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The Optimal Design of Welded Plate Heat Exchanger with Intensified Heat Transfer for Ammonia Synthesis Column

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The modification of heat exchanger networks of industrial enterprises targeting energy saving solutions requires proper heat transfer equipment. The estimation of the optimal design parameters for heat exchangers requires reliable mathematical models for the description of the thermo-hydraulic processes inside the channels, and adequate optimisation methods. This work proposes the novel mathematical model and optimisation algorithm for the selection of welded plate heat exchanger (WPHE) operating in ammonia synthesis column. It enables finding the optimal design with the specified shape of the corrugated plates, distribution of flows and number of plates and passes. The developed algorithm is implemented in Mathcad software. The application of the proposed approach is illustrated by example in which the resulted WPHE with the cross flow in one pass and overall symmetric counterflow of streams has shown a reduction of heat transfer area 25 % compared to previously tested in industry WPHE with unsymmetric passes arrangement.

1. Introduction

The efficient energy usage in the industry is of crucial importance nowadays, especially for production processes with high energy consumption. The broad application of ammonia as a chemical used to produce fertilisers, fibres, polymers and plastics, papers, acids and explosive materials, requires its sustainable production with optimisation of the production processes. It includes the optimisation of ammonia synthesis reactors.
The widely used Haber-Bosch ammonia production process requires gaseous nitrogen from air and hydrogen, which at high temperature and pressure are moved through the catalyst. The occurred reaction is highly exothermic and needs a good cooling system.

$$N_2 + 3H_2 \leftrightarrow 2NH_3 + Q \tag{1}$$

The implementation of this process in the industry has been performed by the following three types of reactors: an internal direct cooling reactor; adiabatic quench cooling reactor and adiabatic indirect cooling reactor. The comparison of the cooling systems made by Khademi and Sabbaghi (2017) showed that the option with the internal direct cooling reactor is the most efficient one. The exergy analysis of three-staged adiabatic reactor with intermediate cooling and cooled reactor done by Penkuhn and Tsatsaronis (2017) showed that the improvement of the reactor design has low improvement potential, but significant efficiency gains can be achieved by changes in system design and implementation of heat integration. The analysis of the autothermal heat recovery reactor, which heats the working fluid and simultaneously preheats the feed gas with ammonia is discussed by Chen et al. (2018). The observed possibility of using the catalysts with columns of different diameter showed that the columns of small diameters are preferable to save the material cost, but the efficient design of the heat exchanger for preheating is required.

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The heat exchangers for severe operating conditions, notable for aggressive working fluids, high pressures and temperature, as a rule, require a high cost. The efficient design of heat exchangers for such positions can reduce the price for the unit, and decrease the energy consumption by implementing compact heat transfer equipment applying the heat transfer intensification approaches. The modern plate heat exchangers (PHEs) of welded construction can operate with the temperatures up to 900 °C and pressures equal to 200 bar (Klemeš et al., 2015). The efficient design of PHEs supposes the selection of the unit with minimal heat transfer area, which can be achieved based on the selection of appropriate channel geometries and organisation of flows movement in the heat exchanger.
The estimation of heat transfer effectiveness in the heat exchanger with the cross flow was discussed by Triboix (2009). A method for the cross-flow heat exchanger design was proposed by Starace et al. (2017). The mathematical model of WPHE for ammonia synthesis column, representing the different arrangement of the streams flows in the WPHE, including the cross flow and complex passes arrangement with overall counter-current flow was presented by Arsenyev et al. (2019). The presented model described the heat transfer processes in the WPHE with eight passes for hot synthesis gas and four passes for cold gas. It was shown the disadvantage of using unsymmetrical passes arrangement for a considered process which is leading to considerable reduction in mean temperature difference in PHE even at overall counter-current movement of streams. The used plates with non-uniform corrugation, distinguished by a different inclination angle to the flow direction, required the reliable approach for calculation of heat transfer and pressure drop in one pass of WPHE with such channels, which was reported in the paper by Tovazhnyanskyy et al. (2016).
The present paper concerns the optimal selection of flow distribution in the WPHE with the symmetric organisation of passes, at the same time providing the optimal design of the PHE for the ammonia synthesis columns of different diameters.

