The Generalized Correlation for Friction Factor in Criss-cross Flow Channels of Plate Heat Exchangers

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The paper concerns with analysis of the influence of corrugation form of PHE plates on hydraulic resistance in the formed channels. The data for models of the main corrugated field of the inter-plate channel considered. It enables to exclude the influence of entrance and exit distribution zones. The specific type of generalizing formula is used, which correlates the data in a wider range of Reynolds numbers, compare to conventional ones. The equation for hydraulic performance of inter-plate channels with sinusoidal and triangular corrugations shapes is obtained, which generalizes experimental data of different authors available in literature. It accounts for the influence of the corrugation inclination angle to the plate vertical axis and corrugations pitch to height ratio.

1. Introduction

New challenges in efficient heat recuperation arise when integrating renewables, polygeneration and CHP units with traditional sources of heat in industry and the communal sector, as it is shown by Klemes et al. (2011). There is a requirement to consider minimal temperature differences in heat exchangers of reasonable size, see Fodor et al. (2010). The Plate Heat Exchanger (PHE) is the one of most efficient types of modern heat exchange equipment, which satisfies this requirement. The design and operation principle of PHE equipment is well described elsewhere, see e.g. Wang et al. (2007). The heat transfer processes in this heat exchanger takes place in the channels of complex geometry formed by plates pressed from thin metal. The plates’ corrugation form influences strongly on heat and hydraulic behaviour of inter-plate channels, the effect similar to that in enhanced tubes, see e.g. Kukulka and Fuller (2010).
The plates with straight-line corrugations inclined with the some angle to the plate’s vertical axis are generally used in modern PHEs (Figure 1). Assembled together in one unit, they form the channels of criss-cross flow type, which are distinguished by complex geometry and by existence of contact points between the opposite walls in the sites of corrugations crossing. Geometry of plates with different corrugation types (sinusoidal and triangular form) are given in Figure 2. Many authors deal in their works with investigation of heat transfer and hydraulic resistance in such channels: Focke et al. (1985), Muley and Manglik (1999), Dović et al. (2009), Tovazhnyansky et al. (1980), Savostin and Tikhonov (1972). Authors mainly generalized the obtained data in

form of separate empirical correlations for hydraulic resistance calculations, which are valid for investigated channels only in limited range of hydrodynamic and thermal parameters. Martin (1996) tried to generalize all the data for hydraulic resistance by the integrated equation on the basis of developed semi-empirical mathematic model. He obtained the relation, which in implicit form expresses the dependence of hydraulic resistance coefficient from Reynolds number and geometry parameters of plates' corrugation. But the calculation deviation for this relation from experimental data of other authors in some cases runs up to 50 % and more. Dović et al. (2009) obtained similar by accuracy result. The low accuracy of generalization in the mentioned works can be explained, first of all, by significant differences in experimental PHE models.

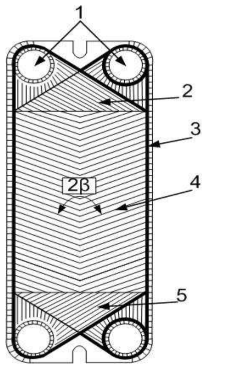

Figure 1: Schematic drawing of PHE plate:
1 – heat carrier inlet and outlet;
2,5 – zones for flow distribution;
3 – rubber gasket;
4 – the main corrugated field.

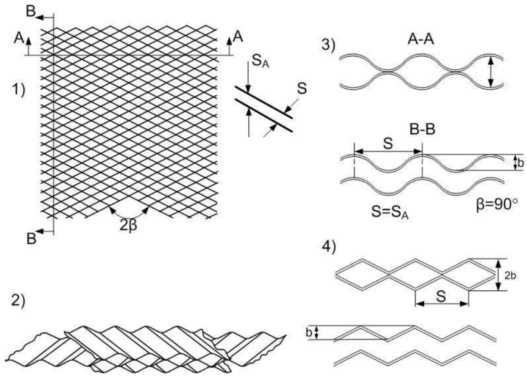

Figure 2: Different corrugation forms
1, 2 – the intersection of the adjacent plates;
3 – channel cross sections for the sinusoidal form of corrugations;
4 – channel cross sections for the triangular form of corrugations.

The plate's surface of industrial PHE, washed by the fluid (see Figure 1), consists of the main corrugated field (4) and zones of flow distribution on the inlet (2) and outlet (5). The most part of heat is transferred on the main corrugated field, which area comes to 80–85 % of total plate's heat transfer surface area. Though on the distribution zones considerably less heat is transferred, their influence on the overall hydraulic resistance of the channel can be significantly higher. First of all, here is the raised velocity of flow movement, which is increasing in following range: from the velocity value for the operating field up to the velocity on the outlet from the channel to the gathering collector of PHE (the same is for inlet from the distributing collector of PHE). In addition, the design of distribution parts can considerably vary for different plates, what affects their hydraulic resistance and evenness of flow distribution.

