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The Utilisation of Waste Heat from Exhaust Gases after Drying Process in Plate Heat Exchanger

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In many industrial applications, a considerable amount of heat is wasted with off and flue gases of different compositions, carrying not only sensible heat but also latent heat of condensable gas contained in the outgoing gaseous mixture. It is especially crucial for waste heat recovery from exhaust gases in such processes as the drying of different materials. Based on the mathematical model published in a previous paper for the models of PHE channels corrugated field the mathematical model of the thermal and hydraulic performance of PHE assembled from commercially produced plates is developed. It accounts for processes at the main corrugated field and also in PHE collectors and channels distribution zones. The results of mathematical modelling are compared with data obtained on a pilot unit for utilisation of waste heat from gases coming after tobacco drying. The PHE type TS-6MFG produced by AlfaLaval is tested. The content of the air incoming air-steam mixture was 10 % at a temperature of 140 °C. The comparison of modelling results and tests data have shown good accuracy of prediction. It allowed recommending obtained correlations and developed a mathematical model for the design of plate heat exchangers in applications with heat utilisation from exhaust gases after drying processes in the industry.

1. Introduction

The cooling of gaseous streams is required in many process technologies of chemical, petrochemical, food, power generation and other industries. When gases are cooled down below the saturation conditions, condensation of some component happens. It is complicating the process, and heat exchanger must transfer beside sensible heat also latent heat of condensing component. The vapour condensation from the mixture with noncondensing gas was investigated in many papers for such applications as in desalination plants, CO_2 and H_2O separation, refrigeration systems, utilisation of heat from flue gases and exhaust gases of combustion engines, food industry, petrochemical industry, biomass combustion, nuclear powers and others.
The present growing requirements for energy efficiency by heat recuperation stipulated the use of more advanced heat exchangers more compact with enhanced heat transfer.
A plate heat exchanger (PHE) corresponds to these requirements in a number of industrial applications. Its construction and operation are sufficiently well described in the literature by Klemeš et al. (2015). PHE has a number of advantages over conventional shell-and-tube heat exchangers. It is smaller size and inventory volume, less cost, lower fouling, flexible design, access for mechanical surface cleaning, and small temperature approach of streams, down to 1 °C. The heat transfer enhancement allows them to have a smaller heat transfer surface area for the same working conditions. Such features render economically favourable solutions in a number of applications in industry, as, e.g. in CO_2 post-combustion capture plants Perevertaylenko et al. (2015), for heat utilisation from exhaust gases Arsenyeva et al. (2016).

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The accurate design of PHE for the condensation of vapour from its mixture with noncondensing gas must account for all factors affecting its performance. The analysis of researches on condensation process in pipes and channels presented in the paper by Huang et al. (2015) show that process intensity is influenced by the nature of gas and vapour, their concentrations, the geometry of channels and process development along the condensation surface. It requires a calculation of heat and mass transfer and pressure loss in PHE channels including film heat transfer coefficients at the cooling side, thermal resistance in condensate film, mass and heat transfer in the vapour-gas mixture and pressure losses in a two-phase flow of gases and liquid.

Single-phase correlations are very important for the design of PHE as condensers. They are needed to determine heat transfer and pressure loss not only in cooling media but also as a reference for relations for condensate film, heat and mass transfer in condensing flow, the pressure loss in a two-phase flow of gas and condensed liquid. Experimental researches on industrially manufactured plates were abundant earlier and are still published, e.g. Kumar et al. (2018) for a specific type of plate. The correlation for friction factor for in PHE channels of different corrugations geometries was presented by Kapustenko et al. (2011). For heat transfer modified Reynolds analogy and modified Von Karman analogy were proposed by Arsenyeva et al. (2014) for different ranges of Prandtl numbers. The use of these correlations for commercial PHEs with a division of channel on the main corrugated field and zones of flow distribution proposed in the paper by Arsenyeva et al. (2013). Such an approach was confirmed later by Gusew and Stuke (2019).

