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# Heat Transfer and Pressure Drop Study of Panel Plate Heat Exchanger

Olexandr Perevertaylenko[a], Leonid Tovazhnyanskyy[a], Jiří Jaromír Klemeš[b], Pavlo Arsenyev[c], Olga Arsenyeva[b], Petro Kapustenko[b,*]

[a]National Technical University "Kharkiv Polytechnic Institute", Dep. ITPA, 21 Frunze st., 61002 Kharkiv, Ukraine
[b]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
[c]AO Spivdruzhnist-T LLC, 2 Kaplunovskiy per., 19, 61002 Kharkiv, Ukraine
kapustenko@fme.vutbr.cz

Heat recovery in different industrial processes is becoming of major importance as requirements for environment protection and climate goals push industries to increase the efficiency of energy usage. It requires the development and application of different types of efficient heat exchangers for specific process conditions. One such types are panel pate heat exchangers. The results of the experimental study of heat transfer and pressure drop in waved form channels of panel plate heat exchanger are presented. The experimental model and experimental unit are described. The basic equations for film heat transfer coefficient and friction factor calculation are obtained in dimensionless form. The proposed construction of a panel plate heat exchanger is optimal for waste gaseous flows heat recuperation when another flow is liquid. It allows enhancement of heat transfer on 50 up to 60 % compared to straight, smooth channels. Such panel plate heat exchangers will be an effective tool for waste heat recovery and its integration in a number of processes to decrease fossil fuel consumption and polluting emissions.

## 1. Introduction

The heat integration improvement in the industry and municipal sector is the key factor in energy consumption and greenhouse gases emissions decrease. Klemeš et al. (2013) analysed the great importance of Industrial Waste Heat Integration. The heat of flue gases, off-gases from different furnaces and waste vapour-gas mixtures is a significant part of industrial waste heat potential because of high-temperature levels (Arsenyeva et al., 2016). The waste gaseous flows' heat recuperation would enable to reduce of fuel demands and carbon emissions, capture waste energy and lower total fuel consumption. The use of mentioned above gaseous flows for heat recuperation is connected with the following challenges:

(i) high volumetric flowrates of gaseous streams with limited permissible pressure drop;
(ii) low values of thermal and physical properties such as density and specific heat capacity that causes the lower values of film heat transfer coefficients compared to liquid streams;
(iii) high contamination with dust and soot;
(iv) possibility of sulphur based acids formation when a gaseous stream is cooled to temperatures lower than the dew point, which may cause the corrosion of heat transfer surface material.

The heat of waste gaseous flows with temperatures 150 – 300 $^oC$ may be used for direct heat transfer for water heating in radiator heating systems or for thermal liquid heating in organic Rankine cycle systems to produce electricity. The key factor of these recuperative technologies is the effective heat exchange equipment.

The main feature of heat exchange position "waste gaseous flow/ liquid flow" is the large difference in volumetric flowrates. The traditional construction of heat exchangers for this position is finned tube heat exchangers where the liquid flows inside tubes, and gaseous media flows outside tubes. A finned heat exchange surface is used to enhance the heat transfer from the gaseous flow. These heat exchangers constructions have such drawbacks as low efficiency, low corrosion resistance below the dew point, and difficulties in exploitation.