2. A mathematical model of flow distribution in WPHEs

The overall heat transfer performance of WPHE depends on flows arrangement between the groups of channels, which correspond to passes of heat exchanging streams. The estimation of the heat transfer performance of the PHE can be done through the determination of heat transfer effectiveness (ε_T). The total effectiveness of the heat exchanger with symmetric passes with counter current flow according to Kays and London (1984) can be calculated as follows:

$$\varepsilon_T = \left[\left(\frac{1-\varepsilon_x \cdot R}{1-\varepsilon_x}\right)^n - 1\right] \cdot \left[\left(\frac{1-\varepsilon_x \cdot R}{1-\varepsilon_x}\right)^n - R\right]^{-1} \tag{2}$$

Here $R=G_1 \cdot c_{p1}/(G_2 \cdot c_{p2})$ is the ratio of streams heat capacities for hot and cold heat carriers in WPHE; c_{p1} and c_{p2} are specific heat capacities of hot and cold stream, J/(kg·°C); G_1 and G_2 are mass flow rates of hot and cold streams, kg/s; n is the number of passes; ε_x is the effectiveness in one pass considered. The value of ε_x required to satisfy needed effectiveness of the whole WPHE derived from Eq(2) is expressed as follows:

$$\varepsilon_X = \left[\left(\frac{1-\varepsilon_T \cdot R}{1-\varepsilon_T}\right)^{\frac{1}{n}} - 1\right] \cdot \left[\left(\frac{1-\varepsilon_T \cdot R}{1-\varepsilon_T}\right)^{\frac{1}{n}} - R\right]^{-1} \tag{3}$$

The number of heat transfer units in the one pass of the WPHE with cross flow according to Tovazhnyanskyy et al. (2016) can be expressed through as by following Eq. (4):

$$NTU_x = -\frac{ln\left(1+R \cdot ln\left(1-\varepsilon_x\right)\right)}{R} = NTU_x^0 \tag{4}$$

This value is required by the thermal process conditions. From another side, the number of heat transfer units that can be obtained in one plates pack of WPHE corresponding to one pass number X is:

$$NTU = \frac{F_{aX} \cdot U}{G_2 \cdot c_{p2}} \tag{5}$$

Where F_a is the heat transfer area of the plates pack, m^2; U is the overall heat transfer coefficient, W/(m^2·K); G_2 is the mass flow rate of the cold stream, kg/s.

The number of heat transfer units in one channel for the cold stream can be determined through the velocity of the flow, the surface area of one plate and channel cross section area:

$$NTU_x = \frac{2 \cdot F_{pl} \cdot U}{c_{p2} \cdot w_2 \cdot \rho_2 \cdot f_{\mathrm{ch}}} \tag{6}$$

Where F_{pl} is the heat transfer area of one plate, m^2; w_2 is the flow velocity of the cold stream in one channel; ρ_2 is the density of the cold fluid, kg/m^3; $f_{\mathrm{ch}} = W \cdot b$ is the channel cross-section area, m^2; W is the width of the channel, m; b is the corrugation height, m.
The area of heat transfer surface of one plate (F_{pl}) is the same for both the cold and hot side, and is determined by the length and width of the plate by the following relation:

$$F_{\mathrm{pl}} = L_{Fpl} \cdot W_{Fpl} \cdot F_{\mathrm{x}} \tag{7}$$

Here L_{Fpl} is the length of the corrugated field, m; W_{Fpl} is the width of the corrugated field; F_{x} is the ratio of developed area to projected area.
When selecting the optimal design of the PHE for ammonia synthesis column, the length of the plate are limited by the internal column diameter and is equal to the plate's width.
The length of the plate, at which the condition for pressure drop for the hot stream is satisfied completely, taking into account the pressure losses in flow distribution zones of the plate (ζ_{DZ}), is determined from the following dependence:

$$\frac{L_{\mathrm{F}}}{b} = \frac{2}{\zeta_1(w_1)} \cdot \left(\frac{\Delta P_1^o \cdot 2}{\rho_1 \cdot w_1^2} - \zeta_{\mathrm{DZ1}} \right) \tag{8}$$

Here ζ_1 is a friction factor for the cold heat carrier, calculated according to Arsenyeva et al. (2013) and depending on the velocity of the observed heat carrier; ΔP_1^0 is total pressure loss in the PHE channel for cold heat carrier; ζ_{DZ} is the value of the coefficient of local pressure losses in flow distribution zones calculated for velocity at the main channel field, that is equal to 0.727 of velocity at the channel entrance/exit. The value of ζ_{DZ} is accordingly 1.89 times bigger than the value of ζ_{DZi} in a paper by Tovazhnyanskyy et al. (2016).
From Eq(6) and Eq(7), for the PHE, which exactly satisfies the process conditions for the heat load, the plate length is equal to:

$$\frac{L_{\mathrm{F}}}{b} = \frac{NTU_x \cdot c_{p2} \cdot w_2 \cdot \rho_2}{2 \cdot U \cdot F_{\mathrm{x}}} \tag{9}$$

