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# A Novel Temperature vs Pressure drop Grid Diagram for Energy Saving in Heat Exchanger Network Retrofit

Bohong Wang[a], Olga Arsenyeva[b], Jiří Jaromír Klemeš[b,*], Petar Sabev Varbanov[b]

[a]National-Local Joint Engineering Laboratory of Harbour Oil & Gas Storage and Transportation Technology/Zhejiang Provincial Key Laboratory of Petrochemical Pollution Control, Zhejiang Ocean University, No. 1 Haida South Road, Zhoushan 316022, P.R. China
[b]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
jiri.klemes@vutbr.cz

Pressure drop in the heat exchanger is a key issue that should be considered in the HEN retrofit, as increasing the pressure of fluid can cost a substantial amount of energy. To accurately estimate the cost-related trade-off factors, the relative cost of pressure drop and heat transfer performance should be determined for each heat exchanger and generally for the whole heat exchanger network. However, there is still lacking a graphical method that can visualise the pressure drop together with a heat exchanger network retrofit. This paper proposes a new Temperature vs Pressure drop (TVPD) Grid Diagram to consider the pressure drops in heat exchangers when retrofitting a heat exchanger network. The method includes the proper design of heat exchangers based on the full utilisation of allowable pressure drop, where several commonly used types of heat exchangers are considered, including shell-and-tube heat exchangers and plate heat exchangers of plate-and-frame and brazed construction commonly used in industry. The new Grid Diagram can be used for energy targeting, visualising the temperature range of different heat exchanger types, and pressure drop. The method provides guidance for engineers to design a heat exchanger network with both considerations on pressure drop and heat recovery.

## 1. Introduction

Energy consumption in Process Systems Engineering has been a major concern for decades, especially at a time when carbon neutralisation has been an emerging topic. For a Heat Exchanger Network (HEN), the energy is not only needed for the hot and cold utilities but also for the pumps and compressors which pressurise the fluid and gas to ensure they can enter the facilities within the required pressure ranges.
The efforts to reduce the energy consumption from hot and cold utilities have been widely studied, and the state-of-the-art works were comprehensively reviewed by Klemeš et al. (2020). However, different heat exchanger types have specific pressure drop calculation methods, which lead to different pressure drop values. The selection of heat exchanger type in the HEN retrofit should take the pressure drop into consideration.

### 1.1 Pressure drop consideration in HEN retrofit

In an early-period contribution of Zhu and Nie (2002), they pointed out that the purchasing cost and electricity cost of pumps and compressors are two main compositions of the total annualised cost (TAC). These two compositions are related to the pressure drop, and thus the pressure drop should be considered together with the heat transfer area of the heat exchanger and the utility cost. A Pinch Analysis based method was applied to determine the optimal $\Delta T_{min}$ according to the trade-offs among heat transfer area, utility cost, and pressure drop. Akpomiemie and Smith (2017) considered the pressure drop in the retrofit design of the heat exchanger network with heat transfer enhancement. The heat exchanger types that disobey the pressure drop requirement are identified and discarded. Then those potential heat exchangers with the pressure drop mitigation techniques were optimised together with the heat exchanger network to maximise the retrofit profit. The results showed that the heat transfer enhancement is a promising option for heat exchanger network retrofit even if the pressure

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drop is considered. Souza et al. (2016) developed a mixed-integer nonlinear programming (MINLP) model that considered the pressure drop from shell-and-tube sides in a heat exchanger, pipelines that connect equipment, and the layout of equipment. The total annualised cost (TAC) was set as the objective function. The case when the pressure drop is considered can save 27.4 % of the TAC compared to the case without pressure drop consideration. And the topology of heat exchangers occupied 4.5 % of the TAC. Panjeshahi and Tahouni (2008) optimised the pressure drop by replacing the pump and/or compressor, and the additional area of heat exchangers, to reduce the operating cost in the HEN debottlenecking.