For the heat transfer in condensate film, the correlations for pure vapour condensation can be used. The analysis of condensation mechanisms is given in the book by Carey (2018). It depends on the geometry of the condensing surface, as shown in the review of researches outside tubes by Bonneau et al. (2019) and for enhanced tubes by Kukulka et al. (2019). The results of the visualisation study of steam condensing in PHE channels are presented by Hu et al. (2017). The review of researches on condensation in PHE channels is made by Eldeeb et al. (2016). For shear driven condensate film flow Arsenyeva et al. (2011) have proposed equation based on a homogeneous-dispersed model in the main flow and condensate film flow on the walls. An acceptable accuracy of calculations with such equation for condensation in PHE is reported by Wang et al. (2000). The acceptable accuracy of calculations with this equation, accompanied by Nusselt equation at small flow velocity, is reported by Kapustenko et al. (2020) for a model of PHE channels. The heat and mass transport in the gas phase can be estimated with single-phase correlations using 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).

The pressure losses in two-phase flow have an important role in PHE design for condensing duty. Besides restrictions imposed on pressure drop, it leads to the change of pressure that affect the vapour equilibrium that causes a redistribution of heat and mass transfer driving forces along the channel. In a review in paper [26] are given some empirical correlations for pressure loss in a whole channel at the condensation of refrigerants in PHE applicable in the range experiments conditions. Qiao et al. (2013) developed the segmental model for phase changing refrigerants in PHE that is validated only for evaporation. Tao et al. (2018) have developed the map of different flow regimes for two-phase flow in PHE channels, which is in general agreement to that inside tubes. The accuracy of pressure loss estimation in two-phase flow depends on how the model corresponds to the real picture.

Based on Lockhart and Martinelli parameters for a separated flow of phases, Kim and Mudawar (2014) correlated a big database of two-phase pressure losses for adiabatic and condensing flows in mini/micro-channels. In the paper of Kapustenko et al. (2020) is presented approach based on one dimensional mathematical model for condensation of steam from an air-steam mixture in models of PHE channels that accounts for the change of local process parameters and transition from a regime of separated phases to dispersed-annular flow.

The state of the art analysis shows the gap between available in literature data for laboratory researches and modelling of heat and mass transfer and hydraulic resistance during condensation of gas-vapour mixtures and their validation in industrial conditions, especially for PHE channels of intricated geometry.

In the present paper, a mathematical model proposed by Kapustenko et al. (2020) for the models of PHE channels corrugated field is further developed for the modelling of a process in PHE with commercial plates. It gives the possibility to analyse process development along the length of the channel and to confirm the accuracy of correlations for local heat-and-mass transfer and pressure losses. The model validity is checked by comparison with data of PHE tests in the industrial application of utilisation the heat from exhaust gases after the process of tobacco drying.

2. The modelling of PHE with commercial plates

The main difference of commercially produced plates for PHEs from considered by Kapustenko et al. (2020) experimental models consists in construction features designed for distribution of heat exchanging streams into the system of channels between plates. The streams are coming into PHE via connections and are distributed between the channels by collectors organised in assembled PHE by an arrangement of gaskets around portholes of plates (Figure 1). In the proposed model, the maldistribution of flow between the channels is not accounted, and the flow rates in all channels assumed as equal. On free from the gasket channel entrance, the flow is distributed from portholes to the main corrugated field by distribution zones (Figure 1).

As it is discussed by Arsenyeva et al. (2013), the total pressure drop in PHE can be calculated as the sum of local pressure drops: at the main corrugated field ΔP_{mf}, at distribution zones on inlet ΔP_{DZin} and outlet ΔP_{DZout} of the channel, in ports and collectors ΔP_{pc}. In the case of condensing two-phase flow, the change of flow velocity and liquid phase concentration from inlet to outlet of the channel must be accounted for.

