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THE ESTIMATION OF HEAT TRANSFER AREA OF PILLOW-PLATE HEAT EXCHANGERS FOR WATER HEATING

Ефективна рекуперація тепла має першорядне значення для вирішення проблеми ефективного використання енергії та подальшого скорочення споживання палива і викидів парникових газів. Для вирішення цієї проблеми можна використовувати різні стратегії, але для всіх підходів потрібно ефективне теплообмінне обладнання. Одним з інноваційних видів теплообмінного обладнання є теплообмінні апарати з пластинами подушкового типу (ТАПП). У даній роботі представлена інформація про основних комерційних виробників ТАПП, описані існуючі підходи до визначення перепаду тиску і теплопередачі. Розглянуто застосування ТАПП для нагріву води, а наведена площа теплообміну порівнюється з поверхнею пластинчастого теплообмінного апарату з гофрованої пластиною, спроектованого для тих же умов процесу.

Ключові слова: теплообмінні апарати, пластини подушкового типу, теплопередача, проектування, гідравлічний опір.

Эффективное рекуперация тепла имеет первостепенное значение для решения проблемы эффективного использования энергии и последующего сокращения потребления топлива и выбросов парниковых газов. Для решения этой проблемы можно использовать различные стратегии, но для всех подходов требуется эффективное теплообменное оборудование. Одним из инновационных видов теплообменного оборудования являются теплообменные аппараты с пластинами подушечного типа (ТАПП). В настоящей работе представлена информация об основных производителях ТАПП, описаны существующие подходы к определению перепада давления и теплопередачи. Рассмотрено применение ТАПП для нагрева воды, а приведенная площадь теплообмена сравнивается с поверхностью пластинчатого теплообменного аппарата с гофрированной пластиной, спроектированного для тех же условий процесса.

Ключевые слова: теплообменные аппараты, пластины подушечного типа, теплопередача, проектирование, гидравлическое сопротивление.

Efficient heat recuperation is of primary importance in resolving the problem of efficient energy usage and consequent reduction of fuel consumption and greenhouse gas emissions. To solve this problem, different strategies can be used, but all the approaches need efficient heat transfer equipment. One of the innovative types of heat transfer equipment is the Pillow-Plate Heat Exchangers (PPHEs). The present paper gives the information about the main manufacturers of PPHEs, describes the existing approaches for determining the pressure drop and heat transfer. The application of the PPHE for water heating is considered, and the resulted heat transfer area is compared with the surface of chevron-type plate heat exchanger designed for the same process conditions.

Keywords: heat exchangers, pillow plates, heat transfer, heat exchanger design, hydraulic resistance.

Introduction.

Efficient heat recuperation is of primary importance in resolving the problem of efficient energy usage and consequent reduction of fuel consumption and greenhouse gas emissions. To solve this problem, different strategies can be used, but all the approaches need efficient heat transfer equipment [1]. One of the innovative types of heat transfer equipment is the Pillow-Plate Heat Exchangers (PPHEs). They have space-effective, light and pressure-resistant construction. They show intensified heat transfer and low pressure loss on the product media side [2]. PPHEs are produced by spot-welding of two steel sheets, followed by hydro-forming to obtain channels for heat carrier movement. The edges are fully seam-welded. The sketches of a pillow plate and resulting channels are presented in Fig. 1.

Pillow-plate surfaces of PPHEs ensure the turbulent movement of heat carriers inside the channels formed by the plates. The particular waviness of the pillow-plate channels promotes lateral mixing and beneficial turbulence, which results in a good thermo-hydraulic performance. The manufacturing technology of PPEs is extremely flexible, and the diversity of the resulting geometries is immense. This brings advantages over standard PHEs, especially when special process conditions must be fulfilled. Further benefits of PPEs, as compared to standard PHEs, are lower weight and lower production costs. The application area of PPEs is broad and expanding.

Commercially produced PPHEs.

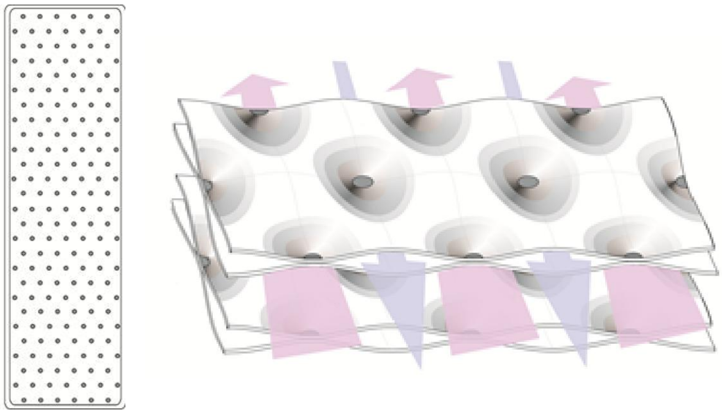
The present paper observes main commercial producers of PPHEs worldwide. Most PPHEs producers are from Germany. Also some companies are located in America. The name of the manufactured equipment differs from company to company, at the same time having the common design features and consisting of pillow plates. The used PPHEs names and producers are presented in Table 1.

