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Heat Transfer and Pressure Loss in Small-Scale Pillow-Plate Heat Exchangers

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In this work, an experimental study of heat transfer between air and water in a small-scale pillow-plate heat exchanger (PPHE) consisting of two pillow plates assembled together in one unit was carried out. In the experiments, cooling water flows in two inner channels (i.e., channels inside welded pillow plates), whereas air is directed to the outer channel between the plates. Heat transfer and hydraulic resistance in inner and outer PPHE channels are analysed based on the experimental data. The measurements were used to develop correlations for the pressure loss and heat transfer coefficients in both inner and outer channels. For the detailed investigation of pressure loss and wall shear stress in the outer channel between pillow plates, CFD simulations were carried out for the considered geometry. The Reynolds number was equal to 5,173, which ensured fully developed turbulent flow. The proposed correlations derived from experimental data were compared with the CFD simulation results. They can be used to predict thermal and hydraulic performance of small-scale PPHEs.

1. Introduction

Increasing heat recovery in industry and household is the key point for reduced energy consumption. It can largely be achieved by improved efficiency of both process plants and equipment units. In this regard, more efficient heat transfer systems with advanced heat transfer equipment is essential (Klemeš et al., 2015). Pillow-plate heat exchangers (PPHEs) represent an innovative type of heat exchange equipment, with space-effective, light and pressure-resistant construction. Furthermore, they show intensified heat transfer characteristics while keeping pressure loss on the product media side low. Heat transfer is realized in channels with complex geometry, which are formed by spot-welding of two metal sheets, according to a particular welding spot pattern, and subsequent expansion by hydroforming. The distance between welded pillow plates, assembled in a single unit, can vary, thus enabling different cross-sectional areas for hot and cold media to be obtained. This feature makes PPHEs very useful for operations in which considerable difference between flow rates on the hot and cold side exists.

Recent experimental studies of PPHEs comprise investigations of pressure loss and heat transfer in the inner (i.e., channels inside welded pillow plates) and outer channels formed by pillow plates. However, they have been performed for just few PPHE geometries. Pressure loss in the outer channel between two pillow plates was investigated for only one pillow plate geometry with one fixed distance between pillow plates (cf. Piper et al., 2015b). A complementary CFD analysis presented by Piper et al. (2016) also addresses this single pillow-plate geometry. The exergy analysis of the pillow-plates was performed by Zhang et al. (2017). The evaporation in PPHEs was investigated by Goedecke and Scholl (2015).

The present tendency towards compact equipment makes investigation of hydraulic performance of small-scale pillow plates interesting for industrial application. Small-scale PPHEs have not been studied, and thus, no reliable correlations for their heat transfer coefficients are available. The data transferability between different pillow-plate geometries is also uncertain. To study the thermal and hydraulic behaviour of PPHEs, we developed an experimental set-up enabling pressure drop and heat transfer coefficients in the inner and outer channels of the small-scale PPHEs to be determined. Two pillow plates, which are two times smaller than those investigated

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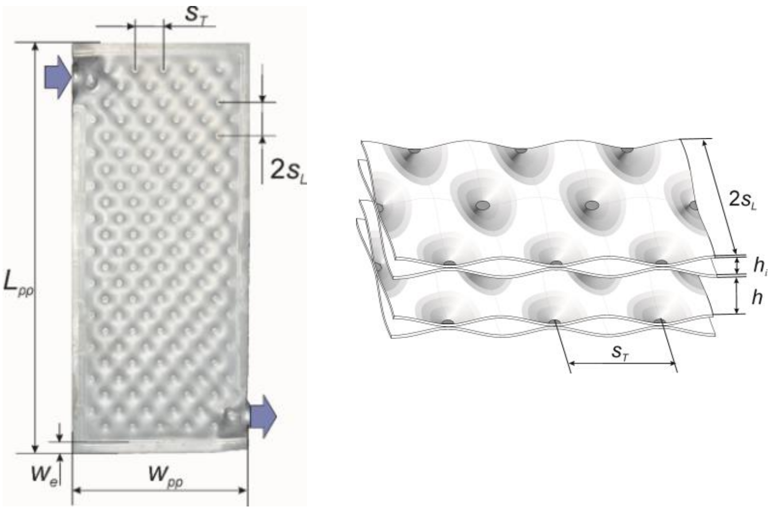
by Piper et al. (2015b) were manufactured. Measurements were carried out and the resulting experimental data were analysed and validated. The obtained results were used to develop the general correlation for the heat transfer coefficient and friction factor in the outer pillow-plate channel based on the least square method. Furthermore, the pressure loss and wall shear stress in the outer channel between pillow plates were analysed by CFD simulations for the considered geometry for a Reynolds number equal to 5,173. The proposed correlations derived from experimental data were compared with the CFD simulation results.

