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The Estimation of Heat Transfer Area of Plate Heat Exchanger for Condensation of Vapour in the Presence of Noncondensing Gas as a Component of Heat Exchanger Networks

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The cooling of gaseous streams that include condensable components is frequently encountered in different industrial applications requiring the use of Heat Exchanger Networks (HENs) for optimal heat recuperation. Plate Heat Exchanger (PHE) with enhanced heat transfer can effectively work with condensation of vapours from a mixture with non-condensable gases. For their integration in HENs, a reliable method for estimation of PHE heat transfer area is required. The description of this method is presented. It is based on the mathematical model of the condensation process in PHE and proposes the approach of estimating minimal PHE heat transfer area that can be achieved by variation of plates size and corrugations geometry. The variables are corrugation inclination angle (varied at 30°, 45° and 60° levels) and corrugation height (varied from 2.5 to 5.5 mm with the step equal to 0.5 mm). The method is illustrated by a case study. Based on this method, the software for estimation of PHE heat transfer area as an element of HEN in condensation of steam from its mixture with air is developed. It can be included in software packages for HEN optimisation as a DLL module.

1. Introduction

The increase of heat recuperation is one of the main strategies to boost energy efficiency in industry, reducing industrial energy consumption and facilitating sustainable development. The cooling of gaseous streams is frequently encountered in different industrial applications requiring the use of Heat Exchanger Networks (HENs) for optimal heat recuperation. During the process of gas cooling below the saturation temperature of some components, condensation happens. The process involves both the sensible heat and latent heat of the condensing component, which complicates the overall heat transfer. The condensation of vapour from the mixture containing noncondensing gas (NCG) is inherent to many industries. A lot of such applications are investigated by different researchers, including refrigeration systems, CO_2 and H_2O separation, utilisation of waste heat from exhaust and flue gases of combustion engines, desalination plants, petrochemical industry, biomass combustion, food industry, nuclear powers and others. This emphasises the importance of this process and the need for efficient heat transfer equipment for its realisation in different conditions, which can be with high efficiency reside in compact type with intensified heat and mass transfer.

A plate heat exchanger (PHE) corresponds to these requirements and can be efficiently used in various industrial processes. Its construction and operation for different working conditions were described in the literature by Klemeš et al. (2015). When comparing them with conventional shell-and-tube heat exchangers, PHEs have a number of advantages, namely: more flexible design, the possibility of access for mechanical surface cleaning, lower fouling, and a small temperature approach of streams down to 1 °C. When applied for the same process conditions, PHEs ensure lower heat transfer area, less inventory volume, and, correspondingly, less cost. An example of its successful application in industry as part of HENs optimised with

