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Shell-and-Plate Heat Exchangers for Efficient Heat Recovery under the Industrial Application

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The developments in design theory of Shell-and-Plate Heat Exchangers (SPHE), aiming to enhance the heat recovery and efficiency of energy usage, are discussed. The thermal and hydraulic performance of the unit is estimated using two approaches: by proper selection of plate corrugation pattern and by the adjustment of plates with different height of corrugation in one unit. The optimization problem targeting the minimal heat transfer area under the requirements of proper operating conditions is observed. The optimizing variables include the number of plates with different corrugation geometries in one pass. To estimate the value of the objective function in a space of optimizing variables the mathematical model of SPHE is developed. The possibilities of their application as heat exchangers in preheat train of crude oil distillation unit of the oil refinery are analysed basing on obtained design parameters with the effect of flow movement arrangement in the unit and its influence on shear stress and fouling formation. The comparison with another Compabloc type welded PHE is discussed.

1. Introduction

The efficient use of energy saving, pollution reduction and the use of modern equipment with enhanced properties are intrinsically interrelated and this cluster of issues constantly grows in importance, as discussed by Klemeš et al. (2013). One way of solving the presented challenges is the application of related engineering solutions for increasing the efficiency of heat recuperation in heat exchanger networks. As heat exchange equipment plays significant role in every technological process, its design should be precisely considered. The shell-and-tube heat exchangers are traditionally used in industry. Modern developments in engineering and technologies allow replacing them by more efficient compact heat exchangers with higher heat transfer parameters and less size, if to compare with traditional ones. The compact heat exchangers, which are generally used for crude oil duties in refineries, are spiral heat exchangers and more recently all-welded plate heat exchangers of Compabloc type (Tamakloe et al., 2013). This energy efficient equipment has some limitations caused by fouling formation during the operation and also high price. The other possibility is to use shell-and-plate heat exchangers (SPHE), which can be less costly and consume less material for production, easy to operate and maintaining. Welded construction of plate pack prevents any intermixing between channels (Freire and Andrade, 2014). SPHE allow using this type of heat exchangers for high temperature and pressure. They can be used for general cooling and heating duties, as condensers, evaporators, reboilers and steam heaters and operate under the temperature beyond 400 °C and the pressure up to 100 bar. Many researchers investigated the application SPHE for different duties. Nakaoka and Uehara (1988) carried out the research of SPHE used for ocean thermal energy conversion. In this work they provide the technique for prediction of overall heat transfer coefficient and friction factor for the water side of the heat exchanger. Freire and Andrade (2014) observe the possibility of SPHE application as steam generator in naval nuclear reactors.
The application of SPHE in oil refinery for pre-heat train of crude oil is the efficient solution for energy saving and needs proper design of the units and investigation of fouling formation in this equipment for the observed duties.

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2. Mathematical modelling

2.1 The construction parameters

The present work analyses the possibility to use SPHE heat exchanger in preheat train of crude oil distillation unit. These heat exchangers have welded plates pack placed in shell, what provides high pressure ratings. It has alternating channels for hot and cold media, and can operate with counter-current or co-current flows with single or multi-pass arrangement of heat carriers. The plate pack has a welded construction and consists of the rounded corrugated plates assembled together in one unit. The general form of the circle plate is presented in Figure 1a. Generally the plates with the same corrugation are welded together to form the channels for heat carriers movement, presented in Figure 1b and channel cross sections for the sinusoidal form of corrugations in Figure 1c.
The thermal and hydraulic performance of a PHE with plates of certain size and type of corrugation can be varied in two ways: (a) by adjusting the number of passes for each of exchanging heat streams and (b) by proper selection of plate corrugation pattern in Compabloc type heat exchanger Arsenyeva et al. (2011). The feature of SPHE application in oil preheat train is the different flowrates for oil and product, what affects the flow velocities on hot and cold sides. Usually the single-pass arrangement ensures higher heat transfer efficiency than for multi-pass arrangement.

a) b) c)

