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Retrofit Synthesis of Industrial Heat Exchanger Networks with Different Types of Heat Exchangers

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Heat Exchanger Network (HEN) synthesis is a powerful tool for the development of more efficient processes with high utilization of mass and energy resources. The implementation of compact heat exchangers with enhanced heat transfer into the industrial flowsheets can provide more efficient and economically feasible solutions. Plate Heat Exchanger (PHE) is one of established types of enhanced HEs. To estimate possible benefits of that kind of heat transfer enhancement, a mathematical model of PHE, which accounts for different plate types and corresponding corrugations geometry, is used. The integration of this model with the P-graph-based HEN synthesis approach allowed to create the method, which considers different types of heat exchangers. This approach enables to integrate not only conventional shell-and-tube heat exchangers, but also PHEs, which overall heat transfer coefficient is in average 2-3 times higher, during the optimization process of a new or existing HEN. The capabilities of the proposed method are presented via a case study for oil preheat train, where an existing network is retrofitted; first with shell-and-tube heat exchangers only, then with the consideration of both shell-and-tube and plate heat exchangers.

1. Introduction

Increasing heat recovery in industry and household is the key point for reduced energy consumption. It can largely be achieved by improved efficiency of both process plants and equipment units. The optimal determination of the network structure with the processing equipment is the task of process network synthesis, which includes the integration of the process design with optimal heat integration (Jiménez-González, 2016). Since the selection of a process network during synthesis has major influence on the cost, the reliability, and the level of heat integration, these three items must be considered simultaneously in process synthesis, implementing more efficient heat transfer systems with enhanced design. To achieve it, a general approach and modelling tool that simultaneously covers the cost, reliability, and level of heat integration targets is highly demanded for optimal process network design.

Huge number of papers have been published on HEN synthesis. Heat integration in process synthesis is an extremely complex task in process system engineering and is of high importance for sustainable operation of industrial plants. The existing process network synthesis (PNS) approaches for HEN synthesis are generally based on Pinch Technology, the current state of which is given by Klemeš et al. (2018), including the development of graphical approaches as discussed by Lai et al. (2019), or superstructure based mathematical optimization, like a heat exchangers-based superstructure for HEN synthesis proposed by Nair and Karimi (2019). One of the effective tools for the integration of PNS and HENS based on superstructure approach is P-graph framework (Friedler et al., 1992). It is applicable for synthesizing highly interconnected networks, and is capable of generating the *n*-best or all process networks in addition to the optimal one. The integration of HEN design with P-graphs, which makes it possible to generate the list of all feasible HENs ranked by the Total Annualized Costs (TAC), was proposed by Orosz and Friedler (2020).

In the HEN synthesis approach the traditional costing methods rely on simple parametric functions. Such relations are based on the sole overall heat transfer surface, and depend on the type of the heat exchanger assuming the conventional equipment configurations only. They obey a single cost law that in practice meant

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that their materials of construction, pressure rating and design type must be assumed uniform. The approach, which allows capital cost targets to take into account the differences in exchanger specification, was firstly proposed by Hall et al. (1990). They have demonstrated that variations in heat exchanger specification can considerably influence the capital/energy trade-off. It can change the resulting design structure of the global cost-optimal HEN. The optimal selection of the heat exchanger construction at the HEN design stage can significantly decrease the total cost of HEN. The recent approaches for HEN retrofit are described by Wang et al. (2021). The conventional shell-and-tube heat exchangers are commonly used in industry and are generally considered during the synthesis. Many approaches for their optimal design are proposed, among which the method based on metaheuristic optimization from the economic point of view (Vasconcelos Segundo et al., 2019). The HEN synthesis with extension for the Grid Diagram with different heat exchanger types was proposed by Wang et al. (2020). In many applications shell-and-tube heat exchangers can be, and should be replaced by more compact units, like plate heat exchangers that have higher heat transfer coefficients. In case of compact heat exchangers with enhanced heat transfer the correct initialization of the design is a complicated task, as the final structure of the network and parameters of constituent heat exchangers heavily depend on the optimality of heat exchanger design and its correspondence to specific process conditions at which heat exchanger is used. It requires the use of adequate enough mathematical models of compact heat exchangers, which as a rule are nonlinear.