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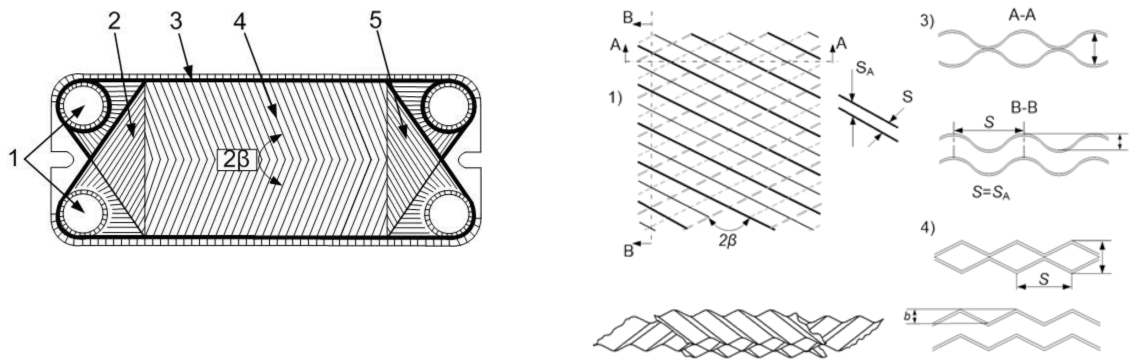
Process Integration is given in a number of papers, e.g. in the chemical industry (Tovazhnyansky et al., 2010) and utilisation of heat from exhaust gas after the drying process (Kapustenko et al., 2022).
The accurate design of PHEs for the condensation of vapour from its mixture with NCG must account for all factors affecting its performance. The analysis of the publications on condensation in the presence of NCG inside pipes and channels is presented in the review paper by Huang et al. (2015). These researches have shown that the process behaviour is affected by the nature of gas and vapour, their concentrations, channel geometry, and process development along the channel. It requires the estimation of the following parameters: mass and heat transfer in the vapour-gas mixture, thermal resistance in condensate film, heat transfer coefficient at the cooling side, pressure losses in PHE channels and in a two-phase flow of gases and liquid condensate.
For the efficient design of PHE as a condenser, the reliable correlations for heat transfer and pressure loss for single-phase fluid are very important. They are used for determining the parameters for the cooling side but also in relation to condensate film, heat and mass transfer in condensing flow, and the pressure loss in a two-phase flow of gas and condensed liquid. Since the 1980s, a lot of studies have been conducted towards the Investigation of heat transfer for single-phase flow in PHEs channels of different geometry for various process conditions, e.g. for a specific type of commercial plate as in the paper by Kumar et al. (2018). The semi-empirical correlation for friction factor in PHE channels of different geometries reliable for laminar, transient and turbulent regimes is proposed by Kapustenko et al. (2011). Qiao et al. (2013) developed the segmental model for the analysis of plate heat exchangers with multi-fluid, multi-stream and multi-pass configurations.
The correlations for condensation of pure vapour can be used for estimation of the parameters of heat transfer in condensate film. The condensation mechanism is briefly described in the book by Carey (2020). The geometry of the condensing surface affects the condensation process significantly, as shown in the research outside tubes, analysed in the review paper by Bonneau et al. (2019) and in an experimental investigation of enhanced tubes by Kukulka et al. (2019). For shear driven condensate film flow, Arsenyeva et al. (2011) have proposed an equation based on a homogeneous-dispersed model in the main flow and condensate film flow on the walls. Good results of calculations with such an equation were reported by Wang et al. (2000) for condensation in PHE. The acceptable accuracy of process simulation using this equation, accompanied by the Nusselt equation at small flow velocity, was reported by Tovazhnyansky et al. (2004) for condensation of a multicomponent mixture of vapours in PHE channels.
The Investigation of the condensation process on the smooth surface with the presence of NCG was done by Alshehri et al. (2020). The correlations for heat and mass transfer coefficients for condensation in the presence of NCG, including light gas in a nuclear reactor, are presented by Benteboula and Dabbene (2020). The heat and mass transport in the gas phase can be estimated with single-phase correlations using the heat and mass transfer analogy. Its different forms are analysed by Ambrosini et al. (2006). At a small mass flux, it was experimentally validated by Kulkarni et al. (2017). The effect of transverse mass flux is analysed based on stagnant film theory for condensation at the flat plate, with experimental data and CFD simulation by Bucci et al. (2008). In a paper by Baghel et al. (2020), the study of moist air condensation in the presence of NCG is presented, proposing a model for the dropwise condensation process on the textured surface. The visual observation of experiments on dropwise condensation of the ethanol-water mixture in commercial PHE channels is presented by Hu et al. (2017).
The pressure losses in two-phase flow have an important role in PHE design as a condenser. In a review paper by Eldeeb et al. (2016), the authors provide some empirical correlations for pressure loss in a whole PHE channel at the condensation of refrigerants valid for the range of experimental conditions. A paper by Tao et al. (2017) presents the Investigation of two-phase flow patterns in PHE channels. Based on Lockhart and Martinelli parameters for a separated flow of phases, Kim and Mudawar (2014) presented and correlated a big database of two-phase frictional pressure gradients for adiabatic and condensing flows in mini/micro-channels for a large number of fluids and broad ranges of operating conditions. The correlation for pressure drops of condensing air-steam mixture in PHE channels of different geometries is presented in a paper by Kapustenko et al. (2020).
The design approaches for heat exchangers can be based on the energy efficiency of the heat exchanger (Zhang et al.,2018) or can find the optimal heat exchangers to fully utilise the available pressure drop, settled by its industrial application, as described by Arsenyeva et al. (2019) for pillow-plate heat exchangers for one-phase flows, or by Sun et al. (2019) for two-phase flow in PHEs. In our previous research, presented in the paper by Kapustenko et al. (2020), the one-dimensional mathematical model for condensation of steam from an air-stream mixture with NCG is presented. The model showed good results when compared with experimental data for channels made from samples of PHE plates corrugated field but was not validated for industrial PHE assembled with commercial plates. Modification of this mathematical model for PHE with commercially produced plates presented by Arsenyeva et al. (2021) has shown acceptable accuracy in comparison with data for the PHE installed for utilisation of heat from the tobacco drying process in the industry.
As shown in the paper of Kapustenko et al. (2020), the plate corrugations geometry is significantly influencing the performance of PHE in the condensation process and can be optimised for the specified conditions of PHE