2. Correlation of the data for hydraulic resistance

Focke et al. (1985) and Tovazhnyansky et al. (1980) made their tests of hydraulic resistance study on models of channels corrugated field. It allows to eliminate the influence of the channel distribution zones. In present work the generalization of their data on hydraulic resistance of criss-cross flow type channels is carried out. These data are obtained for models of plates' corrugated field with different corrugation parameters. Such a generalized equation is required for the developing of reliable technique for optimal PHE heat transfer plates synthesis and for creation of universal calculation method of these units.

All researchers, which have published data on hydraulic resistance of PHE channels generalized the results in form of correlations presented in dimensionless form:

$$\zeta = f(\mathrm{Re}) \,. \tag{1}$$

Here ζ – coefficient of hydraulic resistance of the unit of relative channel length (called also friction factor); Re – Reynolds number for the flow in channel.

The non-dimensional variables in the relation (1) are calculated by the experimental data on pressure losses and flow rate through the channel according to the following formulas:

$$\zeta = \frac{\Delta P \cdot 2 \cdot d_E}{\rho \cdot w^2 \cdot L_{EF}} \tag{2}$$

$$\mathrm{Re} = \frac{w \cdot d_E}{\nu} \tag{3}$$

$$w = \frac{G_{CH}}{\rho \cdot f_{CH}} \tag{4}$$

here ΔP – pressure losses on the measurement part of channel, Pa; ρ – medium density, kg/m^3; ν – coefficient of kinematic viscosity, m^2/s; G – mass flow of medium through the one channel, kg/s; w – medium velocity in channel, m/s; d_E and L_{EF} – specific linear sizes in crosswise and longitudinal directions correspondingly.

Some authors use Fanning friction factor equal to $f = \zeta/4$ instead of ζ. There are exists the differences in defining the specific linear sizes of channel. Some authors, like Focke et al. (1985) and Martin (1996), taken the doubled value of the corrugation height $d_E = 2 \cdot b$ as a crosswise linear size (equivalent diameter d_E), and the channel length L as specific longitudinal size. Such an approach is very useful for the solution of plates' corrugation form optimization problems, because it directly accounts the parameters, which define the PHE dimensions. Further we use this approach for data generalizing.

Others, like Tovazhnyansky et al. (1980) and Dović et al. (2009), use hydraulic diameter of channel d_h as crosswise linear specific size. It is determined as quadruplicate area of the through section, divided by wetted perimeter of channel. The wall length of channel unwrapped in the direction of flow movement used as longitudinal linear size. The single approach should be used for comparison of results of different authors. Conformably, the results of Tovazhnyansky et al. (1980) should be recalculated using the approach $d_E = 2 \cdot b$ and $L_{EF} = L$.

For the generalization of the obtained data the form of equation, proposed by Churchill (1977) for straight tubes, is selected. Its accuracy and convenience is confirmed in a number of papers, see e.g. Turek et al. (2009). The equation is expressed in explicit form and conforms to data for tubes for the laminar, turbulent and transient regimes of flow. Such feature is very useful for PHE channels, the change of flow regimes in which occurs under the different Reynolds numbers. The general correlation is as following:

$$\zeta = 8\cdot\left[\left(\frac{12+p2}{\mathrm{Re}}\right)^{12} + \frac{1}{(A+B)^{\frac{3}{2}}}\right]^{\frac{1}{12}} \tag{5}$$

$$A = \left[p4\cdot\ln\left(\frac{p5}{\left(\frac{7\cdot p3}{\mathrm{Re}}\right)^{0.9} + 0.27\cdot 10^{-5}}\right)\right]^{16}; \qquad B = \left(\frac{37530\cdot p1}{\mathrm{Re}}\right)^{16},$$

where p1, p2, p3, p4, p5 – parameters defined by channel corrugation form.

Figure 3 shows the comparison of calculations by empirical formulas presented by Focke et al. (1985) with calculations according to the Eq.(5) for the following values of its parameters:

$$p1 = \exp(-0.15705\cdot\beta);\quad p2 = \frac{\pi\cdot\beta\cdot\gamma^2}{3};\quad p3 = \exp\left(-\pi\cdot\frac{\beta}{180}\cdot\frac{1}{\gamma^2}\right); \tag{6}$$

$$p4 = \left(0.061 + \left(0.69 + tg\left(\beta\cdot\frac{\pi}{180}\right)\right)^{-2.63}\right)\cdot\left(1+(1-\gamma)\cdot 0.9\cdot\beta^{0.01}\right); \qquad p5 = 1+\frac{\beta}{10}$$

Here $\gamma = 2\cdot b/S$ – the corrugation doubled height to pitch ratio. For the corrugations of plates from paper of Focke et al. (1985) its value $\gamma = 1$. The average mean-square error of the calculation on Eq.(5) for all corrugations forms mentioned in cited paper constitute ±9%.