In the condensation of gas-vapour mixture, the pressure of the condensing stream is influencing the driving forces of heat and mass transfer processes by its effect on vapour partial pressure and its saturation temperature. The change of pressure at the inlet parts of PHE and inter-plate channels has to be accounted for in the thermal design. The pressure losses at inlet collector, the inlet port and inlet distribution zones can be accounted with the approach proposed in the paper by Arsenyeva et al. (2013) for single-phase flow in PHE with the assumption that friction pressure loss in single-phase flow is the same at ports and collectors at the inlet and at the outlet. The recovery of pressure due to the difference of velocities in the collector and in channels must also be considered. When coming to PHE gas-vapour mixture is not containing the liquid phase, the pressure loss at the entrance can be calculated as for single-phase flow. Then the change of pressure at the PHE channel entrance, before the gas-vapour mixture is entering the main corrugated field:

$$\Delta P_{mx.in} = \zeta_{DZin} \cdot \frac{\rho_{mx.in} \cdot W_{mx.in}^2}{2} + 0.65 \cdot \frac{\rho_{mx.in} \cdot W_{pc.in}^2}{2} + \frac{\rho_{mx.in}}{2} \cdot \left(W_{mx.in}^2 - W_{pc.in}^2 \right) \quad (1)$$

Here $W_{pc.in}$ is the velocity of flow in entrance ports, m/s; $W_{mx.in}$ is the velocity of the gas-vapour mixture at the entrance of the main corrugated field, m/s; $\rho_{mx.in}$ is the density of the incoming gas-vapour mixture, kg/m^3.

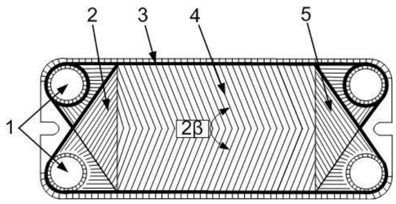

Figure 1: Schematic drawing of PHE plate area: 1 holes forming collectors at inlet and outlet of streams; 2, 5 flow distribution zones; 3 elastomeric gasket; 4 the main area heat transfer area field

The calculations of the gas-vapour condensation process at the channels main corrugated field is performed with the mathematical model described in the paper by Kapustenko et al. (2020) that is validated for the experimental models of PHE channel corrugated field. For these calculations the pressure at the entrance to the main corrugated field $P_{mx.cf1}$ is determined by subtraction of pressure drop at the channel entrance from pressure $P_{mx.in}$ at the PHE inlet (all pressures and pressure drops in this paper are measured in Pa):

$$P_{mx.cf1} = P_{mx.in} - \Delta P_{mx.in} \quad (2)$$

The total pressure drop in PHE also includes the pressure loss in the exit distribution zone, port and collector. These pressure drops are calculated as local hydraulic resistances calculated on the condensed liquid velocity with a correction factor $(dP_{TP}/dP_L)_{out}$ calculated for the closest to the exit section of a channel as follows:

$$\Delta P_{mx.out} = \left(\zeta_{DZout} \cdot \frac{\rho_{L.out} \cdot W_{L.out}^2}{2} + 0.65 \cdot \frac{\rho_{L.out} \cdot W_{Lpc.out}^2}{2} \right) \cdot \left(\frac{dP_{TP}}{dP_L} \right)_{out} \quad (3)$$

In this Equation $W_{L.out}$ is velocity calculated for liquid phase moving alone at the channel exit, m/s; $W_{Lpc.out}$ is velocity calculated for liquid phase moving alone in channel exit port, m/s; $\rho_{L.out}$ is the density of outgoing liquid phase, kg/m^3.

The values of coefficients of local hydraulic resistance at inlet and outlet distribution zones, ς_{DZin} and ς_{DZout} are taken equal to 38 as it was proposed by Arsenyeva et al. (2013) for single-phase flow in PHE with commercial plates. The total pressure drop of condensing gas-vapour mixture in PHE with accounting for velocity change at the channel exit:

$$\Delta P_{mx.PHE} = \Delta P_{mx.in} + \int_0^{L_{pl}} \left(\frac{dP_{TP}}{dx} \right) \cdot dx + \Delta P_{mx.out} + \frac{\rho_{mx.out}}{2} \cdot \left(W_{pc.out}^2 - W_{mx.out}^2 \right) \quad (4)$$

Here $W_{mx.out}$ is gas-vapour mixture velocity at the channel exit, m/s; $W_{Lpc.out}$ is gas-vapour mixture velocity in channel exit port, m/s; $\rho_{mx.out}$ is the density of the outgoing gas-vapour mixture, kg/m^3; x is a distance from gas-vapour mixture entrance to channel, m.