Pan et al. (2016) considered the fouling effect in the HEN retrofit using heat transfer enhancement. A MILP model was developed, which considered the pressure drop constraints and fouling mitigation. Then the balance among energy savings, intensification implementation cost, exchanger cleaning cost and pump power cost were studied. Among these items in the objective function, pump power cost is related to the pressure drop and is seldom considered in the previous publications of HEN retrofit applications. Soltani and Shafiei (2011) considered the pressure drop in the HEN retrofit by proposing a method that integrates genetic algorithm (GA) coupled with linear programming (LP) and integer linear programming (ILP) methods to maximise the energy recovery. The new pump purchasing cost was added to the objective function as the energy provided by the pump to overcome the pressure drop in the retrofit was considered.

The geometries of the heat exchanger affect the heat transfer performance and the pressure drop. There are cases that use straight or corrugated geometries, 'zig-zag' channels and discontinuous fin geometries to reduce pressure drop without sacrificing thermal performance (Yoon et al., 2014).

The Advance Grid Diagram is a useful tool for the HEN synthesis and retrofit. It originated from the Retrofit Grid Diagram (Lakshmanan and Bañares-Alcántara, 1996) and extended to the Shifted Retrofit Thermodynamic Grid Diagram by Yong et al. (Yong et al., 2015). In recent years, the Advanced Grid Diagram was used for the HEN retrofit (Wang et al., 2020a), HEN maintenance planning (Chin et al., 2020), HEN synthesis considering prohibited and restricted matches (Wang et al., 2021b), heat exchanger type selection (Wang et al., 2020b), material type selection (Wang et al., 2021a), and together with the detailed plate heat exchanger design (Wang et al., 2022). The Advance Grid Diagram is a promising tool that can be used to consider pressure drop when performing the task of HEN retrofit.

### 1.2 Plate heat exchanger design considering pressure drop

The proper approach for optimal selection of heat exchangers is needed to implement the compact plate heat exchangers (PHEs) to HEN synthesis or retrofit considering the pressure drop. Among the approaches existing in the literature for heat exchangers design, the method for geometry optimisation of heat transfer channels enables the definition of the minimal heat transfer surface area and enhances the heat transfer processes. The increase of heat transfer characteristics in channels usually is connected with a higher pressure drop. And at the thermal and hydraulic design of heat exchangers, the economic consideration of pumping power costs should be accounted for. It can be done at the stage of HEN design, where the optimal pressures in heat exchangers should be specified, as well as the allowable pressure drop for each heat exchanger.

A commonly selected optimisation parameter under heat exchanger design is the maximisation of the heat transfer coefficient, which enables the reduction of the total heat transfer area in the heat exchanger. However, in practice, it leads to smaller channels, usually with more intricated geometry with a corresponding rise of pressure drop inside the heat exchanger. In PHEs, all geometrical parameters of plates, such as corrugation inclination angle to the flow movement direction, its pitch and height, affects both heat transfer and pressure drop. In the literature, a lot of investigations concerning the optimal geometrical parameters of PHEs are available. The numerical approach for the investigation of wavy corrugated channels with different inclination angles to the flow movement direction and varied height of the wave and channels was performed by Mohammed et al. (2013). Klemeš et al. (2015) proposed a method for PHEs design based on the full utilisation of allowable pressure drop, enabling the optimal geometrical form of the corrugation for both hot and cold sides and the length of the channel to be found. The design approach for the pillow-plate heat exchangers, where channels have different diameters for the hot and cold fluid, was described by Arsenyeva et al. (2019). The approach was based on the full utilisation of allowable pressure drop, which is easier to achieve when process application requires significantly different flowrates between the operating streams. In such a situation, the design of PHEs, as was shown by Wang and Sundén (2003), can fully utilise the allowable value of pressure drop only for one side with a lower flowrate due to the construction of heat transfer channels in PHEs. As they are formed by stacking two corrugated plates, in standard construction, the channel cross-section is equal for both streams, which makes it impossible to maintain the same flow regimes in the channels, where operating conditions have significantly different flowrates.