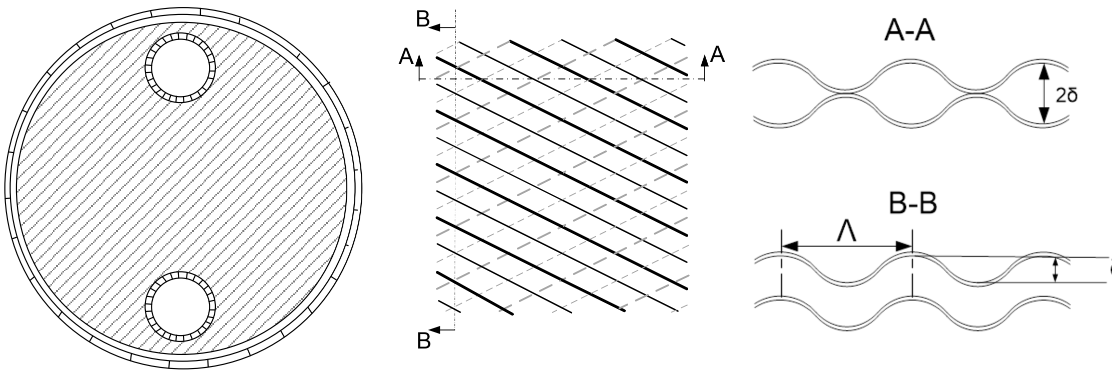

Figure 1: The schematic drawing of SPHE's circle plate (a), the intersection of the adjacent plates (b) and channel cross sections for the sinusoidal form of corrugations (c)

In some industrial applications the flow rate of one heat carrier is significantly higher, than for the other. The design of single-pass SPHE for this case have the low velocity on one side and high for other, that cause the higher level of fouling formation for channel for heat carrier with less flow rate. Basing on previous researches of plate heat exchangers presented in Tovazhnyansky et al. (2010), it was assumed, that application of the plates with unequal corrugation for the hot and cold sides in one-pass SPHE with circle plates will increase the efficiency of the unit and prevent fouling by increasing the velocities in the channels.
The calculation technique, which enables to obtain the design of SPHE with circle plates, was developed and is described in the present paper. SPHE designed as traditional units with typical plates and the combination of plates with unequal corrugation for hot and cold channel in one unit were analyzed basing on their heat and hydraulic performance, calculated according to this technique.
The proposed plate's shapes with unequal area of the channel cross-section are presented in Figure 2. This shape has different sinusoid form along the plate length to obtain the different cross-section area for the cold and hot channel of heat exchanger. The proposed corrugation has the constant pitch and the height of the corrugation (δ, m) is the same for the hot and cold channel. The parameters of the shapes for both sides are presented in Figures 2a, 2b. The angle between two sides of corrugation is $\gamma = 65^o$. It was proposed to use the constant ratio between the channel cross sections area of cold (f_{ch1}, m^2) and hot side (f_{ch2}, m^2). The one should amount 2/3 and another 4/3 of two total cross-section areas.
The mathematical model, which enables to predict heat transfer and hydraulic performance of SPHE with such plates was developed and used for obtaining the units with minimal heat transfer surface for the required conditions.

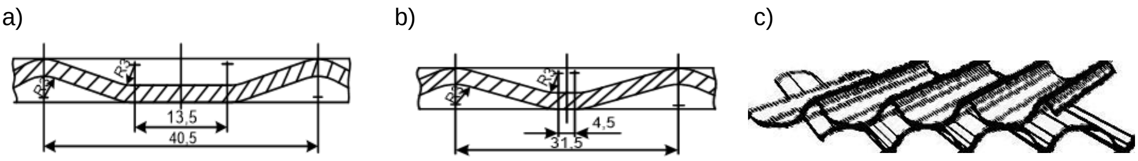

Figure 2: The shapes of the proposed unequal channel sections: (a) the channel with big area, (b) the channel with small area; (c) the intersection of the adjacent plates with different channel cross-section area

2.2 The prediction of heat transfer performance

The overall heat transfer coefficient can be estimated as:

$$U=\left(\frac{1}{h_h}+\frac{1}{h_c}+R_{foul}\right)^{-1} \quad (1)$$

here h_h is the heat transfer coefficient from hot heat carrier to the plate surface, W/(m^2·°C); h_c is the heat transfer coefficient from the plate surface to cooling media, W/(m^2·°C); R_{foul} is the thermal resistance due to fouling on both sides which can be calculated according to Arsenyeva et al. (2013), (m^2·°C)/W.