application. In the present paper, the method of optimising plate corrugations geometry and plate size with heat transfer area as an objective function is created based on the previously developed mathematical models.

2. The mathematical model of PHE with commercial plates

The mathematical model of condensation along the PHE channels is described by Kapustenko et al. (2020). That model is validated for the experimental samples of the PHE channel corrugated field. The model estimates the friction factor, liquid film resistance to heat transfer, local heat and mass transfer coefficients in condensing two-phase flow with accounting for the surface tension at local points along the PHE channels and was verified for different corrugation geometries. But it cannot be directly applied to the commercially produced plates, which include the distribution zones which are adding to the pressure losses in the channel. It also affects the overall heat transfer process by causing a change in partial pressure and saturation temperature distribution of the condensing component along the PHE channels.

The schematic drawing of the commercially produced PHE plate is demonstrated in Figure 1a. It consists of the main corrugated field, distribution zones and collectors. The most amount of heat is transferred on the main corrugated field, and it constitutes from 80 % to 85 % of all transferred heat. The main corrugated field can be of different geometry, which cross-section and main influencing parameters are presented in Figure 1b. It includes the corrugation inclination angle to the vertical axis *β*, which for the commercially produced plate condensers can be from about 30° to 65° (see Figure 3), corrugation height *b* and corrugation pitch *S*.



(a) (b)

Figure 1: (a) Schematic drawing of commercial PHE plate (after Arsenyeva et al., 2021): 1 – collectors at inlet and outlet of streams; 2, 5 – flow distribution zones; 3 – elastomeric gasket; 4 – the main heat transfer area; (b) Cross-sections of the PHE channels (after Arsenyeva et al., 2021)

The distribution zones have smaller lengths and transfer less heat, but as the stream is distributed here, they affect the channel hydraulic resistance. The distribution zones in PHEs can be of different shapes for better distribution of flow from the stream entrance to the channel width. For the condensation processes, the mathematical model of the hydraulic resistance of commercially produced PHEs was made. The total pressure drop in PHE is estimated as the sum of local pressure drops along with the plate: at the main corrugated field, at distribution zones at the inlet and outlet of the channel, in ports and collectors. For the condensation of two-phase flow, the liquid phase concentration and change of flow velocity from inlet to outlet of the channel should be accounted. The estimation of the pressure loss at the distribution zones is based on the local friction factor for those zones for the liquid phase during condensation and is determined by the value of pressure drop on the entrance according to Arsenyeva et al. (2022). The pressure at the entrance to the main corrugated field is obtained by subtracting the pressure drop at the entrance of the channel from the pressure at the inlet of PHE. The pressure drops at exit zones are accounted for as local hydraulic resistances. It is calculated at the velocity of condensed liquid by introducing a correction factor which is determined for the plate zone closest to the exit section of a channel. The heat and mass transfer coefficients were calculated according to the one-dimensional mathematical model of condensation with the presence of NCG proposed in the paper of Kapustenko et al. (2020), which allows estimating the heat transfer and hydraulic resistance on the main field of the PHE channels for various geometrical parameters of corrugation patterns of plates. The model reliability was checked for the PHE assembled from commercial plates installed in the industry, as described in the paper by Kapustenko et al. (2022).