For the thermal design of PHE, the mathematical modelling of heat and mass transfer is performed by Equations of one-dimensional mathematical model proposed in the paper of Kapustenko et al. (2020). The heat and mass transfer correlations are taken according to geometrical parameters of corrugations on the main corrugated field with heat transfer of one plate equal to its total heat transfer area. The calculations were performed for the PHE installed in the industry as is reported in the following Case study to check the model validity.

3. Industrial implementation

The PHE for utilisation of waste heat from exhaust gases after the drying process at the operating tobacco factory was reported in the paper by Arsenyeva et al. (2016). At existing drying plant crushed raw tobacco with the content of moisture, about 22.5 % is fed to a drying tunnel, to which superheated steam at temperature 180 °C is supplied. In this tunnel, the water inside tobacco particles boils up, increasing the volume of the particle and partly evaporates to the mainstream. After being kept in the tunnel for about 6 – 7 s tobacco particles are separated by precipitation in the cyclone. Tobacco is discharged from the cyclone with rotary discharger leaving it with 14.5 % moisture content. The remaining steam-air mixture is circulating in the drying circuit, passing heat exchanger to maintain the required temperature.

Table 1: Main characteristics of tested PHE TS6M-FG

Parameter	Value
Total number of plates N	50
Heat transfer area of PHE F_{PHE}, m^2	4.8
Heat transfer area of one plate F_{pl}, m^2	0.085
Channel cross section area, m^2	0.00108
Plate length L_{pl}, m	0.27
Plate width W_{pl}, m	0.276
Area enlargement factor F_X, m/m	1.14
Corrugation pitch S, mm	14
Corrugation height b, mm	3.9
Corrugation angle to plate vertical axis β, degrees	60

Table 2: Process parameters

Process parameter	Test #1	Test #2	Test #3	Test #4
Steam-air: flow rate, kg/s	0.264	0.278	0.292	0.306
inlet temperature, °C	140	140	140	140
inlet pressure, Pa	132,000	132,000	131,000	130,000
outlet temperature (measured), °C	76.0	79.0	79.5	81.5
outlet temperature (calculated), °C	75.6	77.8	80	82.07
error in outlet temperature), °C	-0.4	-1.2	+0.5	+0.57
pressure drop (measured), Pa	10.1	10.4	12.0	14.4
pressure drop (calculated), Pa	10.22	11.19	12.31	13.50
error in pressure drop, %	+1.2	+7.6	+2.6	-6.3
Cooling media: flow rate, kg/s	7.8	7.8	7.8	7.8
inlet temperature, °C	50	50	50	50
outlet temperature (measured), °C	68	69.0	69.3	69.5
outlet temperature (calculated), °C	67.4	68.2	68.9	69.6
Total heat load: measured, W	75,220	79,400	80,650	81,490
calculated, W	72,720	76,060	78,980	81,910
Error in heat load, %	-3.3	-4.2	-2.1	+0.5

Part of the steam-air mixture containing part of injected steam and steam evaporated from tobacco are discharged into the atmosphere through the adjusting valve. The flow rate of the outgoing part of the steam-air mixture varies from 0.264 to 0.306 kg/s, and its temperature is 140 °C. It is about 15 - 19 % of the circulating stream. These exhaust gases are used to heat up of ethylene glycol solution circulating in the heating system of factory workshops and administrative building. PHE AlfaLaval production type TS6M-FG is used for this purpose. The parameters of PHE and its plates are presented in Table 1.