The heat transfer coefficients can be calculated according to the following relation Arsenyeva et al. (2011)

$$Nu=0.065\cdot \mathrm{Re}^{6/7}\cdot(\psi\cdot\zeta)^{3/7}\cdot \mathrm{Pr}^{0.4}\cdot\left(\mu/\mu_w\right)^{0.14} \quad (2)$$

Here μ and μ_w is the dynamic viscosity at stream and at wall temperatures; $Nu=h\cdot d_e/\lambda$ is the Nusselt number; λ is the heat conductivity of the stream, W/(m·K); d_e is the equivalent diameter of the channel, m; h is the film heat transfer coefficient, W/(m^2·K); Pr is the Prandtl number; $Re=w\cdot d_e\cdot\rho/\mu$ is the Reynolds number; w is the stream velocity in channel, m/s; ζ is the friction factor; ψ is the share of pressure loss due to friction on the wall in total loss of pressure.

The value of ψ is calculated according to:

$$A_1=380/\left[tg(\beta)\right]^{1.75}\text{; at } Re>A_1\ \ \psi=(\mathrm{Re}/A_1)^{-0.15\cdot\sin(\beta)}\text{; at } Re\le A_1\ \ \psi=1 \quad (3)$$

The hydraulic resistance coefficient for cold and hot channel can be calculated according to relation presented by Tovazhnyansky et al. (2011) as $\zeta = B\cdot Re^{-m}$, where Re is the Reynolds number, and constants B and m for the proposed channels can be estimated as B = 3.006 and m = 0.17.

The shear stress on the wall is calculated according to the following relation Arsenyeva et al. (2013):

$$\tau_w=\zeta\cdot\psi\cdot\rho\cdot W^2/8 \quad (4)$$

Eqs.(1)-(4) describe the distribution of heat and hydraulic parameters for the SPHE channels. According to it the problem of proper selection of SPHE unit for specified process condition can be solved targeting the minimization of heat transfer area. The obtained result includes also the proper geometric parameters of corrugation for the both sides.

3. The SPHE design for oil preheat train duties

The case study for SPHE design for preheat oil train was carried out. The restrictions to use the standard SPHE design are imposed for the positions with the significant difference in flow rates for cold and hot sides, which for the preheat oil train applications even four times higher. Consequently it has lower velocity and higher level of fouling formation for the channel with small flowrate. The present paper observes the heat transfer intensification in single-pass SPHE with circle plate by using different cross-section area for the hot and cold sides and calculated according to Eqs(1)-(4). It will prevent fouling by increasing the wall shear stress and higher velocities in the channel.

The problem was to select proper single-pass heat exchanger of SPHE type for the operating conditions presented in Table 1. If to compare the flow rates for the cold and hot sides, the position 5 has the bigger for the hot side, and others for the cold. The temperature of heat carriers vary from 81.4 °C to 289.9 °C.

For proper estimation of the HE design and the fouling effect, the heat carriers' properties are needed, which are listed in Table 2.