3. The estimation of heat transfer area with the best PHE plate geometry

The presented by Kapustenko et al. (2020) mathematical model can be used for the calculation of PHE heat transfer surface area *F* for the specified process conditions and PHE plates geometrical parameters, which characterise the geometry of the channel and include the corrugations angle *β*, corrugation height (equal to channel spacing) *b* and double-height to pitch ratio *γ*. For the given set of required process parameters, the objective function can be regarded as an implicit function of PHE heat transfer area *F* from plate geometrical parameters:

$$F = F(\beta, \gamma, b, L_p, Fpl, Spp) \tag{1}$$

Where L_p is plate length, m; *Fpl* is the heat transfer area of one plate, m², *Spp* is a set of specified process parameters. The function in Eq(1) must satisfy the constraints on PHE operation parameters, namely temperature and pressure drop for the hot side of the heat exchanger. The temperature of outgoing vapour-NCG mixture $T_{mx.out}$ and its pressure drop ΔP_{mx} has not to be higher than specified:

$$T_{mx.out} \leq T^0_{mx.out} \tag{2}$$

$$\Delta P_{mx} \leq \Delta P^0_{mx} \tag{3}$$

Here it has been assumed that conditions on the cooling stream side are satisfied by heat balance, and pressure drop on that side is not the limiting factor. The specified process conditions include the values of flow rates of vapour G_v, NCG G_g and cooling stream G_w incoming to PHE (kg/s), as well as streams temperatures. When the outlet temperature of the cooling stream is not specified directly, it is calculated from the heat balance. In that case, both temperatures at the side of the gas-vapour mixture entrance to PHE are specified. For the given plate and its corrugations geometry, mathematically, it is an initial value problem for the system of ordinary differential equations. It is solved by the finite difference method in series for small parts of the channel. It allows calculating the length of the plate L_p that satisfies the specified NCG-vapour mixture temperature $T_{mx.out}$ smaller than specified $T^0_{mx.out}$. Then the pressure drop ΔP_{mx} on that length can be compared with a specified value of ΔP^0_{mx} . When it is bigger, the flowrate in one channel must be decreased and if smaller, the opposite should be done. It is done equationally until the observed difference becomes smaller than the specified accuracy. In our study, it was equal to 10 Pa. As a result, the length of the plate L_p (m), the total heat transfer area *F* (m²) and the number of plates *N* in one PHE are obtained. For estimation of plates number based on the resulted area, the width of the plate was assumed to equal to half of its length.

To estimate the minimal heat transfer area of PHE that can be achieved by varying plate size and its corrugations geometry, it must be estimated on all space of geometrical parameters possible variation with the satisfaction of constraints imposed by PHE construction features. The space of parameters variation and their levels are chosen according to an analysis of possible geometrical parameters for commercial plates produced by different manufacturers. It allows the selection of commercial plates which are the most suitable for a considered process by estimated values of their geometrical parameters. Differently from single-phase heat transfer, the specific condensation process requires that all channels in a single PHE must have the same geometry. It means that only plates with $\beta = 60°$ or $\beta = 30°$ can be used, or their symmetrical combination that corresponds to $\beta = 45°$. The corrugations height is considered on seven levels equal to 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 5.5 mm, which corresponds to the range of commercially produced plates, excluding 2.0 mm, which is too narrow for the considered process. The corrugation aspect ratio was assumed as 0.56, which is an average value for commercially manufactured plates and was kept constant. The number of plates in one heat exchanger *N* must be limited to the certain value *Nm* that allows for preventing maldistribution of flows between different channels. In this case, for condensation of NCG-vapour mixture, $Nm = 60$ was taken. It is also illustrated by a case study in the next section.

4. Case study

It is required to estimate the heat transfer area of PHE for the HEN position, which requires cooling down the steam-air mixture from 110 °C to 55 °C by water coming with a temperature of 50 °C and flow rate G_w = 15.88 kg/s. The flow rate of air coming in mixture with vapour is G_g = 0.2496 kg/s and of vapour G_v = 0.3489 kg/s. The allowable pressure drop in PHE for this position in HEN is ΔP^0_{mx} = 5 kPa. The results of the calculations are presented in Table 1. The heat transfer load of PHE satisfying these process conditions is 801.8 kW.