The P-graph framework has no limitations on inclusion of different types of heat exchangers whether they are compact, enhanced or traditional shell-and-tubes. The types of the individual heat exchangers do not affect the feasibility of a HEN, as long as the exchange of heat is within the heat exchanger's operability conditions. The problem consists in availability of accurate enough and at the same time quick for computer calculations heat exchanger models and cost functions. A well-established methodology is needed for HEN synthesis with implementation of different types of heat exchangers at the stage of process design and during the retrofit.

The current work proposes the extension of the P-graph-based HEN synthesis method to consider different types of heat exchangers, including plate heat exchangers, besides the usual shell-and-tube ones. The capabilities of the proposed method are presented via a case study for oil preheat train, where an existing network is retrofitted; first by only investing in the minimum required number of heat exchangers, then by generating the best network replacing all heat exchangers.

2. The PHE optimal design for P-graph-based HEN synthesis

2.1 Enhanced heat transfer area targets for plate heat exchangers

Plate heat exchanger is one of the representatives of compact heat exchangers with enhanced heat transfer, where the heat transfer process takes place in the channels with complex geometries, formed by the adjustment of the corrugated plates. PHEs of different construction (plate-and-frame, brazed, welded) are one of the most efficient types of compact heat exchangers used in industry. The generalized correlations for PHEs heat transfer and hydraulic performance for a wide range of geometrical parameters of plates and corrugations on their surface is presented by Klemeš et al. (2015). It enables to create detailed models of PHE and calculate the optimal geometrical parameters of plates and PHE configuration for the given process conditions. The inclusion of such model into P-graph-based HEN synthesis method gives possibility to obtain *n*-best or all process networks in addition to the optimal topology and the target for heat transfer surface for total HEN and at different matches that can be achieved with the optimized geometrical parameters of PHEs. For practical implementation the proposed method estimates the design of the plate with the optimal geometrical parameters for the unit used for specified process conditions and defines the heat transfer area and the corresponding cost of PHE depending on its construction type.

Initial data are specified by the known industrial process conditions: t_{1in}, t_{1out}, the inlet and outlet temperatures of the hot fluid; t_{2in}, t_{2out}, the inlet and outlet temperatures of the cold fluid; G_1, G_2, the mass flow rates of the hot and cold fluids; ΔP_1^o, ΔP_2^o, the allowable pressure losses for the hot and cold streams. When designing PHE the task is to obtain the heat exchanger unit with minimal heat transfer area satisfying required process conditions. The proposed technique assumes that for given geometry of corrugations on the main heat transfer field of the plate, the plate length can vary with the aim of satisfying process conditions. The approach with optimal selection of length and velocity of the heat exchanger for full utilization of allowable pressure drop, described in paper by Arsenyeva et al. (2013), was used for the development of the approach for PHE selection in the P-graph framework.

The heat load of the heat exchanger must not be less than the specified value, defined by the heat balance:

$$Q=(t_{1in}-t_{1out})\cdot c_{p1}\cdot G_1=(t_{2in}-t_{2out})\cdot c_{p2}\cdot G_2 \quad (1)$$

where c_{p1} and c_{p2} are specific heat capacities for inlet and outlet streams.

The required heat transfer surface area F of the heat exchanger is the function of commercially produced sizes of PHEs of different construction types with the heat transfer area of one plate f_{pl}, and the length of heat transfer channel L_F, the number of plates N. It is possible to formulate the optimization problem for PHEs design as a task to find the minimum of the following objective function:

$$F = f(PHE \text{ type}, f_{pl}, L_F, N) \quad (2)$$

This objective function should fulfil some restrictions imposed by the operating conditions, which are as follows:
a) The heat load Q should not be lower than the required specified value Q^0 (Eq(1)):

$$Q \geq Q^0 \quad (3)$$

b) The pressure drops for both streams should not be higher than allowable value for the hot and cold streams:

$$\Delta P_1 \leq \Delta P_1^0; \quad \Delta P_2 \leq \Delta P_2^0 \quad (4)$$

c) To avoid hydraulic stresses in ports and channels, the velocity limitation should be imposed. According to the manufactures' recommendation for chevron-type PHEs the velocity in connections should be less than 7 m/s.
d) The flow velocity in channel is directly related to the cross-sectional area on the same side of the heat exchanger and depends on the mass flowrate and density of the fluid and channel cross section area f_{ch}:

$$w = G/\rho \cdot f_{ch} \quad (5)$$

e) The number of plates is restricted and should be less than 180.