The PPHEs application in industrial flowsheets includes such processes as condensation, exhaust gas cooling, oil cooling and heating/cooling shells for tanks, and nowadays it is still expanding. The industry, in which they can be applied, includes food processing industry; chemical industry; wood processing industry; paper processing industry etc. The PPHEs can be made from stainless steel, Hastelloy or titanium.

The advantages of PPHEs, listed by the manufacturers, include: low purchase price and operational costs; low pressure loss; quick installation and quick replacement of modules; many sizes, forms and materials are possible, as well as complex geometries; low weight; easy to clean; efficient with high degree of usage because of large surface in relation to volume.

The limiting process conditions depend on manufacturer. Gesmex produces PPHEs with the design limits range from vacuum to 60 bar and from -200 to 800 °C. At STRIKO Verfahrenstechnik the maximum operating pressure for the produced PPHEs is 20 bar, or can be higher as special design. German manufacturer LOB produces PPHEs at excess operating pressures of up to 50 bar and temperatures of 300 °C or more.

The heat transfer equipment produced from pillow plates can be manufactured in the form of single plates or they can be assembled in one unit. The single pillow plates are produced by all of the manufacturers, listed in Table 1. They can take different form, including rounded one, and used for warming/cooling fibrous or contaminated process fluids. The single pillow plates or their set is an economical alternative to conventional chemical devices such as the half-tube coil and double-jacket. Also some companies produce the heat exchangers assembled from pillow plates, which can be used as condensers or reactors. LOB produces the WTP-System for head condensers; XPT condensers are manufactured by Gesmex; DEG manufactures the condensers from pillow plates. The pillow plate condensers, as a rule, are designed for the direct assembly at columns, reactors, boilers, or they can be used in lying form. The so-called XPT – reactors produced by Gesmex GmbH are designed to combine the functions of heat transfer and reaction of the product in one apparatus. The distances between the transfer surfaces can be designed to optimize the filling volume needed for the reaction. The examples of different heat transfer equipment produced from pillow plates by different manufacturers are given in Fig. 2.



a) b)

Figure 1. The schematic of a pillow plate (a) and the channels inside a PPE (b)

Table 1. PPHEs manufacturer companies

Manufacturer	**Country**	**The name of equipment similar to PPHEs**
Gesmex GmbH [3]	Germany	Thermoplate heat exchangers
STRIKO Verfahrenstechnik [4]	Germany	Thermo Plate
LOB [5]	Germany	WTP-heating system
DEG Engineering GmbH in cooperation with Mueller Manufacturing B.V. [6]	Germany	Thermo-plates
ATHCO-Engineering [7]	Denmark	Pillow plates
Tranter [8]	USA	Prime Surface Heat Exchangers
WCR Incorporated [9]	USA	Immersion Plates

a) a) c)

Figure 2. Different design of pillow plate heat transfer equipment:
a) Single thermo plate produced by STRIKO [4]; b) WTP head condenser produced by LOB [5];
c) XPT – reactor produced by Gesmex [3]

The reliable design of PPHEs includes the identification of the geometrical parameters (gap width, height and length of the plates) and estimation of heat transfer and hydraulic parameters of the unit. The special attention should be paid to the location of the inlet and outlet connectors, which affect the pressure losses and operability of the heat exchanger. However, in contrast to conventional equipment, no reliable design methods for compact PPEs are available in the open literature [9].