When both conditions, for the pressure drop, Eq(8), and heat load, Eq(9), are satisfied, the system of two algebraic equations with two unknowns, L_{F} and w_2, takes place. The received equation for the velocity in the hot channel is as follows:

$$w_1 = \sqrt{\frac{\Delta P_1^0}{\rho_1} \cdot \frac{1}{\frac{\zeta_{\mathrm{DZ1}}}{2} + \zeta_1(w_1) \cdot \frac{NTU_x^0 \cdot c_{p2} \cdot w_2 \cdot \rho_2}{8 \cdot U(w_2, w_1) \cdot F_{\mathrm{x}}}}} \tag{10}$$

The velocities for the cold fluid (w_2) and hot fluid (w_1) are linked according to the following relation:

$$w_1 = w_2 \cdot \frac{G_1 \cdot \rho_2}{G_2 \cdot \rho_1} \tag{11}$$

In WPHE fully satisfying specified temperature program heat transfer effectiveness determined by Eq. (1) must be equal to its value calculated from required thermal parameters:

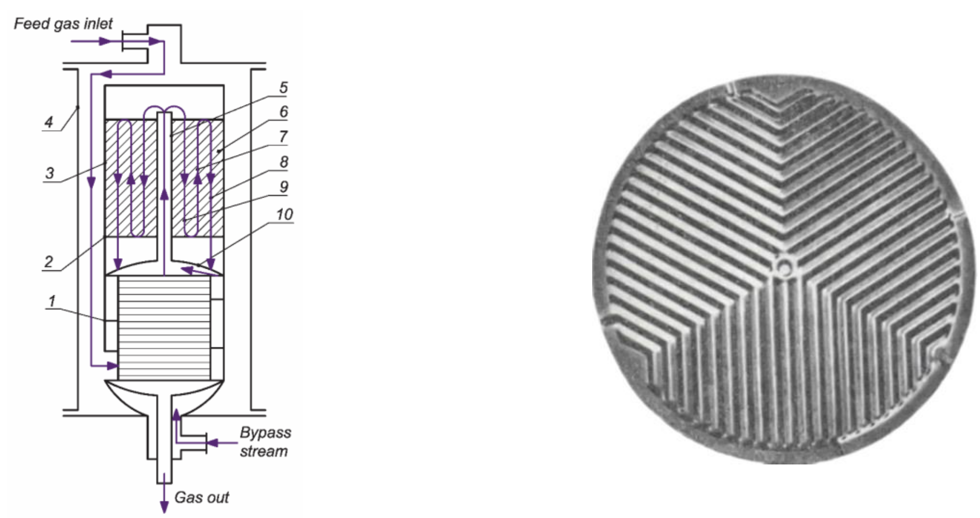
$$\varepsilon_T^0 = \frac{t_{22} - t_{21}}{t_{11} - t_{21}} \tag{12}$$

where t_{11} and t_{21} are the inlet temperatures of hot and cold streams, ºC; t_{22} is the outlet temperature of cold stream, ºC.
The Eq(10) can be solved by simple iteration method for the given value of channel spacing b and parameters of channel geometry using correlations for heat transfer coefficients and friction factors presented in the paper

by Arsenyeva et al. (2012). The solution is giving the plate length required to exactly satisfy heat transfer effectiveness in WPHE expressed by Eq(12) with a given number of passes and pressure drop of the hot stream. Using the Eqs(2) - (12), the main design parameters of the WPHE with symmetric multi-pass flow arrangements, such as optimal velocity in the channels and the length of the heat transfer plate, can be estimated at any channel spacing *b*. The possibility to use different channel geometry reveals the ways for heat transfer enhancement, determining the best geometry parameters of the corrugated plates including the height of the corrugation, length of the plate and corrugation pitch. It also enables to optimise the flow distribution in the PHE with symmetrical flow arrangement and equal passes numbers of both streams for better utilisation of the allowable pressure drop. The developed mathematical model ensures the design of the WPHE with minimal heat transfer area for the pre-set operating conditions. The developed algorithm was implemented in the Mathcad software (Mathcad, 2019). For analysing the heat transfer and hydraulic behaviour of the multi-pass WPHE, the design of the heat exchanger for ammonia synthesis column was carried out.