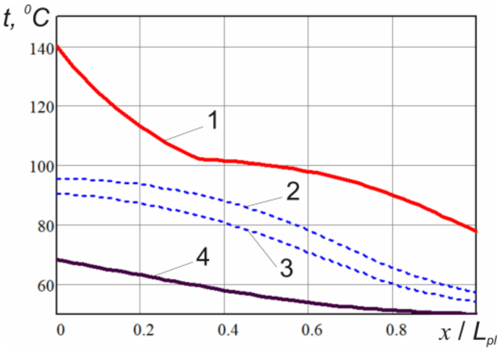

Figure 2: The distribution of temperatures t along PHE channels relative distance from the entrance of gas-vapour mixture (x/L_{pl}) in test #2: 1 – Steam-air mixture; 2 – Condensate film surface; 3 – Wall; 4 – Cooling media

The measurements of process parameters at the inlet and outlet of tested PHE were performed during the operation of the drying unit. The results of measurements for four test runs are presented in Table 2. They have also presented the results of process modelling with the presented mathematical model. The calculations were performed for the measured values of streams flow rates and their parameters at the inlet of PHE. The calculated outlet temperatures and pressure of the steam-air mixture are also presented in Table 2.
The calculated distribution of process parameters along the length of the PHE channel is presented in Figure 2 for the conditions of test #2. At the sections of the channel close to the inlet of the steam-air mixture, up to about 0.25 of relative channel length (x/L_{pl}), there is a steep decrease of gaseous mixture temperature. In this zone, the steam-air mixture is overheated over its saturation temperature. The cooling of the gaseous mixture in this zone is happening mostly by convection heat transfer from flow bulk to the channel wall with some condensation at the wall, which temperature is lower than the steam saturation temperature. After the saturation temperature reached the rate of temperature change is lowed and following the equilibrium conditions, but increasing again towards the channel exit with increasing of air content in the mixture. The calculated temperature at the channel exit is lower from its measured value on 1.2 °C; in the other three test runs (see Table 2) this difference is not higher than this value. The difference between the calculated and experimental values of the heat load is less than 4.2 %. This accuracy of thermal modelling of steam-air mixture condensation in PHE assembled with commercially manufactured plates. The accuracy of prediction the pressure drop is also not exceeding 7.6 %. It is acceptable for practical engineering applications.

4. Conclusions

The mathematical model of PHE consisting of commercially produced plates is developed for the process of utilising heat from a steam-air gaseous mixture with steam partial condensation. The model validity is confirmed by results of tests performed for commercially produced PHE installed for utilisation of heat from exhaust gases coming after the process of tobacco drying at an operating factory. The analysis of modelling results revealed a considerable change of process parameters along the length of PHE channels starting with the cooling of the superheated gaseous mixture at about third part of PHE surface followed by condensation of steam from a saturated mixture. The developed mathematical model can be used for the design of PHE in the processes of waste heat utilisation from the gaseous stream in different industrial applications and widen the use of PHEs.in such conditions Judjing by previous experience in different industries, e.g. Perevertaylenko et al. (2015), it can save about two times the space for installation, weight and inventory volume compare to traditional tubular heat exchangers, with cost reduction up to 20 %.

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References

Ambrosini W., Forgione N., Manfredini A., Oriolo, F., 2006, On various forms of the heat and mass transfer analogy: Discussion and application to condensation experiments. Nuclear Engineering and Design, 236(9), 1013-1027.

Arsenyeva O.P., Čuček L., Tovazhnyanskyy L.L., Kapustenko P.O., Savchenko Y.A., Kusakov S.K., Matsegora O.I., 2016. Utilisation of waste heat from exhaust gases of drying process, Front. Chem. Sci. Eng. 10 (1), 131–138.

Arsenyeva O., Kapustenko P., Tovazhnyanskyy L., Khavin G., 2013, The influence of plate corrugations geometry on plate heat exchanger performance in specified process conditions. Energy, 57, 201-207.

Arsenyeva O.P., Tovazhnyanskyy L.L., Kapustenko P.O., Demirskiy O.V., 2014, Generalised semi-empirical correlation for heat transfer in channels of plate heat exchanger. Applied Thermal Engineering, 70(2), 1208-1215.

Arsenyeva O., Tovazhnyansky L., Kapustenko P., Perevertaylenko O., Khavin, G., 2011. Investigation of the new corrugation pattern for low pressure plate condensers. Applied Thermal Engineering, 31(13), 2146-2152.

