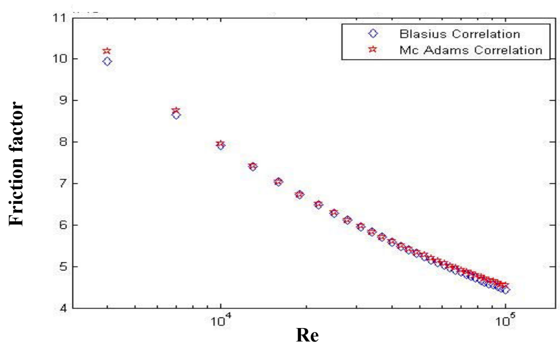

Fig. 3. Friction Factor vs. Reynolds Number in Smooth Annulus.

The heat transfer behavior is illustrated by Fig. 4. This figure shows that the heat transfer expressed by Stanton number decreases at higher Reynolds numbers. This can be explained by considering the facts that Reynolds number is the ratio of inertial forces to viscous forces while Stanton number is the ratio of heat transfer to the thermal capacity. Meaning that the inertia emphasize in the flow is higher than the contribution of heat transfer.

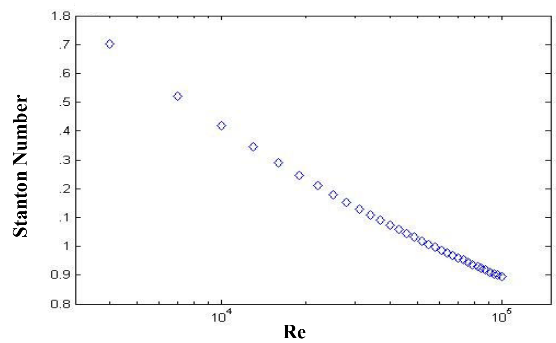

Fig. 4. Stanton Number vs. Reynolds Number in Smooth Annulus.

3.2. Ribbed cases

In this paragraph, the contributions of the rib on the thermo-hydrodynamic performance of the annular heat exchange process are presented and are compared with experimental results.

3.2.1. Effect of ribs height

The results of friction factor for ribbed annulus with p/e =10 at various ribs heights, e/D_h ratio are shown in Fig. 5. The values of the friction factor in the ribbing case are much higher than these of the non-ribbed case, which indicates that the presence of the ribs increases resistance to the flow resulting in larger pressure drop. This is attributed to the fact that the ribs induce local stagnation points in the flow. These stagnation points are increasing the momentum and consequently the friction in the flow. It is also noted that the friction factor increases with the rib height. That is, as the rib height increases so does the local stagnation area and as a result, more volume of the flow encounters the increase in momentum.

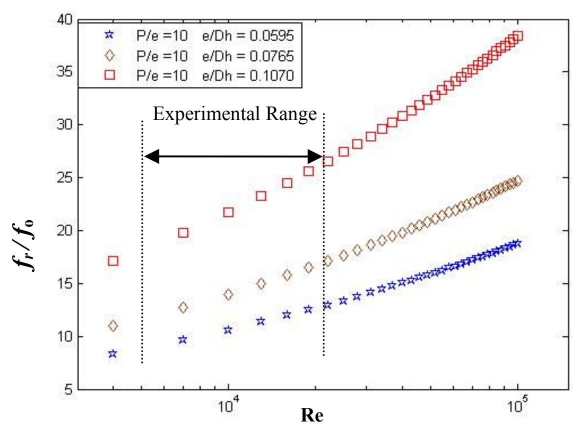

Fig. 5. Changes in Relative Friction Factor (*fr/fo*) vs. Reynolds Number.

The heat transfer enhancement is depicted by Fig. 6 which shows that the use of ribs enhances the heat transfer by more than 2.5 times than in the smooth case. It also shows that the heat transfer enhancement decreases at higher Reynolds numbers. This behavior is due to the decrease of the thermal capacity of the flow at high speeds.

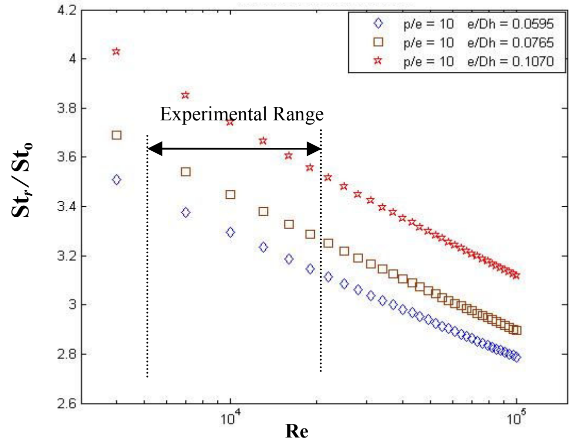

Fig. 6. Enhancement in Heat Transfer (St_r/St_o) vs.Reynolds Number Due to Ribbing.

3.2.2. The hydrothermal performance

As reported by previous works in the literature [2-6] and [8-10], the heat transfer enhancement by the use of the ribs is found to be accompanied by increasing pressure drop. Table 2 shows the range of heat transfer enhancement along with the range of pressure drop for different rib heights at P/e = 10.

Table 2. Range of Heat Transfer Enhancement and the Corresponding Increment in Pressure Drop (P/e=10).

e/D_h	St_r/St_o range		f_r/f_o range	
	from	to	from	to
0.0595	2.7873	3.5080	8.366	18.747
0.0765	2.8949	3.6892	11.026	24.708
0.1070	3.1173	4.0270	17.127	38.381

3.2.3. Annulus efficiency index

A parameter used to measure the efficiency of using the ribs is the annulus efficiency index. This is the ratio of the relative enhancement of the heat transfer (St_r/St_o) to the relative increase of the pressure drop (f_r/f_o) and is given as follows:

$$\eta = \frac{St_r}{St_o} \bigg/ \frac{f_r}{f_o} \quad (15)$$

This index which was first introduced by Webb [2] is used to evaluate the rib efficiency for three different rib heights as in Table 3 (for *P/e*=10). At ribs height e/D_h=0.0595, better efficiency is achieved than that of the other higher rib height cases.