3. Optimal design of WPHE for ammonia synthesis column

The construction of the ammonia synthesis column with direct internal cooling is shown in Fig. 1(a). The WPHE (1) and reactor catalyser box (3) are encased in the high-pressure shell (4) with internal diameter d_{in}. The feed gas is supplied from the top of the column and going down through the annular space between the shell and encased equipment to the inlet of WPHE with temperature t_{21}. There it is heated to high-temperature t_{22} by the gas coming after the reactor. After the WPHE gas is mixing with the stream of bypass gas, which is supplied from the bottom of the column and coming to mixing area through two special pipes at the sides of WPHE. After mixing the gas is directed to the central pipe (5) from which to the upper space of the catalyser box (3) and to field tubes, internal (9) and external (7), where it is heated and after going to direct contact with catalyser (8). After catalyser zone (6) and header (2) gas with temperature t_{11} is directed to the WPHE where it is cooled down to temperature t_{12} and leaving column from the bottom.



(a) (b)

Figure 1: The schematic flow of streams in ammonia synthesis column (a) and the picture of the plate (b)

The external diameter of the considered ammonia synthesis column equals to 0.8 m, and the length of the heat transfer plate of the WPHE should be less than its internal diameter. The design was done for the limiting plate diameter 0.6 m, which correspond to effective channel length L_F = 0.54 m, which is equal to the effective channel width. The operating conditions are presented in Table 1. During the design process, the corrugation height *b* was varied from 0.3 mm to 0.5 mm, affecting the channel cross-section area, f_{ch}. The design was done for the different number of passes for heat carriers' movement. The design parameters, which were assumed as fixed are presented in Table 2. The equivalent diameter of the channel $d_e = 2 \cdot b$. The corrugation inclination angle for the hot stream was β_1 = 40°, and for the cold stream, β_2 = 50°. The coefficients of local pressure losses in the flow distributions zones were taken as ζ_{DZ1} = 20.8 for the hot side, and ζ_{DZ2} = 32.14 for the cold side. The calculations are made for bypass on the cold stream 20 % to allow the possibility of process control and an increase of recuperated heat with catalyser ageing.

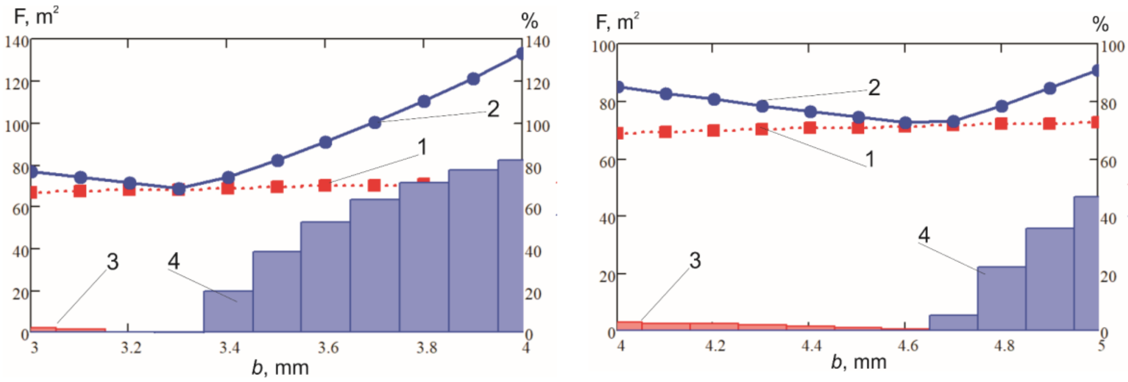
Table 1: The operating conditions for WPHE design

Parameter	Value		
Hot gas flow rate G_1, kg/s	8.375	The temperature of hot gas inlet t_{11}, ºC	505
Cold gas flow rate G_2, kg/s	6.7	The temperature of hot gas outlet t_{12}, ºC	180
Heat load Q^0, kW	9,320	The temperature of cold gas inlet t_{21}, ºC	40
Allowable pressure loss ΔP, kPa	25	The temperature of cold gas outlet t_{22}, ºC	431.5