2. Experimental investigations

A specific PPHE sample was studied. It consists of two small-scale pillow plates manufactured by BUCO Laserplate GmbH (Germany) and shown in Figure 1. They are made of AISI 304 stainless steel, with the thickness of metal plate equal to 0.8 mm. The main geometrical parameters of the investigated small-scale pillow plates are presented in Figure 1 and Table 1. The pillow plates were assembled together to compose a heat exchanger with one outer-plate channel for air and two inner-plate channels for water. The distance between the pillow plates (*h*) was fixed to 12 mm. Water was directed inside pillow plate channels. For a better flow distribution inside this small-scale pillow plate, the entrance to the pillow plate was made at the plate side, while the outlet was placed diagonally opposite at the other side (see Figure 1a). The inner diameters of the entrance and outlet tubes were 24.9 mm.



a) b)

Figure 1: Dimensions of the investigated PPHE: (a) front view of the pillow plate; (b) channels inside the PPHE

Table 1: The geometrical parameters of investigated pillow plates

Parameter	Description	Value, mm
d_{ws}	welding spot diameter	6
h_i	inner expansion of the pillow plate	3.5
$2s_L$	longitudinal distance between welding spots	42
s_T	transversal distance between welding spots	36
w_{pp}	width of the pillow plate	230
L_{pp}	height of the pillow plate	530
w_e	width of the edges of the pillow plate	30

2.1 Experimental set-up

To study the pressure drop and heat transfer in the inner and outer channels of a PPHE, an experimental set-up shown schematically in Figure 2 was developed. It consists of two cycles, one for water and one for dry air. Water was heated in the thermostat up to 20 °C and pumped to the inner channel of the PPHE. The water flowrate was kept equal to 900 kg/h and measured using the Coriolis flow and density meter CMF025M (G2). To measure pressure drop in the inner pillow plate channel for water, sensors were installed in the inlet and outlet pipes of the pillow plate. The pressure drop measurements were made using the Rosemount pressure transmitter 3051CD (∆P2).

Dry air with the inlet temperature equal to 325 °C was directed to the outer pillow plate channels by an air compressor. The flowrate of the air was varied from 40 to 105 kg/h and measured using the Rosemount 8800D vortex flowmeter (G1). The pressure drop was determined with the Rosemount pressure transmitter 3,051 (ΔP1), using sensors installed at the inlet and outlet of the channel. Calibrated B-type thermocouples were used to measure the temperatures of air and water at the inlet and outlet. The total accuracy of the pressure drop experimental measurements was estimated as ± 0.10 % for water side and ± 0.50 % for air. The accuracy of flowrate measurements was ± 0.50 % and ± 0.80 % for water and air, correspondingly.

