World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:10, No:5, 2016

Numerical Investigation of the Effect of Geometrical Shape of Plate Heat Exchangers on Heat Transfer Efficiency

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International Science Index, Mechanical and Mechatronics Engineering Vol:10, No:5, 2016 waset.org/Publication/10004387

***Abstract*—**Optimizations of Plate Heat Exchangers (PHS) have received great attention in the past decade. In this study, heat transfer and pressure drop coefficients are compared for rectangular and circular PHS employing numerical simulations. Plates are designed to have equivalent areas. Simulations were implemented to investigate the efficiency of PHSs considering heat transfer, friction factor and pressure drop. Amount of heat transfer and pressure drop was obtained for different range of Reynolds numbers. These two parameters were compared with aim of *F* "weighting factor correlation". In this comparison, the minimum amount of F indicates higher efficiency. Results reveal that the *F* value for rectangular shape is less than circular plate, and hence using rectangular shape of PHS is more efficient than circular one. It was observed that, the amount of friction factor is correlated to the Reynolds numbers, such that friction factor decreased in both rectangular and circular plates with an increase in Reynolds number. Furthermore, such simulations revealed that the amount of heat transfer in rectangular plate is more than circular plate for different range of Reynolds numbers. The difference is more distinct for higher Reynolds number. However, amount of pressure drop in circular plate is less than rectangular plate for the same range of Reynolds numbers which is considered as a negative point for rectangular plate efficiency. It can be concluded that, while rectangular PHSs occupy more space than circular plate, the efficiency of rectangular plate is higher.

***Keywords*—**Chevron corrugated-plate heat exchanger, heat transfer, friction factor, Reynolds numbers.

I. INTRODUCTION

PHEs are one of the most common and useful types of heat exchangers [1]-[3]. They have the advantages of requiring less space than shell and tube ones (approximately one third), better efficiency and easy cleaning. Such advantages have made them better candidates for different applications. [4]-[6]. Recently, PHSs are more likely to be used rather those other types of heat exchangers, because they have advantages such as compactness, ease of production, sensitivity, easy care after set-up and efficiency [2], [7]-[10].

To achieve improvement in PHE's, two important factors namely amount of heat transfer and pressure drop have to be considered such that amount of heat transfer needs to be increased and pressure drops need to be decreased [7]. In PHSs, due to presence of corrugated plate, there is a significant resistance to flow with high friction loss. Thus, to design PHSs, one should consider both factors.

For a variety range of Reynolds numbers, many correlations and chevron angles for PHSs exist [11]. The plate geometry is one of the most important factor in heat transfer and pressure drop in PHSs, however such a feature is not accurately prescribed [12]. Therefore, to obtain the correct characteristics of a plate, it is necessary to implement performance testing [13].

The most important factors in evaluating PHSs performance are efficiency of heat transfer and pressure drops. In the corrugated PHSs, because of narrow path between the plates, there is a large pressure capacity and the flow becomes turbulent along the path. Therefore, it requires more pumping power than the other types of heat exchangers [14], [15].

To reach high efficiency in PHSs, numerous corrugated plates with variety of fluid flow have been studied. To achieve high efficiency ,higher heat transfer and less pressure drop are targeted [2].

To that end, different corrugated angels in a variety of Reynolds numbers have been studied. Also various researches have focused on the flow characteristics in the PHEs. Furthermore, there are many investigations into reducing the pressure drop in the path of flow [10], [11].

The effect of different angles of corrugated plates on the overall efficiency employing an empirical equation have been investigated [16], [17]. Martin [14], in a theoretical study, investigated the amount of Nusselt number and friction factor. Furthermore, to achieve a better shape, the correlation relating heat transfer and friction factor have been developed [18]-[22].

The effect of different angles of corrugated plate or the manner of flow in the PHEs has been previously studied, but this study is the first attempt in the literature to compare the efficiency of rectangular and circular plates. To that end, the amounts of heat transfer and friction factor are compared.

The shape of PHS is very important for industrial applications. In this study, rectangular PHEs were compared with circular PHEs to investigate their corresponding efficiency considering the same equivalent area. Simulation results indicate that amount of heat transfer in rectangular plate is greater than circular one for a range of Reynolds number. However, the pressure drop in rectangular plates is more than circular ones.