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Modern high effective plate heat exchangers with corrugated plates as heat exchange surfaces are an effective means of heat integration in different heat exchangers networks because of high heat transfer coefficients, compactness and corrosion resistant plate materials (Klemeš et al., 2015). Such heat exchangers are successfully used in a plurality of different industrial processes, power generation plants and district heating systems. There are different kinds of plate heat exchangers: plate-and-frame, brazed, welded and semi-welded. The calculations of such units are based on mathematical models, for example, proposed by Arsenyeva et al. (2011) with the use of empirical (Arsenyeva et al., 2011), semi-empirical (Kapustenko et al., 2011) and theoretical correlations (Arsenyeva et al., 2014).
Taking into account specific features of waste gaseous flows heat recuperation with liquid flows, the plate heat exchangers' construction needs appropriate modifications for this duty. To enhance the performance of plate heat exchangers, the constructions of panel and sandwich heat exchangers were proposed and studied by different authors. Garelly et al. (2019) investigated numerically heat transfer enhancement in panel type radiators using vortex generators. The analysis of flow in mini channels of plate heat exchangers was reported by Giurgiu et al. (2016). The utilisation of flat panel heat exchangers in ground-coupled heat pumps was studied numerically by Habibi et al. (2020). The special construction of the sandwich panel exchanger was investigated by Kong et al. (2019). The hydraulic and heat transfer performance of sandwich panels with plate fins was analysed by Ma et al. (2020). A novel heat exchanger for photovoltaic panel cooling application and its design procedure is considered in a paper by Saddiqui et al. (2019). One of the special constructions of plate heat exchangers is the pillow plate heat exchanger, which is very attractive for waste heat recuperation (Arsenyeva et al., 2018). The numerical study of such heat exchangers was performed in a paper by Piper et al. (2019). The drawback of such construction for mentioned above duty concludes in approximately equal form and dimensions of adjacent channels that causes very low liquid velocity and low film heat transfer coefficient to liquid flow.
The construction of a panel plate heat exchanger was proposed with waved form channel for gaseous flow and a curved zig-zag channel for liquid flow to eliminate these drawbacks. The experimental study of hydraulic and heat transfer performance of this heat exchanger is the subject of the present paper.

## 2. Experimental investigations

The experimental investigation on heat transfer and pressure drop in waved form channels of panel plate heat exchanger had been carried out. The pack of plates of the industrial-scale heat exchanger was taken as an experimental model. The pack was the welded construction that consisted of five panels, and each panel was formed by welding two plates. The plate is shown in Figure 1.

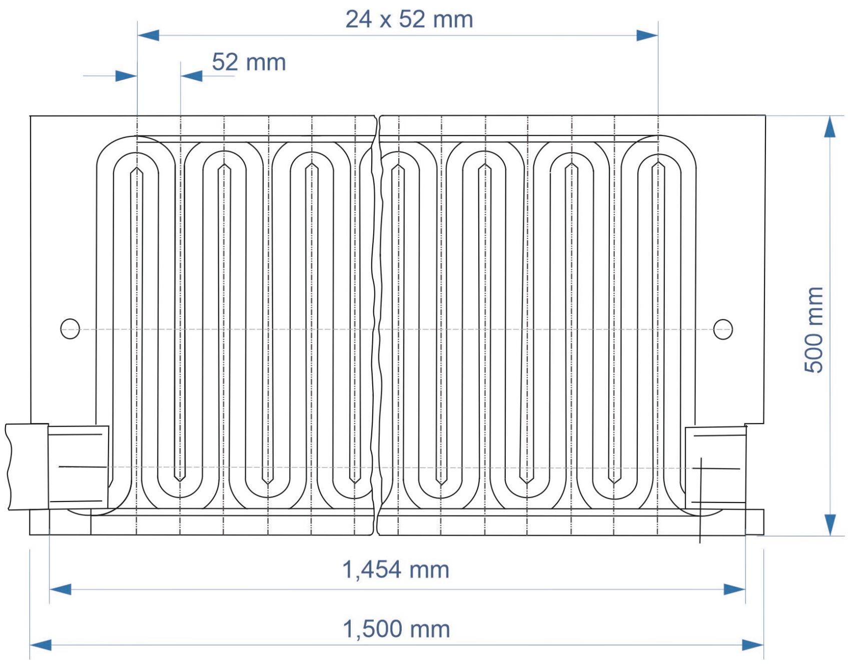


*Figure 1: The plate panel plate heat exchanger*

The pair of welded adjacent plates formed a panel with a curved zig-zag tube channel for liquid streamflow. Two adjacent panels formed the wavy channel for gaseous streamflow.
The scheme of streams flow in the experimental model of the panel plate heat exchanger is shown in Figure 2. The geometric characteristics of waved form channel are presented in Table 1.