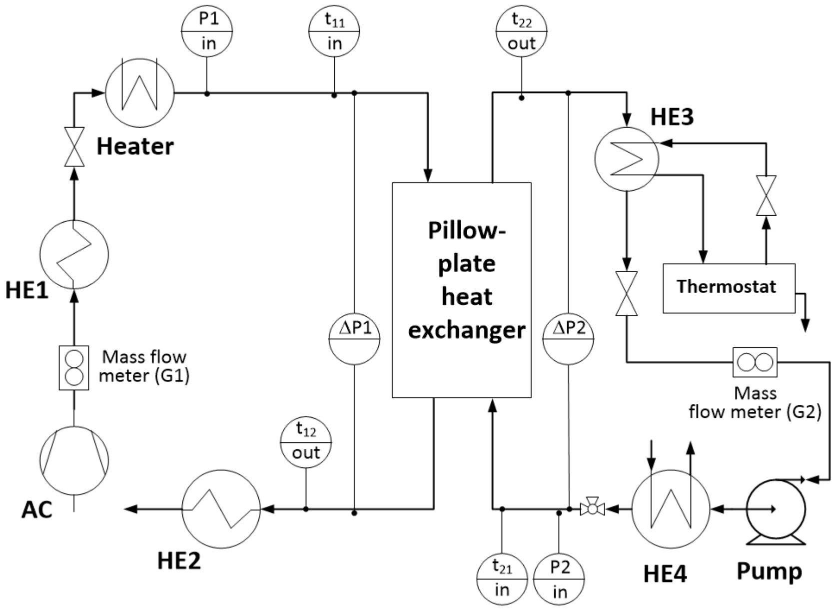


Figure 2: Experimental set-up: HE – heat exchanger; AC – air compressor

To decrease the uncertainty of the air flowmeter data, non-ideal gas behaviour was taken into account, and the dry air thermo-physical properties were estimated for each specific gas flow measured. The data acquisition system based on the LabVIEW software together with sensors and digital multiplexers was used to process the measured data.

2.2 Experimental results

During the experiments, the flowrate of dry air varied, the air inlet temperature was kept around 325 °C, water flowrate was equal to 900 kg/h and water inlet temperature to 20 °C.
The overall heat transfer coefficient was defined according to the following relation:

$$\frac{1}{U}=\frac{1}{h_1}+\frac{1}{h_2}+\frac{\delta_w}{\lambda_w}+R_f \tag{1}$$

where h_1 and h_2 are the heat transfer coefficients for the air side and water side of the PPHE, R_f is the thermal resistance of the fouling deposit on the heat transfer surface, δ_w is the thickness of the plate metal, λ_w is the heat conductivity of the plate material. In this work, only clear surfaces were considered, and thus, $R_f = 0$.
For the estimation of the overall heat transfer coefficient, the correlations for both heat transfer coefficients must be known. These correlations depend on the fluid physical properties, friction factor and channel geometry. Piper et al. (2017) proposed the correlations for heat transfer and pressure drop in the inner pillow-plate channel based on dimensionless combinations of pillow-plate geometry parameters. Generally, these correlations are suitable for the wide range of the pillow-plate geometries.
For the pillow plate with the geometrical parameters presented in Table 2, the dimensionless combinations introduced by Piper et al. (2017) take the following values: a = 1.17; b = 0.17; c = 0.097. These values fall outside of the reliable range for the proposed correlations. Therefore, further pressure drop studies in inner pillow-plate channel were carried out by Arsenyeva et al. (2017), who derived the following correlation for the friction factor in inner pillow-plate channels:

$$\zeta = 8\cdot\left[\left(\frac{12+p2}{\mathrm{Re}}\right)^{12}+\frac{1}{(A+B)^{\frac{3}{2}}}\right]^{\frac{1}{12}};\ A=\left[p4\cdot\ln\left(p5\Big/\left[\left(\frac{7\cdot p3}{\mathrm{Re}}\right)^{0.9}+0.27\cdot10^{-5}\right]\right)\right]^{16};\ B=\left(\frac{37530\cdot p1}{\mathrm{Re}}\right)^{16} \quad (2)$$