Bonneau C., Josset C., Melot V., Auvity, B., 2019, Comprehensive review of pure vapour condensation outside of horizontal smooth tubes. Nuclear Engineering and Design, 349, 92-108.

Bucci M., Sharabi M., Ambrosini W., Forgione N., Oriolo F., He S., 2008, Prediction of transpiration effects on heat and mass transfer by different turbulence models. Nuclear Engineering and Design, 238(4), 958-974.

Carey V.P., 2018. Liquid vapor phase change phenomena: an introduction to the thermophysics of vaporisation and condensation processes in heat transfer equipment. CRC Press, Boca Raton, FL, USA.

Eldeeb R., Aute V., Radermacher R., 2016, A survey of correlations for heat transfer and pressure drop for evaporation and condensation in plate heat exchangers. International Journal of Refrigeration, 65, 12-26.

Gusew S., Stuke R., 2019, Pressure drop in plate heat exchangers for single-phase convection in turbulent flow regime: experiment and theory. Intern. Journal of Chemical Engineering, 2019, 1 - 11.

Hu S., Ma X., Zhou W., 2017, Condensation heat transfer of ethanol-water vapor in a plate heat exchanger. Applied Thermal Engineering, 113, 1047-1055.

Huang J., Zhang J., Wang L., 2015. Review of vapor condensation heat and mass transfer in the presence of non-condensable gas. Applied Thermal Engineering, 89, 469-484.

Kapustenko P., Arsenyeva O., Dolgonosova O., 2011. The heat and momentum transfers relation in channels of plate heat exchangers, Chemical Engineering Transactions, 25, 357-362.

Kapustenko P.O., Klemeš J.J., Arsenyeva O.P., Kusakov S.K., Tovazhnyanskyy L.L., 2020, The influence of plate corrugations geometry scale factor on performance of plate heat exchanger as condenser of vapour from its mixture with noncondensing gas. Energy, 201, 117661.

Kim S.M., Mudawar I., 2014. Review of databases and predictive methods for pressure drop in adiabatic, condensing and boiling mini/micro-channel flows. Int Journal of Heat and Mass Transfer, 77, 74-97.

Klemeš J.J., Arsenyeva O., Kapustenko P., Tovazhnyanskyy L., 2015, Compact Heat Exchangers for Energy Transfer Intensification: Low Grade Heat and Fouling Mitigation, CRC Press, Boca Raton, FL, USA.

Kumar B., Soni A., Singh S. N., 2018, Effect of geometrical parameters on the performance of chevron type plate heat exchanger. Experimental Thermal and Fluid Science, 91, 126-133.

Kukulka D.J., Smith R., Li W., 2019. Experimental comparison of the evaporation and condensation heat transfer coefficients on the outside of enhanced surface Tubes with Different Outer Diameters. Chemical Engineering Transactions, 76, 31-36.

Kulkarni K. S., Madanan U., Mittal R., Goldstein R. J., 2017, Experimental validation of heat/mass transfer analogy for two-dimensional laminar and turbulent boundary layers. International Journal of Heat and Mass Transfer, 113, 84-95.

Perevertaylenko O.Y., Gariev A.O., Damartzis T., Tovazhnyanskyy L.L., Kapustenko P.O., Arsenyeva O.P., 2015. Searches of cost effective ways for amine absorption unit design in CO_2 post-combustion capture process. Energy, 90, 105-112.

Qiao H., Aute V., Lee H., Saleh K., Radermacher, R., 2013. A new model for plate heat exchangers with generalised flow configurations and phase change. Int Journal of Refrigeration, 36(2), 622-632.

Tao X., Nuijten M.P., Ferreira C.A. I., 2018, Two-phase vertical downward flow in plate heat exchangers: Flow patterns and condensation mechanisms. International Journal of Refrigeration, 85, 489-510.

Wang L., Christensen R., Sunden B., 2000, An experimental investigation of steam condensation in plate heat exchangers, International Journal of Heat Exchangers, 1(2), 125-150.