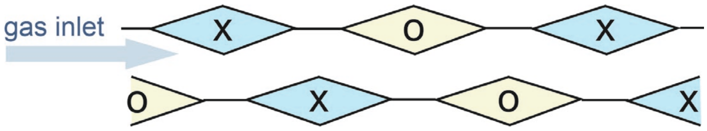


*Figure 2: The scheme of streams flow in the experimental model of panel plate heat exchanger; o – liquid flow towards, x – liquid flow outwards*

*Table 1: The geometric characteristics of waved channels of panel plate heat exchanger*

| Parameter | Value |
|---|---|
| Cross-cutting area, $m^2$ | 0.0046 |
| Hydraulic diameter, m | 0.0193 |
| Total channel length, m | 1.47 |
| Waved channel length, m | 1.248 |
| Plate width, m | 0.5 |

The cross-cutting of a curved tubular channel is rhombic, and its area equals 0.00042 $m^2$; the total length of this channel inside the panel is 10.6 m. The flow scheme for the experimental model was countercurrent.
The experimental model was assembled into the experimental unit presented in Figure 3, containing the closed water loop and opened air loop. Water flow was used as a heating medium, and the water heating was carried out in a heat exchanger up to 85 °C. Air was used as a heated medium and supplied into waved-form channels (see Figure 2) at 20 °C.

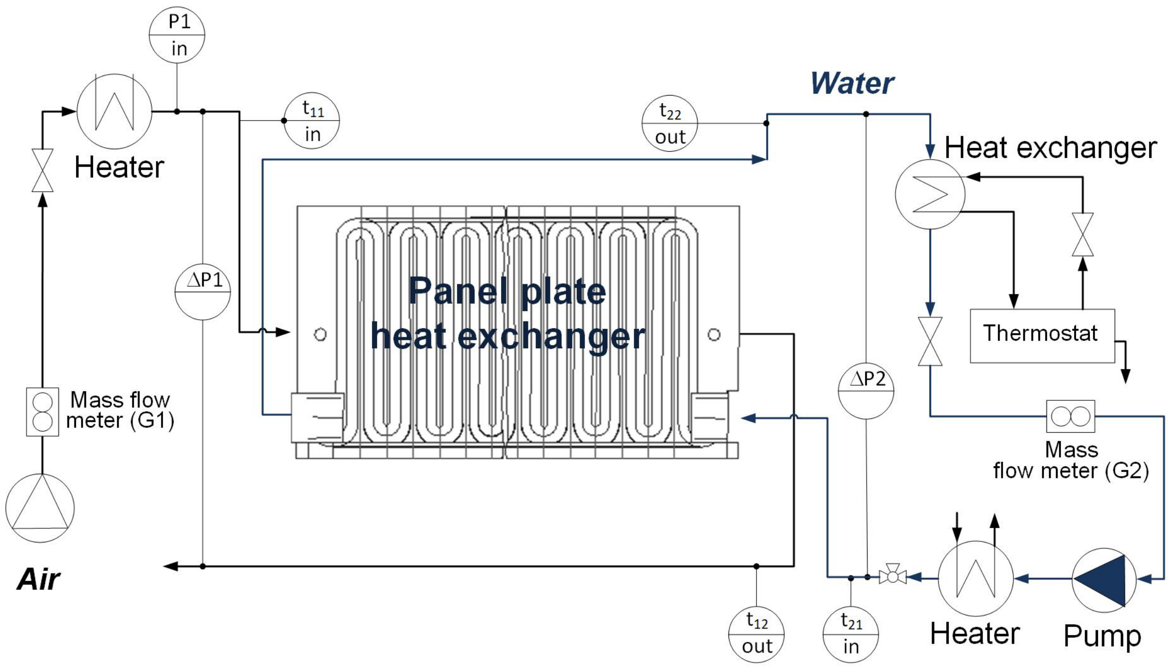


*Figure 3: The experimental set-up*

During the experiments, the inlet air pressure did not exceed 1.1 bar, and air velocity in channels was changed from 1.3 m/s to 5.3 m/s. The water flow rate was measured using the Coriolis flow and density meter (*G*2) with the reference accuracy equal to ±1.0 %. To measure pressure drop in the water loop and the inlet and outlet of air, two Rosemount pressure transmitters (Δ*P*2 and Δ*P*1) were used with the accuracy of ±0.075 % for water and ±0.10 % for air. The flow rate of the air varying was measured using the Rosemount vortex flowmeter (*G*1), the accuracy of which was ±0.10 %. 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 the waterside and ±0.50 % for the air.