where $p1$ to $p5$ are parameters depending on the channel form. For the investigated pillow plate geometry (Table 2), the values of these parameters are as follows: $p1$ = 136.321; $p2$ = 7.387; $p3$ = 0.382; $p4$ = 0.515; $p5$ = 4.622. The obtained values of experimental heat transfer coefficients were equal to $6.28\cdot10^3$ W/(m^2·K) for inner channel and to 57.47 W/(m^2·K) for the outer channel. These parameters are used in the estimation of the overall heat transfer coefficient according to Eq(1), while the reciprocal value for water is far too small to affect the overall value. This justifies the assumption that the equation derived for large-scale PPHEs can also be used for the estimation of heat transfer coefficient in small-scale inner pillow-plate channels. Thus, the following relationship suggested by Tran et al. (2015) for the large-scale pillow-plate was applied:

$$\mathrm{Nu}_2 = 0.067\,\mathrm{Re}^{0.774}\,\mathrm{Pr}^{0.338} \quad (3)$$

The experimental data for the outer pillow-plate channel are shown in Figure 3. For accurate estimation of the heat transfer and hydraulic parameters, the dry air thermo-physical properties, namely density, viscosity, heat capacity and heat conductivity were defined for the varied dry air temperature and pressure along the channel length. The experimental data in the outer PPHE channel are presented in Figure 3a and can be approximated using the following correlation:

$$\zeta = 0.7155\cdot\mathrm{Re}^{-0.361} \quad (4)$$

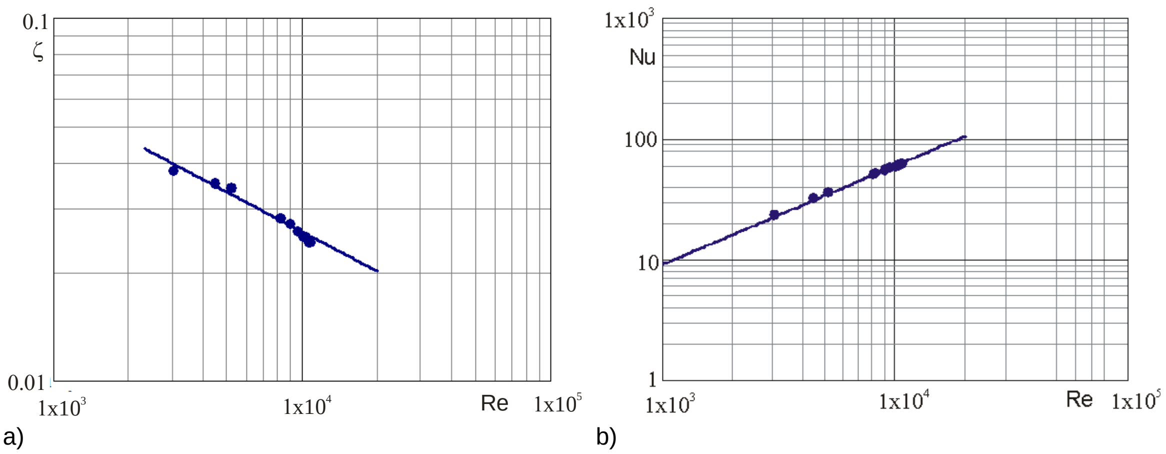


Figure 3: Pressure drop (a) and heat transfer coefficient (b) in outer PPHE channel: dots – experimental results; lines – values calculated according to Eqs(4), (5)

For the prediction of heat transfer in the outer PPHE channel, the following relationship based on the heat and momentum transfer analogy can be used (Figure 3b):

$$\mathrm{Nu} = 0.0275\cdot\mathrm{Re}^{0.8175}\cdot\mathrm{Pr}^{0.4} \quad (5)$$

Values calculated according to Eqs(4), (5) differ from experimental data by less than ±10 % and are valid in the range of Reynolds numbers between 3,000 and 20,000, what corresponds to developed turbulent flow regime, which is caused by the artificial turbulence in the PPHE channels of complex geometry.