The optimization problem for optimal PHE design includes finding the minimum of function (1) taking into account the limitations (a)-(e), listed above. For thermal and hydraulic design of the heat exchanger it is necessary to have correlations for friction factor and heat transfer coefficients on the both sides of heat exchanging streams. For PHEs such correlations are determined by the geometry of heat transfer plate corrugations. For prediction of pressure drop in PHE, the relation, which accounts for change of pressure in connections, distribution zones and on main heat transfer area, is applied (Kapustenko et al., 2019). For calculation of the film heat transfer coefficients in channels of PHEs and friction factor, the empirical equation for friction factor calculation in criss-cross flow channels formed by two corrugated plates (Klemeš et al., 2015) was used.

According to Eq(4), the pressure losses in heat exchanger must be not bigger than allowable for each stream. It permits to exactly satisfy pressure drop condition only for one stream, for another stream pressure drop will be less than allowable. Under the calculation the hot stream is considered.

Finally, the plate with the fixed corrugation parameters is achieved for the specified conditions, due to full utilization of pressure drop, with the maximum overall heat transfer coefficients and minimal heat transfer area. It enables to determine the influence of plate corrugation geometrical parameters on ability of PHE to satisfy specific process conditions with minimal required heat transfer area.

2.2 Estimation of optimal cost of heat exchanger

Both retrofit and grass root design projects of heat exchanger network require a reliable enough cost estimate in different stages of the project to be able to make the right decision on structure and heat transfer area of the HEN. The literature data for the cost of compact heat exchangers are rather limited, especially when this data is required for multiple calculations in the process of designing heat exchanger networks. Some equations for estimating the cost of plate heat exchangers are published in the book Klemeš et al. (2015). The summarised parameters of heat exchangers application and the cost function equation based on heat transfer area, are listed in Table 1.

For estimation of the purchasing cost of gasketed PHE with stainless steel plates in the range of surfaces from 4.65 m^2 to 836 m^2, the equation proposed by Vatavuk (1995) was used (Table 1, row 2). This Equation was obtained for prices at different time and different money value. To calculate the prices in 2020, the cost of PHEs produces by Alfa Laval was analysed, resulting in the multiplier equal to 1.588 for the Equation.

The introduction of Brazed PHEs allowed significant price reduction for the range of heat transfer surface areas up to 80 m^2, for which BPHE are produced. These heat exchangers are made by brazing in standardized sizes with the step of heat transfer surface area about 8 to 10 plates for one plate dimension. The prices for small BPHEs with the surface from 0.13 m^2 to 5.8 m^2, can be calculated within error ± 20 % (Table 1, row 3). For the larger BPHEs, when heat transfer surface varies from 2 m^2 to 86 m^2, the provided equation (Table 1, row 4) has maximal error ± 17 %.

The welded Compabloc PHE can have bigger heat transfer area, up to 320 m^2. It is more expensive compared to other PHE types but has higher working parameters. The price of this heat exchanger can be estimated in

EURO by correlating the limited number of quotations with maximal error ± 18% with the equation provided in Table 1, row 5.

Table 1: Cost functions for heat exchangers of different construction types based on (Klemeš et al., 2015)

#	HE construction type	Cost, EURO
1	Shell-and-tube HEs	$C_{STHE} = 145.63 \times 1.15 \times F^{0.6}$
2	Gasketed PHEs	$C_{PHE} = 231 \times F^{0.639}$
3	Brazed PHEs, 0.13 m^2 < F < 5.8 m^2	$C_{BPHE1} = 540 \times F^{0.8}$
4	Brazed PHEs, 2 m^2 < F < 86 m^2	$C_{BPHE2} = 805 \times F^{0.74}$
5	Compabloc PHEs	$C_{CBL} = 4{,}280 + 4{,}690 \times F^{0.7}$

The comparison of shell-and-tube and gasket-plate heat exchangers from economic point of view, published by Hajabdollahi et al. (2016) revealed 13% reduction in the total cost in the case of gasket PHEs. The comparison of Compabloc PHE price with the price of all stainless-steel shell-and-tube heat exchanger of the same heat transfer area showed the same level. Counting that this enhanced PHE requires much less heat transfer area than shell-and-tube for the same duty, Compabloc can have smaller cost even compared to shell-and-tube heat exchanger with carbon steel shell and stainless-steel tubes.