## 3. Results and discussion

The experimental investigation on heat transfer and pressure drop in waved form channels of panel plate heat exchanger had been carried out. The pack of plates of the industrial-scale heat exchanger was taken as an experimental model. The pack was the welded construction that consisted of five panels, and each panel was formed by welding two plates. The plate is shown in Figure 1. The experimental investigation aimed to obtain the basic correlations for friction factor and film heat transfer coefficient. Friction factor results were obtained for the total length of the waved channel, including inlet and outlet parts ($f_t$) and for only waved part of the channel ($f_c$).

The friction factor for the total length waved channel was correlated by Eq(1):

$$f_t = 1.03 \cdot Re^{-0.21} \quad (1)$$

where Re is the Reynolds number calculated for the waved channel geometry.

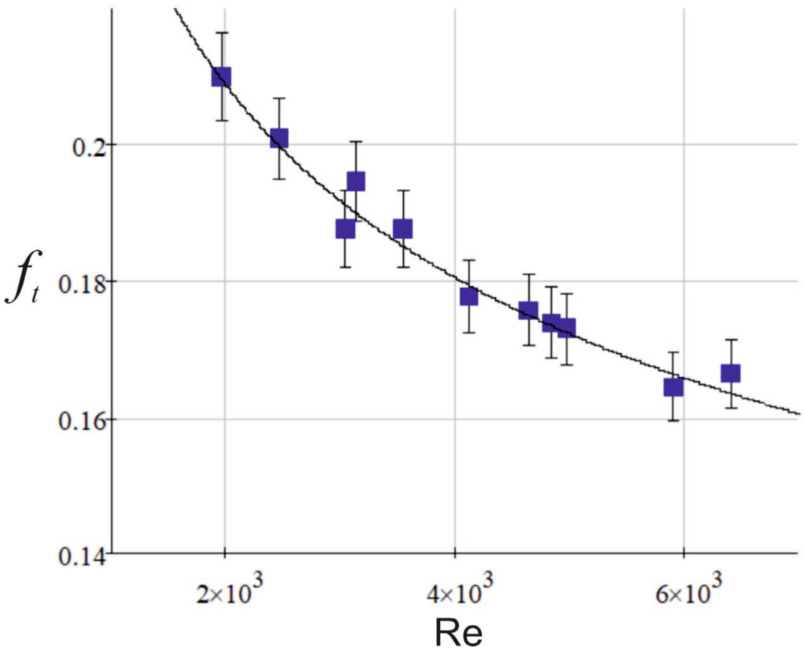


*Figure 4: Experimental data for friction factor of a total length of waved channel including inlet-outlet parts*

The friction factor for only waved part of the channel was correlated according to Eq(2):

$$f_c = 0.88 \cdot Re^{-0.18} \quad (2)$$

Graphical interpretations of the above friction factor correlations are presented in Figures 4 and 5. For comparison in, Figure 5 are presented data of correlation for friction factor in pillow-plate heat exchanger channel (Piper et al., 2019). At Re < 3,000, data differ not more than 5 %, but with the increase of Re to 7,000, the friction factor for panel heat exchanger becomes up to 30 % higher.

Results of film heat transfer coefficient were correlated in dimensionless form by Eq(3):

$$\mathrm{Nu} = 0.053 \cdot \mathrm{Re}^{0.77} \cdot \mathrm{Pr}^{0.43} \quad (3)$$

where Pr is the Prandtl number.

Graphically, the film heat transfer coefficient correlation may be presented in a form $K_0 = f(\mathrm{Re})$, where $K_0$ is dimensionless complex expressed by Eq(4):

$$K_0 = {}^{\mathrm{Nu}}\!\big/_{\mathrm{Pr}^{0.43}} \tag{4}$$

In this form, the heat transfer data for panel HE are presented in Figure 6. The comparison with correlation for pillow-plate HE calculated according to Piper et al. (2019) for Pr = 6 (curve 1 in Figure 6) reveals a small difference in heat transfer in these heat exchangers of similar construction type (no more than 5 %). Both heat exchangers are showing enhancement of heat transfer on 50 up to 60 % compare to the straight, smooth tube (curve 3 in Figure 6), depending on the Reynolds number. Accounting also for a close similarity of data for friction factor in Figure 5 for both heat exchangers it can be concluded that similar principles of heat transfer intensification in pillow-plate and panel heat exchangers with some advantages for pillow-plate HE. However, the solution of HE choice should be made by accounting for specifics of heat exchanger application.