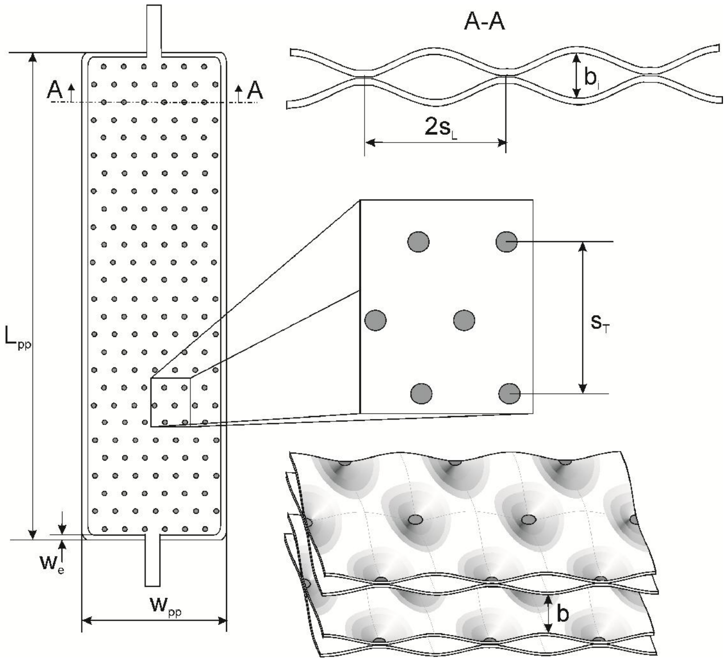


Figure 3. The schematic of pillow plate with specification of its main geometric parameters

The correlations for PPHEs design

The design of PPHEs is mostly influenced by the geometry of the heat transfer channels, which determine the heat transfer and hydraulic parameters of the unit. The PPHE, investigated in [2] with different pillow plate geometries are under consideration. The geometry of pillow plates used in PPHE is schematically shown in Fig. 3. The standard pillow plates are assembled together in one unit, what enables to vary the distance between them, and consequently adjust the hydraulic resistance and heat transfer process in the outer channels between welded pillow plates (external or E-channel). The geometry of inner-plate channel (inner or I-channel) determines the whole performance of the PPHE. For the mathematical modelling of thermal and hydraulic performance of PPHE the geometries of I-channels are presented in Table 2.

The empirical equations for calculation of friction factors in the I-channel, which has smaller cross-section area, ζ_1 is presented in paper by [2] for three geometrical types presented in Table 3. The friction factor in E-channel ζ_2 is investigated in [10] by the means of CFD methods and based on the experimental data for PPHE of 3[rd] type geometry pillow-plate panels with the distance between them equal to 12 mm. The given equation for friction factor is valid for the Reynolds numbers from 9500 till 30000.

The correlations for friction factor for I-channel and E-channel are presented in form of power equation for the Reynolds number:

$$\zeta_1 = A \cdot \mathrm{Re}^{-n} \tag{1}$$

where coefficients A and n are parameters, which depend on pillow-plate geometry, and for the observed types their values are presented in Table 3; Re is the Reynolds number, $\mathrm{Re} = w \cdot d_e \cdot \rho / \mu$, where μ is the dynamic viscosity of the fluid, Pa·s.

The equivalent diameter and channel cross-section of the I-channels can be calculated according to the simplified relations:

$$d_{e1} = 2 \cdot \left(\frac{b_i}{\sqrt{2}} \right), \tag{2}$$

where b_i is the inner expansion of the pillow plate, m.

For the bigger channel between welded pillow-plate panels (E-channel) the equivalent diameter is equal to the biggest expansion between pillow-plate panels (see Fig. 3):

$$d_{e1} = 2 \cdot \left((b_i + b) - \frac{b_i}{\sqrt{2}} \right), \tag{3}$$

Table 2. The main geometric parameters of pillow plates [2]

Parameter	PPHE geometry type		
	PPHE 1	PPHE 2	PPHE 3
$\delta_{pp}\cdot 10^{-3}$, m	0.8	1	1
$b_i\cdot 10^{-3}$, m	3.4	3	7
$2s_L\cdot 10^{-3}$, m	42	72	72
$s_T\cdot 10^{-3}$, m	72	42	42
$w_{pp}\cdot 10^{-3}$, m	300	300	300
$L_{pp}\cdot 10^{-3}$, m	1,000	1,000	1,000
$w_e\cdot 10^{-3}$, m	15	15	15
Material	EN 1.4541 (AISI 321)		

Table 3. The parameters A and n from Eq.(1) for different geometry of pillow-plate channels

Parameter	Channel and geometry types			
	I-channel, PPHE 1	I-channel, PPHE 2	I-channel, PPHE 3	E-channel, PPHE 3
A	2.128	0.962	1.351	2.187
n	0.357	0.152	0.13	0.356

Table 4. The parameters *i*, *j*, *k* for Eq.(7) reported in [2]

Parameter	PPHE geometry type		
	PPHE 1	PPHE 2	PPHE 3
i	0.065	0.057	0.067
j	0.699	0.752	0.774
k	0.341	0.348	0.338

where b is the distance between pillow panels in narrowest place, m.