2.3 Integration of optimal PHE design with P-graph HEN synthesis

In the original approach for HEN design with P-graphs proposed by Orosz and Friedler (2020), only shell-and-tube heat exchangers with overall heat transfer coefficient equal to 1.7 kW/(m^2 °C) for all streams. The method was modified to integrate the optimal PHE design in HEN synthesis. The modifications were made during the global mathematical modelling and defining the feasible networks, namely at the stage of "generation of the potential heat exchanger networks" and at "determination of total annualized cost (TAC)". One of the restrictions for HEN synthesis with P-graphs is that temperature difference on the hot or cold end of a heat exchanger cannot be smaller than the minimum allowed temperature difference (ΔT_{min}). The feasible ΔT_{min} for PHEs can be settled as small as 1 °C, what makes the benefit of PHE application, comparing with shell-and-tube units.
During the synthesis process the area for each heat exchanger was calculated using the approach, proposed by Linnhoff & Ahmad (1990) for the vertical heat transfer and implemented for all HEN positions as follows:

$$F_{HEN} = \sum_{k}^{HEN\ positions} \frac{1}{\Delta T_{LMTD}} \left[\sum_{i}^{Hot\ streams} \frac{q_{ik}}{h_i} + \sum_{j}^{Cold\ streams} \frac{q_{jk}}{h_j} \right] \tag{6}$$

where F_{HEN} is the heat exchange area for vertical heat transfer required for the overall process, k is the total number of heat transfer units in HEN, ΔT_{LMTD} is the logarithmic mean temperature difference for the position k, q_{ik} is the stream duty on hot stream i for position k, q_{jk} is the stream duty on cold stream j for position k and h_i, h_j the film heat transfer coefficients for hot stream i and cold stream j.
To estimate the optimal cost of the heat exchanger and to reduce the computational effort, the costs of heat exchangers, presented in Table 1, were linearized to determine the optimal heat exchanger of possible construction type for HEN on the current position.
After the optimal solution for heat exchanger network design is obtained, at the stage of final equipment selection, the design of PHEs should be made by manufacturer of that equipment according to specified in HEN design process requirements. The preliminary results obtained during the HEN design can be used as a reference to what can be achieved with this kind of heat transfer equipment.
The developed approach can be used for multiple calculations when optimizing heat exchanger network (HEN). In that case the procedure of optimal HEN development is stepwise, creating the superstructure with all possible variants in the beginning, after that the matches and streams, where conditions are suitable for the use of PHEs, are identified. For these positions the obtained values of heat transfer coefficients and cost functions of PHEs are taken. With these values, the possible optimal solutions are found using P-graph framework.

3. Case study: retrofit of crude oil preheat train

The required process conditions in heat exchangers are taken on example of oil preheat train at a refinery currently operating with shell-and-tube HEs. As some of the temperature of the original data changed due to a change in the process, the retrofit of HEN was made. The part of existing flowsheet with streams splitting, including totally 10 positions are taken for this, case study. The required flow rates and temperature programs for these HEs are presented by Grid Diagram in Figure 1. The streams data are listed in Table 2. The design is performed for pressure drop equal to 1 bar at each side of HE. In a case study the calculations for light crude oil were made. The properties of this crude oil, required for design, are obtained by the relations (7) for its density, dynamic viscosity, heat conductivity and specific heat capacity calculated for average temperature (T) of the stream in Kelvin:

$$\rho_2 = 783\cdot\left[1-0.0011\cdot(T-293.15)\right]; \quad \mu_2 = \rho_2\cdot 10^{-6}\cdot\left\{\exp\left[\exp(19.46-3.3\cdot\ln T)\right]-0.8\right\}$$
$$\lambda_2 = 0.168-0.000466\cdot(T-293.15); \quad c_{p2} = 1825+5.46\cdot(T-293.15) \tag{7}$$

The properties of the oil distillation products were received by approximation according to refinery data at temperatures corresponding to HE positions.