Table 1: Process conditions

HE No	Side	Heat carrier	Flowrate, t/h	Tin, °C	Tout, °C	Heat capacity of SPHE, kW
1	Cold	Crude oil 2	107.339	150	157	637.3
	Hot	P/A top T-101 1	37.0	177.4	155.6	
2	Cold	Crude oil 2	107.339	81.4	117.5	2,457
	Hot	P/A middle T-101 2	39.2	228.3	145.4	
3	Cold	Crude oil 2	107.339	161.2	178.5	1,312
	Hot	Bottom T-101	26.327	275	211	
4	Cold	Oil	82.422	265.7	269.3	260.3
	Hot	Bottom T-101	24.372	300	291	
5	Cold	Oil	82.422	224.6	250.5	1,753
	Hot	P/A middle T-101 1	102.426	289.9	270.2	
6	Cold	Oil	120.755	224.6	247.5	2,259
	Hot	P/A middle T-101 1	102.426	289.9	264.4	

Table 2: Physical properties of heat carriers

Heat carrier	T, °C	ρ, kg/m^3	Cp, kJ/(kg·K)	λ, W/(m·K)	μ, cP
Oil	250	579	3.081	0.06052	0.2898
Crude oil 2	140	683.9	2.480	0.1118	0.7728
P/A top T-101 1	170	585.3	2.9	0.0714	0.04443
P/A top T-101 4	160	662.2	2.644	0.09727	0.1107
Bottom T-101	320	550.6	3.28	0.064	0.226
P/A middle T-101 1	270	535.8	3.15	0.0565	0.0457
P/A middle T-101 2	200	622.8	2.81	0.0854	0.068

In industry for such duties the Shell-and-Tube HE are commonly used. To increase the efficiency and provide the energy saving it is better to introduce compact heat exchangers, but only few types of them can be used for such pressures and temperatures. The high fouling formation in oil pre-heaters also limits the range of the equipment. In the present study it was also analyzed the possibility to use Compabloc HE and standard SPHE. The basic construction and flow arrangement principle of these devices are presented in Figure 3.

The working principle of Compabloc heat exchanger is based on the different passes combination in packages for hot and cold heat carriers movement. It requires proper assembling of the welded packages and complicates the construction of the heat exchanger. The passes can be arranged in the way to obtain similar flow rates for cold and hot sides and to increase heat transfer efficiency. The complex construction and specific arrangement of counter-current passes for each unit requires proper solution for each application and increases the cost of such equipment. The SPHE also have welded construction of plate packages, which is assembled in the round unit with high pressure capacities. They are produced of standardized sizes for the given range of application. The proper design of SPHE type HE was estimated for the presented positions of preheat oil train, and the results are given in Table 3.

For the design of SPHE the following parameters were determined: The material of plate is AISI 316 with its thickness equal to 0.5 mm; The corrugation inclination angle was 65°; The corrugation height is equal to 0.2 mm; The maximal number of plates in one unit is 300 with maximal area of one plate 1 m^2.

The results of calculations show 2-3 times higher velocities for the cold side for position 1, 2, 3, 4, 6 and for position 5 the less cold side velocity. The resulting values of shear stresses for the sides are 10 times as much. According to Arsenyeva et al. (2012) the fouling formation dynamic in PHE channels can be predicted basing on its shear wall stress value, and consequently, the formation of fouling on the side with less shear stress will be more intensive. In presented cases, when the values differ in several times, it can be concluded, that cold channels of SPHE will be precipitated faster and it will decrease the heat transfer performance of the unit during the operation and it is better to use another equipment.

a) b)

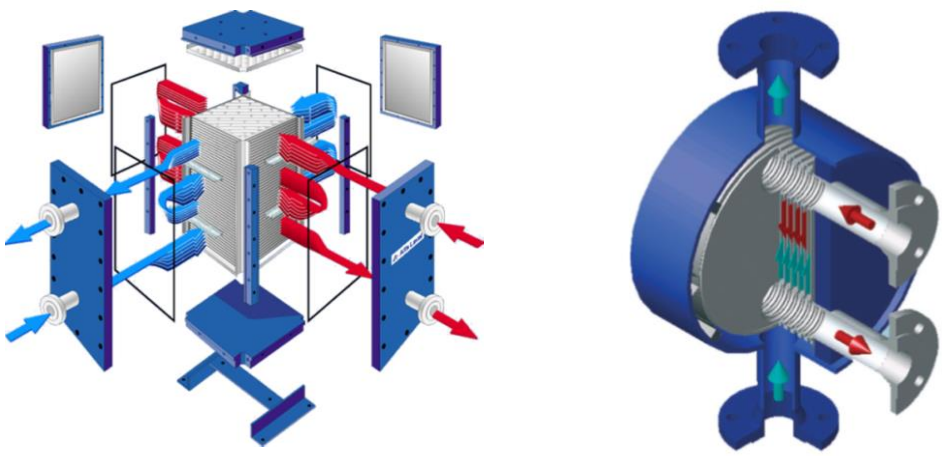

Figure 3: The construction and flow principle in heat exchangers (a) – Compabloc HE, (b) – Shell-and-Plate HE