The analysis of Table 1 shows that the minimal heat transfer area of PHE for considered process conditions is 10.5 m² at a plate length of 0.19 m, the biggest corrugations angle is $\beta = 60°$ and plate spacing *b* = 2.5 mm. But to satisfy the required heat load, the plates of such length are too small, and their number would be 505, which is too much for one heat exchanger. With an increase in plate spacing *b*, the heat transfer area increases up to 9 % at *b* = 5.5 mm (*F* = 11.5 m^2), with a much bigger relative increase in plate length up to 0.51 m and a decrease in the number of plates to *N* = 77. However, this number of plates is still bigger than allowed. Increasing the plate corrugations angle to β = 45° allows the reduction of the required number of plates to *N* = 51 at *b* = 5 mm, which satisfies the limitation. But required heat transfer area correspondingly increases to *F* = 14.5 m^2, which is smaller by 21 % for β = 60°. This value can be taken as an estimation of the required heat transfer area of PHE for condensation of the air-steam mixture in this position in HEN. Another option is a further decrease of the inclination angle to β = 30° that allows to obtain a solution at *N* = 50 and *b* = 4 mm, but with heat transfer area *F* = 17.7 m^2, which is smaller than 18 % for β = 45°. The increase of β on 15 degrees between two neighbour levels is leading to the decrease in estimated heat transfer area by about 20 %. But the increase of plate spacing more than two times from 2.5 to 5.5 mm leads to a smaller relative increase of estimated heat transfer area, equal to about 10 % (see Table 1). It means that for correct estimation of PHE heat transfer area, the determination of required corrugation inclination angle β is of primary importance.

Table 1: The parameters of PHE with different plates and corrugations geometries for the case study

	$\beta = 30°$			$\beta = 45°$			$\beta = 60°$		
b, mm	*N*	L_p, m	*F*, m^2	*N*	L_p, m	*F*, m^2	*N*	L_p, m	*F*, m^2
2.5	160	0.42	16.3	273	0.29	13.2	505	0.19	10.5
3.0	102	0.54	17.1	178	0.36	13.2	324	0.24	10.8
3.5	70	0.66	17.5	122	0.44	13.6	224	0.29	10.9
4.0	50	0.78	17.7	88	0.53	14.1	164	0.34	10.9
4.5	37	0.92	18.3	66	0.61	14.2	123	0.40	11.3
5.0	29	1.05	18.5	51	0.70	14.5	96	0.45	11.3
5.5	18	1.34	18.0	40	0.79	14.6	77	0.51	11.5

The presented method of PHE heat transfer area estimation was implemented as a programming code in C# programming language that allows including it as a DLL module in HEN optimisation software.

5. Conclusions

The method for estimation of PHE heat transfer area in case of air-stream mixture condensation is described. It allows estimating parameters of PHE plates and their corrugations that allow satisfying specified process conditions. The calculations are made for the fixed value of corrugations aspect ratio equal to 0.56. The parameters of plates corrugations are varied as follows: corrugations inclination angle *β* = 30°, 45° and 60°; the corrugations height *b* changes from 2.5 to 5.5 mm with a step equal to 0.5 mm. The application of the method is illustrated with the case study, which has shown that the estimated heat transfer area is increasing about 20 % with a decrease of corrugation angle at 15°, from 60 to 45° and from 45 to 30°. The increase of corrugations height in the full examined range from 2.5 to 5.5 mm is leading to a much smaller relative increase in the heat transfer area, about 10 % at all fixed values of corrugations angle. However, it leads to a considerable increase in the plate length. According to the presented method, the software is developed for PC that can be included in HEN optimisation software as a DLL module. The method allows for an estimated PHE heat transfer area (and according to its PHE cost) in a preliminary stage of HEN and its structure development project (Klemeš et al., 2015) with accuracy not lower than ± 20 %. In definitive and detailed project stages, the calculations must be made for specific plate types by the specialised software of the PHE manufacturer. The parameters of the plate and its corrugations obtained by the proposed method can be used for a choice of plate type with parameters close to their estimated values.

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