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II. MODELING

In order to compare amount of heat transfer and pressure drop in circular and rectangular plates, the two plates shown in Figs. 1 and 2 were designed by the commercial modeling software, Solid Work. The model geometry was completed in Gambit software. These figures show the geometry of circular and rectangular plates that were designed with a chevron corrugation of 60 degrees. After designing the plates, the model was imported to Gambit software to build two ports one as an inlet and one as an outlet on each plate. Then the mesh is generated in the Gambit software. The mesh for the rectangular and circular plates was generated using Tet/Hybrid elements with interval size of one. The model consists of 1041262 cells for rectangular plate and 971014 cells for circular plate.

To model the actuate geometry, the configuration of the plate designed by Mulley [1] was adopted. In this study, the length of rectangular plate is 392 mm with the width of 163 mm, thickness of 0.6 mm and diameters of both inlet and outlet ports are 5.08 mm. The circular plate has the same equivalent area as of a plate with 14.26 mm diameter. Mulley proposed a function to determine a corrugation depth (b) as:

$$b = 1.27\left(1 + \sin(\pi(\lambda - 2.25)/4.5)\right) \quad (1)$$

where λ is the corrugation wavelength. Fig. 3 shows the corrugation depth, b as function of corrugation wave length, λ for Chevron plates of SS304. This function relates the depth of corrugation as function of corrugation wavelength. In this study, λ is 9 mm, similar to Mulley's studies.

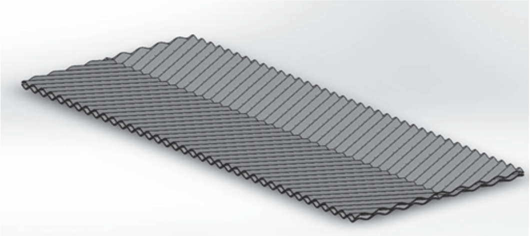

Fig. 1 Simulated Rectangular plate in Solid work software

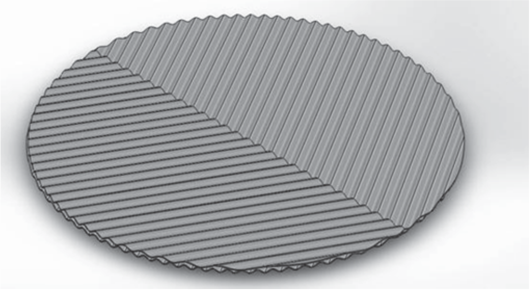

Fig. 2 Simulated circular plate in Solid work software

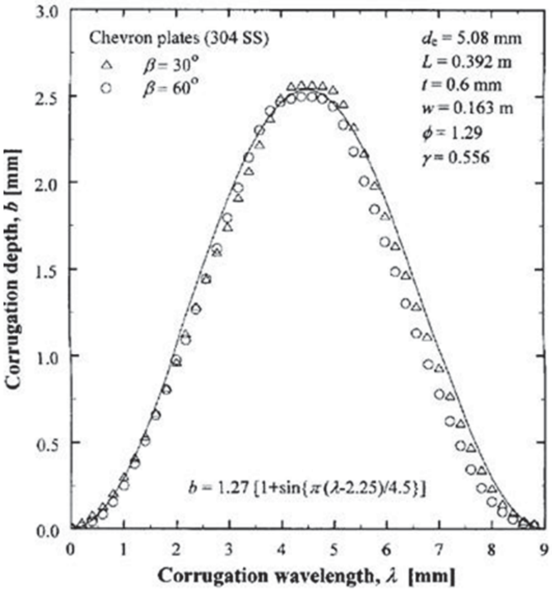

Fig. 3 Geometrical characteristics of plate surface corrugations [1]

III. BOUNDARY CONDITIONS

In the simulations, inlet flow mass and the inlet temperatures were specified such that the fluid inlet temperature is 300 K, the wall temperature is 400 K, and equivalent diameter is 5.06 mm. The outlet pressure was defined as a standard atmosphere. The boundary conditions of the PHEs walls are assumed to be aluminum with the following specifications: Thickness of 0.6 mm, density of 2719 kg/m3, cp of 871 J/kg K, and K is 202.4 W/mK.

IV. RESULTS

A. Temperature, Pressure, and Flow Fields Analysis

In this study, due to the high Reynolds number, the flow is turbulent [23], [24]. Previous studies have shown that k–ε realizable model for the present simulation is the most accurate [1], [25], [26]. Therefore, this model is used to simulate the temperature, pressure, and heat transfer. The following assumptions have been used in the simulation

1) The working fluids are incompressible and the chosen Newtonian fluid is water.
2) Body forces are assumed to be negligible in the momentum equation.
3) In the energy equation, viscous dissipation is negligible.
4) The Mass flow inlet of fluid is known, and outlet pressure is constant.
5) Pressure drop is determined from simulation results.