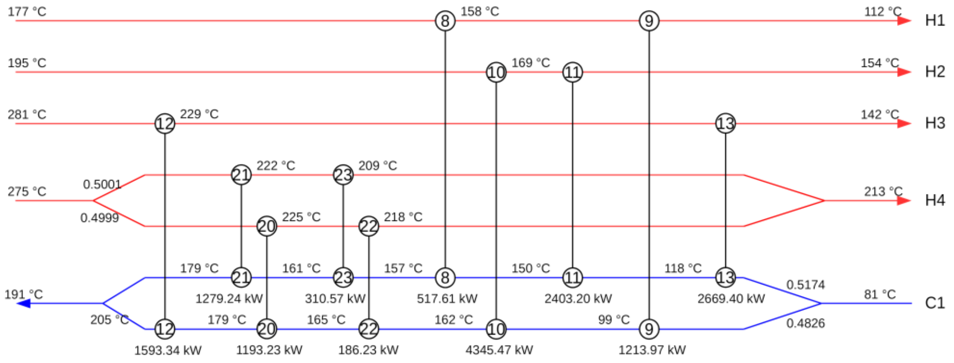

Figure 1: HEN of 10 heat exchangers for crude oil preheat train

Table 2: Parameters of the cold and hot streams

Stream	Inlet temperature, °C	Outlet temperature, °C	Flow rate, t/h	Heat capacity, KJ/(kg·°C)
H1	177.4	112.10	37	2.58
H2	195.3	153.94	211.319	2.78
H3	281.4	142.09	39.2	2.81
H4	275	213.1	26.321	3.28
C1	81.4	191.34	100.126	2.48

For this case study, the inlet temperature of H3 changed to 260 °C, the inlet temperature of H4 changed to 290 °C, and the outlet temperature of C1 changed slightly to 191.79 °C. Two cases were examined for retrofit. The first case aims to achieve minimum capital cost, that would be achieved by only performing the absolutely necessary replacements. In the original network, heat exchangers 12, 20, and 21 are affected by the change of temperatures. While heat exchangers 20 and 21 need to be replaced by a larger heat exchanger, the heat transfer area of heat exchanger 12 can be smaller. As a result, the minimal capital cost is achieved by moving the current heat exchanger at position 12 to position 21, and investing in two new heat exchangers for positions 12 and 20 with 938.55 kW and 1,553.00 kW of heat load. The common size of two new Compabloc heat exchangers is equal to 22.84 m^2, and the total investment cost is 63,323.08 EUR.

The second case examines the possibility of replacing the whole network with more efficient plate heat exchangers. The minimal cost solution for this is shown in Figure 2 and needs only 4 heat exchangers in total. The investment cost of the new network is 391,185.60 EUR.

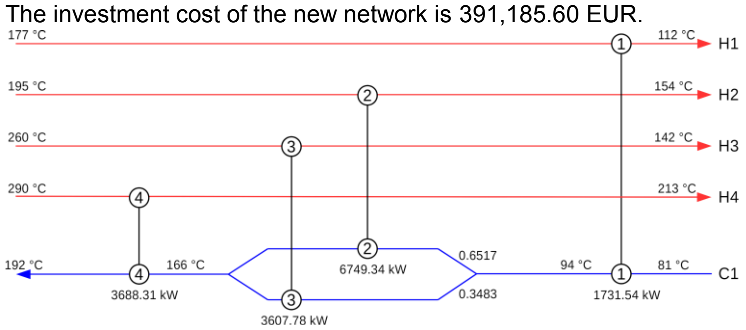

Figure 2: Minimal cost network if the whole network should be replaced

4. Conclusions

The use of enhanced PHEs widens the space of possible HENs options and can lead to the better global optimum. When performing HEN retrofit, the developed software can be utilized for a detailed capital-energy trade-off. It can help when estimating new heat transfer area to be added to existing matches in a form of additional PHEs or by changing existing heat exchanger to PHEs with the enhanced heat capacity.
The current work demonstrated the application of PHEs together in system design and retrofit. The method combined the HEN synthesis algorithm for generating multiple networks with the individual designs of PHEs. The solution with minimal cost for the retrofit of preheat oil train results in four new Compabloc PHEs with investment cost equal to 391,185.60 EUR.

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