The cross-section area of I-channel and E-channel is defined as:

$$f_{ch\,I} = \frac{b_i}{\sqrt{2}}\left(w_{pp} - 2w_e\right); \quad (4)$$

$$f_{ch\,E} = \left((b_i + b) - \frac{b_i}{\sqrt{2}}\right)\cdot\left(w_{pp} - 2w_e\right) \quad (5)$$

where w_{pp} is the width of the pillow plate, m; w_e is the value of edges of the pillow plate, m.

Eqs.(1)-(5) enable to predict the friction factors in both channels formed by pillow plates with observed geometry. The correlations are valid for fully developed turbulent flow with the Reynolds numbers from 9500 to 30000.

To account for pressure losses in connections, it has been introduced the coefficient of local hydraulic resistance in those zones ζ_{DZ} for the inner-plate channel, assuming that these coefficients for the inlet and outlet zones are equal $\zeta_{DZ} = 1.5$. The average velocity of stream in the I-channel w_I is assumed as characteristic velocity, when determining these coefficients. The total pressure loss in the PPHE channel can be calculated as follows:

$$\Delta p = \zeta \cdot \frac{L_F}{d_e}\cdot\frac{\rho \cdot w^2}{2} + \zeta_{DZ}\cdot\rho\cdot w^2 \quad (6)$$

where L_F is the effective length of heat transfer plate (the length of heat transfer channel) without the welded edges, m.

The estimation of heat transfer coefficients for both channels requires the reliable correlations. Paper [2] provides the equation based on modified Reynolds analogy for the heat transfer in the I-channel of the following form:

$$Nu_I = i\cdot \mathrm{Re}^j \cdot \mathrm{Pr}^k \quad (7)$$

where coefficients *i*, *j*, *k* depend on the geometry of pillow plates; Nu is the Nusselt number, $\mathrm{Nu} = h\cdot d_e/\lambda$; λ is the thermal conductivity of the stream, W/(m·K); h is the film heat transfer coefficient, W/(m^2·K); Pr is the Prandtl number; ζ is the friction factor, calculated by Eq.(1). The parameters for Eq.(7) for the considered geometry of pillow-plates are listed in Table 4.

The film heat transfer coefficients in the channel between pillow panels (E-channel) can be determined according to the following equation [11]:

$$Nu = \frac{\left(\psi\cdot\zeta_2/8\right)\cdot \mathrm{Re}\cdot \mathrm{Pr}}{1.07 + 12.7\sqrt{\psi\cdot\zeta_2/8}\left(\mathrm{Pr}^{\frac{2}{3}} - 1\right)} \quad (8)$$

where ψ is the correction coefficient, $\psi = 0.58$; ζ_2 is the friction factor, calculated by Eq.(6) for the parameters for E-channel.

The mentioned equations are valid for the Reynolds numbers from 9500 to 30000. The error for the proposed correlation for film heat transfer coefficient is reported within 5 %.

The heat transfer area of heat exchanger can be expressed as follows:

$$F = \frac{Q}{C_{FT} \cdot \Delta T_{\ln}} \cdot \left[\frac{1}{h_1} + \frac{1}{h_2} + \frac{\delta_{\mathrm{w}}}{\lambda_{\mathrm{w}}} + R_{f1} + R_{f2} \right], \quad (9)$$

where Q is the heat load, W; h_1 and h_2 are the film heat transfer coefficients for the hot and cold stream respectively, W/(m^2·K); $\Delta T_{\ln}$ is the logarithmic mean temperature difference (LMTD); C_{FT} is the correction factor for LMTD; R_{f1} and R_{f2} are the thermal resistance of fouling deposit on heat transfer surfaces for 1st (hot) and 2nd (cold) side respectively, (m^2·K)/W; δ_{w} is the wall thickness, m; λ_{w} is the thermal conductivity of the wall material, W/(m·K).

For the observed geometry of pillow plate the friction factor $\zeta_1(w_1)$ depends on the velocity w_1 and overall heat transfer coefficient $U(w_1)$. The first can be determined by Eq.(1), and the overall heat transfer coefficient is the invers value of thermal resistance, expressed by the second multiplier of the right part in Eq.(1):

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} + \frac{\delta_{\mathrm{w}}}{\lambda_{\mathrm{w}}} + R_{\mathrm{f1}} + R_{\mathrm{f2}} \quad (10)$$

where δ_{w} is the wall thickness, m; λ_{w} is the thermal conductivity of the wall, W/(m·K); R_{f1} and R_{f2} are the thermal resistance of fouling for hot and cold side respectively, (m^2·K)/W; h_1 and h_2 are the film heat transfer coefficients for the hot and cold stream respectively, W/(m^2·K).