3. CFD modelling

The CFD simulation was carried out to investigate the heat transfer and wall (plate surface) shear stress for the turbulent single-phase flow inside the outer pillow-plate channel. The computations were performed for the periodic simulation element selected according to the approach presented by Piper et al. (2015a) for large-scale pillow-plate channels. The periodic computational domain together with structured body-fitted mesh is shown in Figure 4.

The commercial software STAR-CCM+ by Siemens PLM based on the finite volume method was used for computations. The following properties of the flow were considered: single-phase, steady-state, incompressible, three-dimensional, turbulent. The flow was performed by Reynolds-Averaged-Navier-Stokes (RANS) equations. For the description of turbulence in the observed sample, the "elliptic blending k-ε" turbulence model was selected.

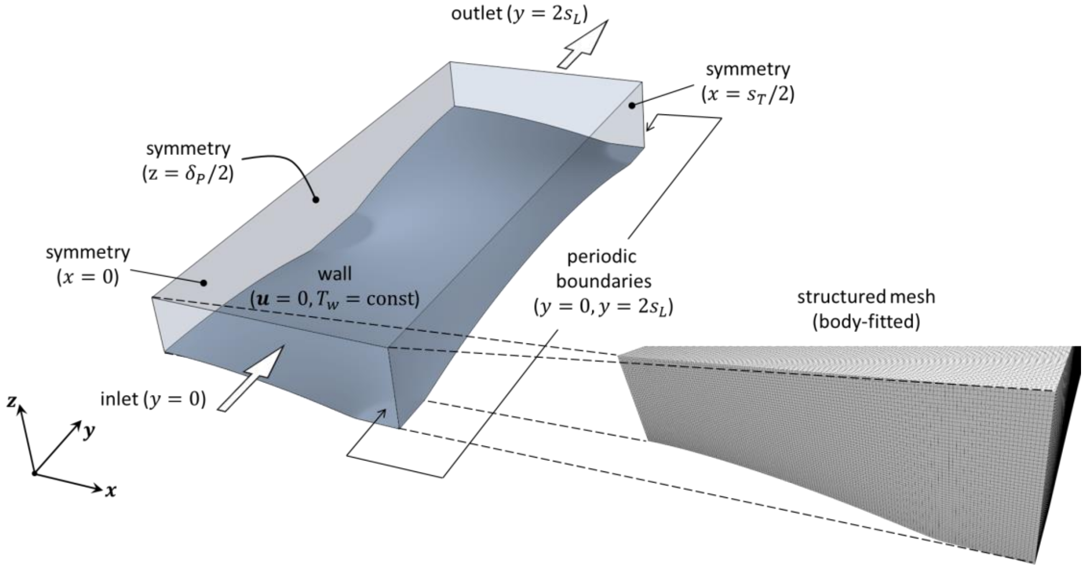


Figure 4: The periodic computational domain and structured body-fitted mesh of the outer pillow-plate channel

Simulations were accomplished for the experimental conditions corresponding to one of the points shown in Figure 3, with Re = 5,173 (developed turbulent flow). The following assumptions were made: the welding spots have the same temperature as the rest of the pillow plate; the physical properties of dry air are constant. The fixed temperature of the wall was selected as a boundary condition. The mass flowrate for the selected experiment was equal to 0.01413 kg/s. Physical properties of dry air used for simulation were calculated for an average temperature along the plate equal to 233 °C. They are listed in Table 2.