At the design stage, the geometrical parameters of heat exchangers should be determined in such a way that the resulted heat transfer surface area ensures the operation at specified process conditions and fulfils the requirements for allowable pressure drops for both fluids. Here the initial data should include the operating

requirements for both streams, as well as the limitations caused by PHE construction. The operating parameters should include the heat load, inlet and outlet temperature, flowrate for both fluids, specification of operating fluids and maximal allowable pressure drop in the channel. The construction limitation for PHEs design includes the maximal number of plates in one unit, what is settled for each PHE type by manufacturers, and the velocity in ports and collectors, which should be less than 7 m/s. Based on these, the design of PHE with minimal heat transfer area should be obtained.
In this paper, the pressure drops of different types of heat exchangers are considered in the HEN retrofit, together with the reduction of energy consumption in utilities. An Advanced Grid Diagram method is proposed to meet this requirement.

## 2. Methodology

### 2.1 Plate heat exchanger design considering pressure drop

Based on optimal geometry parameters for PHEs from Klemeš et al. (2015), and the aim of full utilisation of pressure drop (Arsenyeva et al., 2019), the method for PHE design under HEN retrofit allows to fully utilise the allowable pressure drop in heat exchangers, is developed.
Let us assume that the heat exchanger should be designed for the following specified 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; $G_{m1}$, $G_{m2}$, the mass flow rates of the hot and cold fluids; $\Delta P_1^o$, $\Delta P_2^o$, the allowable pressure losses for the hot and cold streams, respectively.
On the one hand, the geometry of corrugated plates largely governs the heat transfer processes in the PHE and pressure losses in its channels. On the other hand, at the initial stage of the design process, the geometrical parameters of plates and corresponding channels are unknown. The aim is to select the geometry of plates which will fully utilise the allowable pressure drop for one side and ensure a high overall heat transfer coefficient and corresponding small heat transfer surface area.
The approach based on estimation of the velocities in channels, which fully utilises the allowable pressure drop (Arsenyeva et al., 2019), can be applied for different types of PHEs. The resulting velocity specifies the unique value of the channel length and, consequently, the heat transfer surface area of the PHE. For the known geometry of the plates, the velocities in the PPHE channels can be determined, and the corresponding PHE design ensuring full utilisation of pressure drop can be obtained. The method assumes that the condition for full utilisation of pressure drop for hot fluid should be satisfied. We use this approach for PHEs to determine the exact value of the velocity in the hot channel as well as the number and the corresponding length of the channel. The completely exploited pressure drop for the hot stream gives the following relation allowing the length of the channel to be determined:

$$L_F = \frac{2d_e}{\zeta_1(w_1)} \cdot \left( \frac{\Delta P_1^0}{\rho_1 \cdot w_1^2} - \zeta_{DZ} \right) \tag{1}$$

where $L_F$ is the length of the channel, m; $\rho_1$ is the fluid density of the hot stream, kg/m$^3$; $w_1$ is flow velocity in the hot channel, m/s; $\Delta P_1^0$ is allowable pressure loss in the hot channel, Pa; $\zeta_1(w_1)$ is the Darcy friction factor for the hot stream with the flow velocity $w_1$; $\zeta_{DZ}$ is local hydraulic resistance coefficient in connection zones.
The satisfaction of the requirements for the Number of Transfer Units (NTU) in the heat exchanger leads to the set of equations:

$$\begin{cases} L_F = \dfrac{2d_e}{\zeta_1(w_1)} \cdot \left( \dfrac{\Delta P_1^0}{\rho_1 \cdot w_1^2} - \zeta_{DZ} \right) \\ NTU^0 = \dfrac{2\sqrt{2} \cdot U \cdot F_x \cdot L_F}{c_{p1} \cdot w_1 \cdot \rho_1} \end{cases} \tag{2}$$

where $F_x$ is the ratio of real surface area to initial plain surface area; $c_{p1}$ is the specific heat capacity of the hot fluid, J/(kg·K); $U$ is the overall heat transfer coefficient, W/(m$^2$·K).
By excluding $L_F$ from Eq(2), the velocity in the hot channel ($w_1$) can be estimated. Using the energy balance - Eq(3), the flow velocity in channels for the cold stream ($w_2$) can be expressed via the flow velocity in channels for the hot stream ($w_1$) (and vice versa).

$$w_2 = \left( w_1 \cdot c_{p1} \cdot \rho_1 \cdot \left( t_{1in} - t_{1out} \right) \right) \Big/ \left( c_{p2} \cdot \rho_2 \cdot \left( t_{2out} - t_{2in} \right) \right) \tag{3}$$

where subscript 2 denotes the parameters for the cold fluid.