Table 3: The standard SPHE design parameters

HE No	Heat transfer area, m^2	Velocity, m/s		Shear stress, Pa	
		Hot	Cold	Hot	Cold
1	41.37	0.270	0.808	7.01	120.98
2	20.07	0.420	0.922	14.13	150.96
3	27.60	0.229	0.866	8.47	135.91
4	8.50	0.531	1.343	34.77	187.10
5	24.82	1.210	0.871	87.01	89.83
6	31.62	0.930	1.005	55.67	115.37

Table 4: The Compabloc design parameters

HE No	Heat transfer area, m^2	Velocity, m/s		Shear stress, Pa		Passes, Cold/Hot
		Hot	Cold	Hot	Cold	
1	26.57	0.9656	1.19	44.16	97.09	4/8
2	14.78	0.7638	1.294	29.09	127.8	3/4
3	9.184	1.256	1.502	92.62	149.5	2/6
4	11.42	0.1608	1.616	1.754	139.3	3/1
5	26.57	0.7419	1.323	24.21	95.74	5/2
6	33.13	0.8905	1.236	34.08	84.78	4/3

The design of Compabloc HEs for the same positions is presented in Table 4. Owing to complex counter-current arrangement of passes it allows to prevent big differences in velocities and wall shear stresses for the sides. The showed number of passes for the designed units points out the complexity of their construction.

Based on the described mathematical model for SPHE with different cross-section area for cold and hot sides and single-pass hat carriers' movement, the design parameters of such SPHE were obtained and presented in Table 5.

Comparing with Compabloc HE the SPHE with different cross-section area design parameters show even less heat transfer area for positions 4, 5, 6. The wall shear stress values are more, than for standard SPHE design, what means less fouling formation. The price of the single-pass SPHE unit will be less than for Compabloc due to more standardized construction. The positions 3, 5 show, that application of Compabloc is more suitable.

Table 5: The design parameters of SPHE with different cross-section area for hot and cold sides

HE No	Heat transfer area, m^2	Velocity in channels, m/s		Wall shear stress, Pa	
		Hot	Cold	Hot	Cold
1	35.89	0.290	0.868	8.63	119.85
2	17.72	0.448	0.984	17.18	148.04
3	24.60	0.147	1.198	3.54	257.05
4	7.96	0.531	1.343	30.67	204.27
5	23.36	1.172	1.054	73.73	89.57
6	25.93	1.04	1.096	72.57	117.19

4. Conclusions

The applications of compact heat exchangers for crude oil preheat train duties increases heat transfer efficiency and energy saving potential of industrial sites. For the oil preheat train the heat exchangers of Compabloc type and shell-and-plate type can be designed and introduced instead of Shell-and-Tube units. The obtained design show that the application of SPHE units will decrease the operation time of the equipment due to fouling formation on the heat transfer surface, as it has single-pass arrangement of flow movement. The approach of designing SPHE with variable cross section area for cold and hot sides can significantly improve their heat and hydraulic performance for the processes with significant differences in flow rates of cold and hot media. It allows increase the wall shear stresses for the channels with lower velocity, and reduce the fouling formation on heat transfer surface. The correct calculation of SPHE with variable cross section area for cold and hot sides require to employ one dimensional mathematical model and correlations to predict the heat transfer and friction factors. Such correlations for proper SPHE design to investigate the influence of plate corrugations are obtained. The results demonstrate higher shear stress values than for standard SPHE construction and consequently, less fouling formation during the operation can be expected.

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