Eqs.(1)-(10) enable to predict the friction factor and film heat transfer coefficients in PPHE channels with specified geometry of pillow plates, knowing the distance between them. Along with the geometry parameters, the physical properties of the fluids are needed for the PPHE design, as well as the velocities in channels. The physical properties can be defined in reference books according to given process conditions. In the present study we try to design the PPHE with three different geometries, presented in Table 2, and to compare the obtained heat transfer area of the PPHE with standard chevron-type PHE [12], designed for the same process conditions.

Case study - PPHE design for water heating

For PPHE design the case study of water heating, reported in [13] was taken. The authors did the design of standard chevron-type PHE for the operating conditions with fluid properties, presented in Table 5. To do the PPHEs design, three types of pillow plate geometry, presented in Table 2 were considered. The construction of PPHE enables to vary the distance between pillow plates and in the present design the distances b was taken 12 mm. As the flow rate for cold fluid is smaller than for hot one, this stream was directed to the I-channel, and the hot fluid was moved to E-channel.

Table 5. Operating conditions and fluid properties for the case study

	Fluid 1 (hot)	**Fluid 2 (cold)**
Operating conditions		
$t_{1\mathrm{in}}$, $t_{2\mathrm{in}}$, °C	70	10
$t_{1\mathrm{out}}$, $t_{2\mathrm{out}}$, °C	40	50
ΔP_1^{o}, ΔP_2^{o}, kPa	40	60
G_{m1}, G_{m2}, kg/s	40	30
Fluid physical properties		
ρ_1, ρ_2, kg/m^3	980	980
μ_1, μ_2, Pa·s	$5 \cdot 10^{-4}$	$8 \cdot 10^{-4}$
λ_1, λ_2, W/(m·K)	0.654	0.618
c_{p1}, c_{p2}, J/(kg·K)	4175	4175

Table 6. The parameters of designed PPHEs and chevron-type PHE, for water heating with allowable pressure drop 40 kPa and 60 kPa for fluid 1 and fluid 2 respectively

Type of PPHE	**F, m^2**	**L_F, m**	**n_{pl}**	**ΔP_1, Pa**	**ΔP_2, Pa**	**U, W/(m^2·K)**
PPHE1	36.85	2	68	$1.894 \cdot 10^4$	$6 \cdot 10^4$	5,512
PPHE2	35.02	1.2	110	$9.785 \cdot 10^4$	$6 \cdot 10^4$	5,800
PPHE3	43.45	2.32	67	$6.887 \cdot 10^3$	$6 \cdot 10^4$	4,676
PHE	68.8	-	-	$4 \cdot 10^4$	$2.39 \cdot 10^4$	4.946

Using Eq.(1)-(10) for each PPHE geometry type enabled to find the corresponding solution for each PPHE type, presented in Table 6.

The PPHE with type 2 pillow-plate geometry contains the minimal heat transfer surface area that equals to 35.02 m^2. For every type of PPHE the obtained surface area is less, than for chevron-type PHE, as in our approach the stream with bigger allowable pressure drop was considered. The requirement for the allowable pressure drop for the other stream is kept. The design of PPHE enables to utilise more allowable pressure drop for the second stream by adjusting the distance between plates and increasing the velocity and overall heat transfer in the unit. The PPHEs can be used for the operation conditions, when flow rates of the fluids are significantly different. With the PPHEs the possibility to use the different cross-sections for cold and hot side allows decreasing the heat transfer surface areas in heat transfer equipment.

Conclusions

The applications of novel type of plate heat exchangers can increase the heat transfer efficiency of industrial sites. Pillow-plate surfaces of PPHEs ensure the turbulent movement of heat carriers inside the channels formed by pillow plates. The particular waviness of the pillow-plate channels promotes lateral mixing and beneficial turbulence, which results in a good thermo-hydraulic performance. The possibility to use the different cross-sections for cold and hot side allows decreasing the heat transfer surface areas in heat transfer equipment. The PPHE design for water heating showed the smaller heat transfer area of PPHE comparing with chevron-type PHEs. The comparison of the PPHEs with different geometries of pillow plates revealed a significant influence of main geometrical parameters of pillow plates on heat transfer performance of the whole unit. The correct calculation of PPHE and optimisation of the geometry of pillow plates requires the reliable correlations to estimate the overall heat transfer coefficient and friction factors. The information, provided in the literature, is available only for three geometry types of welded pillow-plate panels. The further investigations of such equipment are needed due to promising results for applications, where the bigger channel for hot fluid is needed.

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