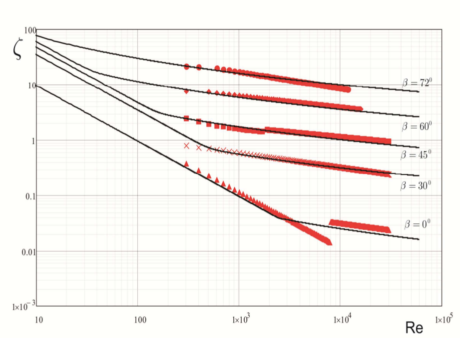

Figure 3: The correlation by Eq.(5) of data from Focke et al. (1985).

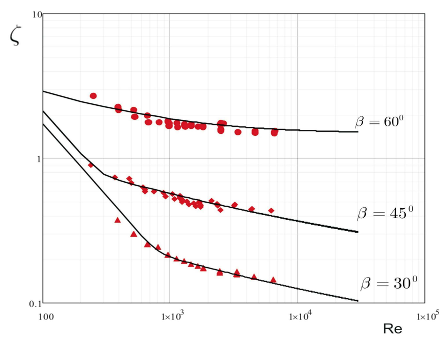

Figure 4: Correlation of data from Tovazhnyansky et al. (1980).

For the proper comparison of hydraulic parameters of channels formed by plates with triangular corrugation patterns the processing of data from paper of Tovazhnyansky, et al. (1980) was carried out at $d_E = 2\cdot b$ and $L_{EF} = L$. The processing was done using the initial data of tests by Tovazhnyansky et al. (1980). The results of tests are also well predicted by Eq.(5) at the value $\gamma = 5/9$ for the triangular corrugations (with rounded edges) of the prototypes used in that work.

Calculated (solid lines) and experimental data (dots) are presented in Figure 4. The mean-square error of the experimental data generalization comes to ±6.5%. As for the plates with sinusoidal corrugation, the influence of the corrugation inclination angle is the same and can be defined by the same correlation.

3. Comparison with other experimental data

Figure 5 shows the comparison of calculations according to Eq.(5) at the parameters values (6) with the experimental data of paper by Dović et al. (2009). These data are obtained for two test models of channels with sinusoidal corrugations with inclination angels of 28º and 65º. The value of parameter γ was equal to 0.52. Data for ζ and Re were corrected to account for difference in d_E and d_h. The data agree with calculation rather good. The discrepancy for β= 65^o is less than 20% (the calculation according to formula presented by Dović et al. (2009) gives the overestimation up to 50 %). For the β= 28^o the discrepancy is the same for Re up to 300, but increase at Re=1200 up to 50%. It should be noticed, that data were estimated from the graphs given in cited paper and they give rather qualitative picture. But it allows us to conclude, that the accuracy of data generalizing is higher, that it was for the model presented in that paper.

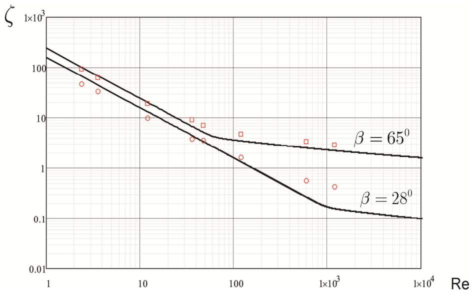

Figure 5: The comparison with experimental data of Dović et al (2009).

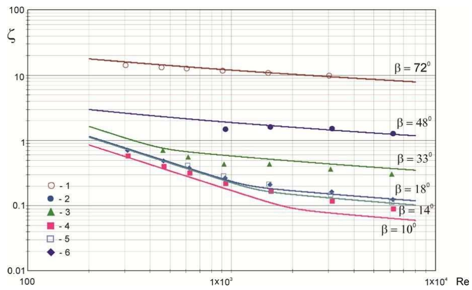

Figure 6: The comparison with experimental data of Savustin and Tikhonov (1972).

One of the earliest studies for channels with triangular form of corrugations was reported by Savostin and Tikhonov (1972). The agreement with Eq.(5) is rather good for β in the range 14^o – 72^o (the error mostly less than 20 %). It increased at β= 10^o to 35 % (see Figure 6). The parameter γ varied from 0.872 to 1.02. Data for bigger γ we not considered and regarded γ = 1.02 as upper limit of Eq.(5) application.

4. Conclusions

The influence of corrugation form of PHE heat transfer plates on hydraulic resistance is very significant. The obtained correlation enable to predict friction factors at corrugated field of criss-cross flow channels, formed by plates with inclined corrugations in wide range of corrugation parameters. It was confirmed for corrugations inclination angle from 14^o to 72^o and double height to pitch ratio from 0.52 to 1.02 in the range of Reynolds numbers from 5 to 25,000. The difference between sinusoidal and triangular (with rounded edges) shapes practically not significant for coefficient of hydraulic resistance.

5. Acknowledgements

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