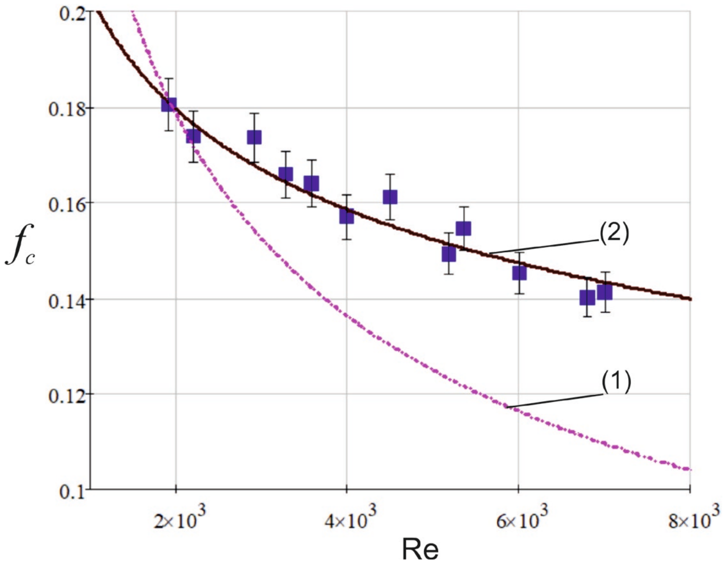


*Figure 5: Experimental data for friction factor of the only waved channel part: (2) – this study results; (1) – for a pillow-plate heat exchanger according to Piper et al. (2019)*

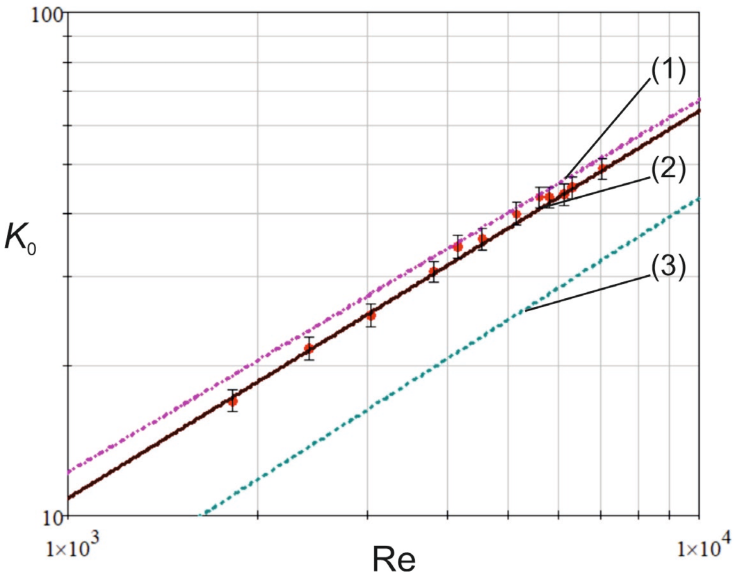


*Figure 6: Experimental data on heat transfer in the dimensionless form: (1) pillow-plate HE (Piper et al., 2019); (2) panel HE, this study; (3) straight smooth pipe*

Values calculated according to Eqs(1)-(4) differ from experimental data by less than ±5 % and are valid in the range of Re between 1,000 and 7,000, which corresponds to the developed turbulent flow regime developed in the channels of wavy geometry.
The presented results describe the heat transfer and pressure drop parameters only for investigated geometry of wavy channels with the countercurrent movement of liquid flow inside the curved zig-zag tube channel. Its numerical investigation and generalisation for a wider range of parameters is needed and is the subject of further research work.

## 4. Conclusions

The investigation of heat transfer and pressure drop in waved form channels of panel plate heat exchanger is carried out. The intensification of heat transfer from 50 to 60 % is experimentally confirmed. The comparison with data for pillow-plate heat exchanger reveals the close similarity of data for heat transfer and friction factor with some advantage for pillow-plate HE. The basic equations on friction factor and film heat transfer coefficient are obtained. These equations may be used in the development of panel plate heat exchangers design methodology and facilitate the application of these efficient heat exchangers in waste gaseous flows heat utilisation.

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