B. Effect of Heat Exchanger Plates Geometry on Heat Transfer

In this study, the effect of Reynolds number on the amount of heat transfer for both rectangular and circular plates investigated and compared to each other. To that end, six different Reynolds numbers were selected. The amount of flow rate for each Reynolds number, hydraulic diameter and Reynolds number are obtained from (2)-(4):

$$m^{\circ} = \rho u A \tag{2}$$

$$\mathrm{Re} = \frac{u D_h \rho}{\mu} \tag{3}$$

$$D_h = \frac{4A_f}{P} \tag{4}$$

Logarithmic temperature difference obtained from (5) is as:

$$\mathrm{LMTD} = \frac{(\Delta T_A - \Delta T_B)}{\mathrm{Ln}\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{\Delta T_A - \Delta T_B}{\mathrm{Ln}\Delta T_A - \mathrm{Ln}\Delta T_B} \tag{5}$$

In this simulation, the amount of heat transfer in the rectangular and circular plates is specified.

As shown in Fig. 4, heat transfer in rectangular plates is more than circular plates. In both plates, with increasing Reynolds number, the flow rates increases resulting in an increase in heat transfer. The rate of increasing heat transfer in circular and rectangular plates are the same however, the amount of heat transfer in rectangular plate is more than a circular one for all Reynolds number. As can be seen, this increase is more evident for higher Reynolds number.

As shown in Fig. 4, heat transfer in rectangular plates is approximately 15 % more than circular plates.

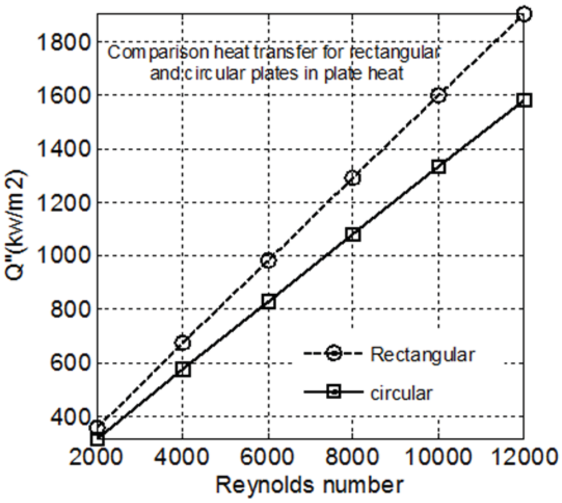

Fig. 4 Comparison of heat transfer for rectangular and circular plates in PHS

C. Effect of Heat Exchanger Plates Geometry on Pressure Drops

Another important factor that must be considered in plate exchangers is pressure drop in the fluid path. This pressure drop can have a dramatic effect on the efficiency of the heat exchangers. The higher the pressure drop is in heat exchangers, a larger pump is required, and this increases costs and reduces efficiency.

In this study, the pressure drop of friction factor is defined in (6). According to this equation, the friction coefficient changes for different Reynolds numbers for rectangular and circular plates shown in Fig. 5.

$$f = \frac{\Delta P}{L} \frac{D_h}{\rho u^2/2} \tag{6}$$

As seen in Fig. 5, pressure drop in rectangular plate is more than circular plate which is considered a negative point for rectangular plate efficiency. With an increase in Reynolds number, the amount of friction factor in rectangular and circular plates is gradually decreasing. It can be seen that the circular plate has less amount of friction factor in all range of Reynolds number in comparison with rectangular plate.

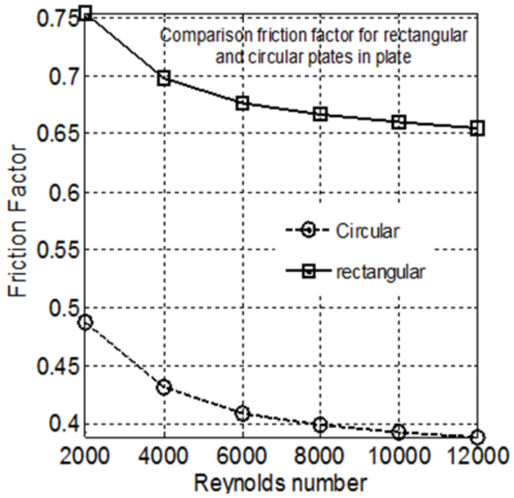

Fig. 5 Comparison of friction factor for rectangular and circular plates in PHS

D. Comparison of the Two Geometries with Respect to Heat Transfer and Pressure Drop

The approach to evaluate the efficiency of each plate has been thoroughly discussed in [27], [28]. To indicate the performance of a PHS, the function should be defined to include both enhanced heat transfer and frictional losses [29], [30]. As a result, a thermal function (ηNu) for smooth surface is defined as:

$$\eta_{\mathrm{Nu}} = \left(\frac{\mathrm{Nu}}{\mathrm{NU}_0}\right)^{-1} \tag{7}$$

where the Nusselt number (Nu) is expressed as:

$$\mathrm{Nu} = \frac{h D_h}{k} \tag{8}$$

The Dittus–Boelter correlation, Nu0, is Nusselt number for fully developed flow in the pipe when it is assumed smooth [31]:

$$\mathrm{Nu}_0 = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.3} \tag{9}$$

Therefore, the function that is related to friction is defined as:

$$\eta_f = \left(\frac{f}{f_0}\right)^{1/3} \tag{10}$$

where the friction factor, f, is given in (6). In (10), f0 is determined [31] as:

$$f_0 = \frac{64}{\mathrm{Re}}, \mathrm{Re} < 2300 \tag{11}$$

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$$f_0 = (1.8\log\text{Re} - 1.5)^{-2} \quad \text{Re} \geq 2300 \tag{12}$$

Finally, (7) and (10) are linearly combined in an objective function, F that indicates the amount of heat transfer and friction losses [17]:

$$\text{F} = \eta_{\text{Nu}} + \beta\eta_{\text{f}} \tag{13}$$

where β is a weighting factor that represents the amount of pumping cost to thermal cost, in other words, β is related to the cost of a unit of heat produced by a common fuel like natural gas and the same cost for amount of energy that is produced by electricity [28], [32]-[34]. This linear function has also been mentioned in the fundamental work of Bejan et al. [35]. β is ranging between 0 and 0.1 [33].

In this study, the results are shown for different Reynolds numbers and for 0.06 as weighting factor which relates to present conditions in Iran. Moreover, to achieve maximum performance of PHS in this study, the amount of F has to be minimized [28]. In this paper, amount of F determined for both rectangular and circular plates to investigate the efficiency.

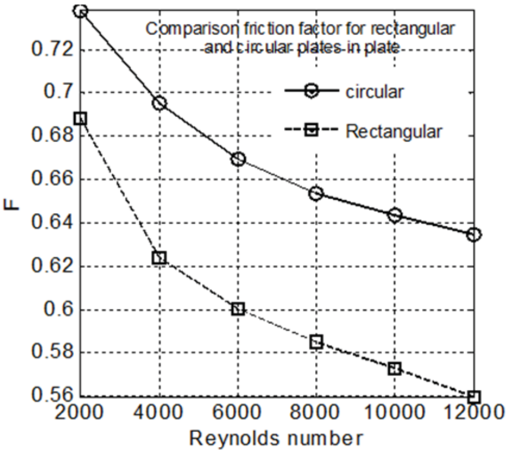

Fig. 6 Comparison of amount of F for rectangular and circular plates

As seen in Fig. 6, amount of F in rectangular plate is less than circular plate for all ranges of Reynolds number. In PHSs to have a good design, amount of heat transfer must be increased whereas, amount of friction factor must be reduced. Fig. 6 shows that when Reynolds number increases the amount of F decreases, this shows that for high Reynolds number the weight factor for PHSs yields satisfactory results. As a result of minimum amount of F in rectangular plate, it can be concluded that this plate has more efficiency in comparison with circular plates [28].

V.CONCLUSION

To optimize the design for PHSs, two different shapes of plates; rectangular and circular plates have been simulated. To evaluate the efficiency, two important factors need to be considered. First heat transfer must be maximized, while friction factor must be minimized. These factors are determined for two different shapes with equivalent area by numerical simulation. The obtained results suggest that, amount of heat transfer and pressure drop in rectangular plate is more than circular plate. To evaluate the efficiency, weighting factor, F, was defined such that the plate with a lower amount of F has higher efficiency. Consequently, obtaining a lower value of F for rectangular plate compared to circular plate indicates that the rectangular plate is more efficient. Simulation results suggest that the amount of friction factor decreased when Reynolds number increased. The reason of this decreasing of friction factor is related to the high velocity as a result of higher Reynolds number. The results also indicate that with an increase in Reynold Number, the amount of heat transfer is also increased such that higher Reynolds number is directly proportional to the Nusselt number and therefore results in higher heat transfer.

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