Table 2: The fixed parameters for the optimal design of WPHE

Parameter	Value
Corrugations pitch, S, m	0.018
Average channel width, W_{ch}, m	0.54
Plate thickness, δ_w, m	0.001
Plate metal	AISI 304
The ratio of developed area to projected area, F_x	1.1

The results of calculations for different passes numbers have shown that at considered temperature program the use of one pass heat exchanger is not feasible and required a change of streams temperature cannot be achieved at any big heat transfer area. The calculations for two passes flow arrangement gives the size of the heat transfer area more than 120 m^2, and the required a length of the plate not less than 1.3 m at any channel spacing more than 2 mm. It is happening because of a too big loss in mean temperature difference. The modelling of WPHE with passes numbers n = 3 and more gives the size of heat transfer area in the range from 60 to 80 m^2, but in this case, the constraints applied by WPHE construction features and the need of its adjustment in the high-pressure shell has to be accounted for. As it is discussed in Chapter 3 of a book by Klemeš et al. (2015) the decrease of equivalent diameter for channels of compact heat exchangers is leading to smaller heat transfer area and higher compactness. However, it requires the use of channels with smaller length and the problem is to adjust this length to the required by necessity to fit WPHE into a needed diameter of the shell. In our case, the plate length must be 0.54 m.



(a) (b)

Figure 2: The design results for different channel height b and number of passes n – (a) n=3; (b) n=4; line 1 – the heat transfer area for case 1; 2 – the heat transfer area for case 2; 3 – the margin of heat load; 4 – the margin of pressure loss for the hot side

The design was made for two scenarios: with a number of passes in the heat exchanger equal to 3, and equal to 4. The calculations for passes number higher than four gave much worse results. For each scenario the design was performed for two cases: case 1 – the length of the plate is selected corresponding to the optimal velocity in the channel calculated by Eq. (10); case 2 – the velocity in the channel was estimated for the fixed length of the plate, L_f=0.54 m. In the second case the adjustment of the plate length to the specified value required to increase heat transfer area to satisfy the required pressure drop (with some increase of heat load Q with some margin over required value) or to satisfy the heat load (with a decrease in pressure drop below the allowable limit). The results of the calculations are presented in Figure 2. The margins for heat load and pressure drop were received by comparison of the values, calculated for the obtained PHE with the fixed length of the plate and the heat load and pressure drop specified by process conditions, Q^0 and $\Delta P°$ correspondingly. The scenario, made for three passes in PHE showed lower heat transfer area, compared with four pass flow arrangement. The calculation results for both cases showed that for the fixed length of the plate, the explicit minimum for heat transfer area of the heat exchanger exists, what occurs for the specific height of the corrugation. For the scenario 1 with n = 3 the minimal heat transfer area equals to 68.3 m^2 at b = 3.3 mm; for n = 4 it corresponds to 72.9 m^2 at b = 4.7 mm. The use of existing plate with corrugation height b = 4 mm requires at passes number n = 4 heat transfer area of WPHE equal to F = 85.12 m^2 that is 25 % more than in the best case at n = 3 and b = 3.3 mm. In this WPHE, an allowable pressure drop of 25 kPa is completely satisfied, and heat load has a margin of 3.1 %. However for passes number n = 3 the required heat transfer area of WPHE with the existing plate is much bigger and equal F = 132.94 m^2 with exact satisfaction of heat load and pressure drop 4.43 kPa, that is 82 % smaller than allowed by process conditions. Finally is recommended the heat exchanger with heat transfer area 85.12 m^2 and n = 4. This area is still 25.4 % smaller than of WPHE described in the paper of Arsenyev et al. (2019).

4. Conclusions

The mathematical model of the heat transfer process in the channels of WPHE with equal numbers of passes for both streams is created. It enables to estimate the optimal design parameters for a heat exchanger for the pre-set operating conditions, focusing on minimal heat transfer area as an optimisation criterion. The optimal design of WPHE was performed for recuperating heat exchanger operating in ammonia synthesis column. The cheapest design with the specified shape of the corrugated plates has a heat transfer surface area equal to 68.78 m^2 at plate spacing 3.3 mm, with three passes for cold and hot fluids and total counter-current flow movement. However, the smallest heat exchanger assembled from existing plates with fixed corrugation height 4 mm should have four passes and heat transfer area 85.12 m^2, that is 25 % bigger, but at a margin of 3.1 % for the heat load. The mathematical model can be used for the optimal design of WPHE plate geometry for different diameters of ammonia synthesis columns.

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