Table 3. Annulus Efficiency Index for *P/e*=10.

e/D_h	Annulus efficiency index η	
	Lowest	Highest
0.0595	0.1487	0.4193
0.0765	0.1172	0.3346
0.1070	0.0812	0.2351

Figure 7 shows the efficiency index variation for various ribs conditions, *P/e* and *e/Dh*. It is concluded from the graph above that generally, the annulus efficiency is decreasing as the rib height increases; in other words, the increase in the pressure drop outweighs the heat transfer enhancement. It is also seen that the heat transfer enhancement increases with pitch distance. This result agrees with the results obtained by Yildiz et al. [4]. However the efficiency index should not be over looked. That is, although the overall heat transfer is enhanced, pressure drop increases as well which implies a greater pumping power requirement. A compromise should be made between the heat transfer enhancement and the pumping power requirements.

3.2.4. Effect of the pitch distance

The effect of the pitch distance, *P*, was investigated by varying the pitch to height ratio (*P/e*) which is directly related to the friction factor. Four different ratios were investigated; these are *P/e* = 5, 10, 15, 20. The heat transfer enhancement versus the pressure drop increase combined in the annulus efficiency index, η, is used to compare the results of these cases, as shown in Fig. 7.

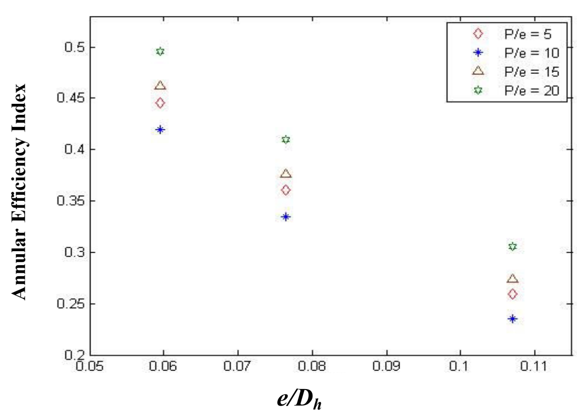

Fig. 7. Variation of the Annulus Efficiency with the Rib Height for Different Pitch Distances (Considering Maxim Values for each *P/e* Value).

3.3. Comparison with experimental results

Figures 8 and 9 are showing the change in the friction factor and the heat transfer, respectively, due to the installation of the ribs. The f_r/f_o and the St_r/St_o values were obtained from the measurements Al-Habeeb [5] at various Reynolds number ranging from 2×10^3 to 2×10^4 in the annulus.

A good agreement can be concluded by comparing the theoretical results of f_r/f_o shown in Fig. 5 with the corresponding experimental results shown in Fig. 8; and the theoretical results of St_r/St_o shown in Fig. 6 with corresponding experimental ones shown in Fig. 9. The maximum deviation between the experimental and theoretical results in f_r/f_o comparison is 3.7% absolute percent of error, while the maximum deviation between the experimental and theoretical results in St_r/St_o is 3.6% , This is demonstrating the validity of the developed analytical procedure.

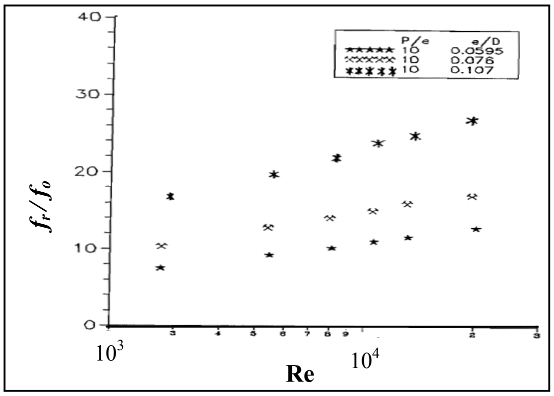

Fig. 8. Relative Increases in Pressure Drop as Obtained Experimentally [5].

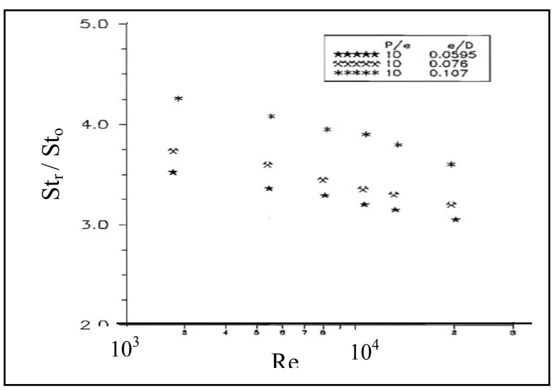

Fig. 9. Heat Transfer Enhancement by the Use of Ribs as Obtained Experimentally [5].

4. Conclusions

An analytical procedure is developed in MATLAB to study the heat transfer and pressure drop behavior in double pipe heat exchangers. The model results were validated by comparison with experimental results. The investigation is conducted at various annulus flow rate within Reynolds number ranging from 2500 to 150000. Heat transfer expressed by Stanton number is enhanced by more than 4 times in the presence of ribs. This enhancement, however, is accompanied by increase of the pressure drop as expressed by the friction factor of more than 38 times. Annulus efficiency index was used to evaluate the feasibility of ribbing. Pitch distance was also investigated using the ratio (*P/e*). It was found that the heat transfer enhancement increases with pitch increment.

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