Table 2: Physical properties of the dry air at 233 °C used for CFD simulations

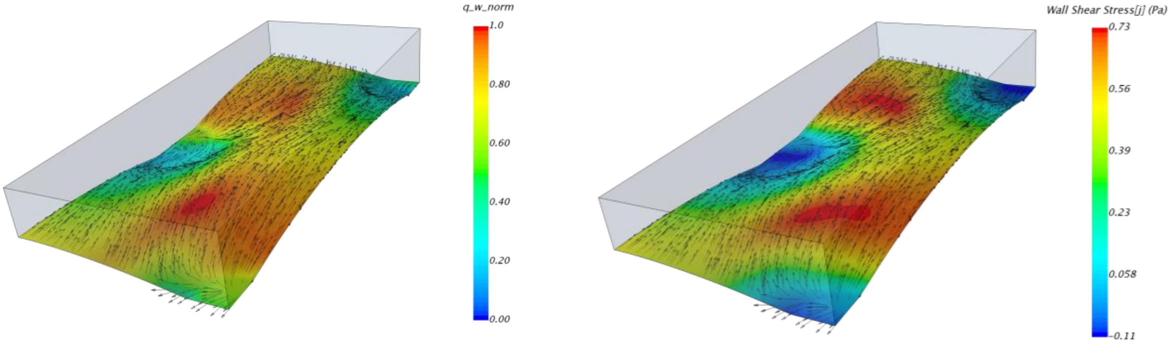
Parameter	Value
Density	0.68798 kg/m^3
Kinematic viscosity	$3.96921 \cdot 10^{-5}$ m^2/s
Specific heat capacity	$1.02565 \cdot 10^3$ J/(kg·°C)
Heat conductivity factor	0.04076 W/(m·°C)
Prandtl number	0.68713

4. Results and discussion

The results of CFD simulations were compared with the experimental data using the value of the heat transfer coefficient in outer pillow-plate channel. The numerical heat transfer coefficient (47 W/(m^{2}K)) deviates from the corresponding experimental value (56.81 W/(m^{2}K)). The discrepancy is nearly 17 %, which exceeds the experimental error estimated as ±10 %. This deviation can be explained by the enhanced heat transfer in the entrance region which was not considered in the CFD simulations performed with the periodic boundary conditions.

The distribution of heat transfer intensity on the pillow plate surface is shown in Figure 5a. The normalized values are obtained using the maximum value of the wall heat flux. The lowest values are at the welding spots and highest are on the convex part of the plate. The heat flux fluctuates both in longitudinal and transversal directions. The character of the vortex structure is similar to the structure reported by Piper et al. (2016) for large-scale outer pillow-plate channel. The recirculation zones occupy more than 20 %. The visible uneven distribution of the heat flux leads to high temperature gradients and more intensive heat transfer.

For the calculation of the fouling thermal resistance, a mean wall shear stress over the entire plate is commonly used (Klemeš et al., 2015). Calculation results show that the fluid flow inside the wavy passages formed by the pillow plates becomes intricate due to large secondary flows. This leads to an uneven distribution of the shear stress over the wall surface, as shown in Figure 5b. In this way, CFD results help to identify different wall shear stress regions and to predict the fouling deposition formation on the surface.



(a) (b)

Figure 5: (a) The illustration of the normalized wall heat flux for the outer pillow-plate channel. The normalization is done using the maximum value of the wall heat flux. (b) The illustration of the wall shear stress component in longitudinal direction. The vectors represent the wall shear stress direction

5. Conclusions

In this work, the experimental data for small-scale PPHE were obtained and compared with CFD simulations. The correlations for friction factor and heat transfer in PPHEs outer channel were worked out, with a deviation from experimental results within ± 10 %. They are reliable for the Reynolds numbers varying between 3,000 and 20,000. The CFD simulations were performed to test the proposed correlations and to investigate the heat transfer and wall shear stress for the turbulent single-phase flow inside the outer pillow-plate channel. The simulations were carried out for one value of the Reynolds number equal to 5,173, what corresponds to fully developed turbulent flow in outer PPHE channels. The deviations between experimental and numerical values of heat transfer coefficient do not exceed 15 %, which is a satisfactory agreement. Using the CFD simulations, it was possible to predict the shear stress distribution on the surface of pillow plates.

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