The estimation of heat transfer coefficients and Darcy friction factor in both channels is calculated according to Klemeš et al. (2015). As a result, the optimal corrugation parameters, plate numbers, and plate length will be obtained.
The pressure drop of a channel of the PHE can be calculated by Eq(4) (Gusew and Stuke, 2022).

$$\Delta p_{ch} = \zeta \frac{\rho w^2}{2} \frac{L_F}{d_e} \quad (4)$$

where $\zeta$ is the Darcy friction factor calculated based on the channel geometrical parameters (Klemeš et al., 2015), $\rho$ is the average density of the fluid in the channel, kg/m$^3$; $w$ is the average velocity of the fluid in the channel, m/s; $L_F$ is the average length of the flow path in the channel, m; $d_e$ is the equivalent diameter, m.

### 2.2 Pressure drop calculation of shell-and-tube heat exchanger

Shell-and-tube heat exchanger is another commonly used type. Its pressure drop can be calculated by the following two equations. Eq(5) describes the shell-side pressure drop when the viscosity correction term is neglected (Towler and Sinnott, 2008).

$$\Delta p_s = 8 j_f \left(\frac{D_s}{d_e}\right)\left(\frac{L_s}{l_B}\right)\frac{\rho u_s^2}{2} \quad (5)$$

where $\Delta p_s$ is shell-side pressure drop, N/m$^2$ (Pa); $j_f$ is tube-side friction factors, $D_s$ is shell inside diameter, mm; $d_e$ is equivalent diameter, m; $L_s$ is tube length, m; $l_B$ is baffle spacing, m; $\rho$ is the average density of the fluid in the shell-side; $u_s$ is the average velocity of the fluid in the shell-side, m/s.
Eq(6) describes the shell-side pressure drop when the viscosity correction term is neglected (Towler and Sinnott, 2008).

$$\Delta p_t = N_p \left[8 j_f \left(\frac{L_t}{d_i}\right) + 2.5\right]\frac{\rho u_t^2}{2} \quad (6)$$

where $\Delta p_t$ is tube-side pressure drop, N/m$^2$ (Pa); $N_p$ is the number of tube-side passes; $L_t$ is the length of one tube, mm; $u_s$ is the average velocity of the fluid in the tube-side, m/s; $d_i$ is the tube inside diameter, mm; $l_B$ is baffle spacing, m; $\rho$ is the average density of the fluid in the shell-side, kg/m$^3$, $u_t$ is the average velocity of the fluid in the tube-side, m/s.

### 2.3 Temperature vs Pressure drop (TVPD) diagram

A Temperature vs Pressure drop (TVPD) diagram is proposed to consider the pressure drop in the HEN retrofit. This tool is derived from the Shifted Retrofit Thermodynamic Grid Diagram (SRTGD), which is an insight-based method and is excellent in energy targeting (Yong et al., 2015). An example is illustrated in Figure 1, which is derived from Wang et al. (2020b).

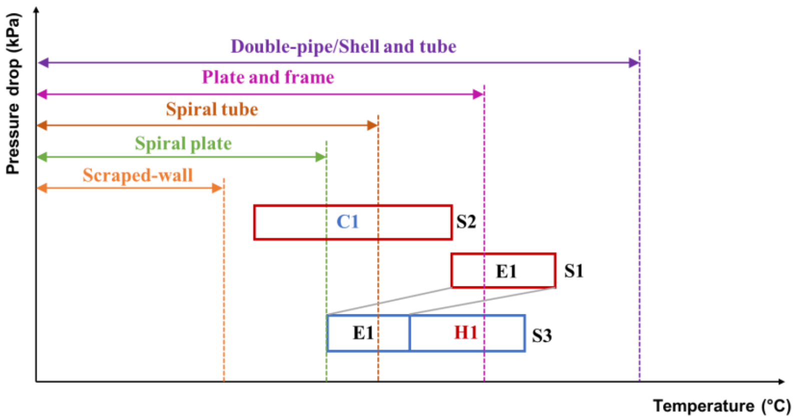


*Figure 1: An illustrative example of the temperature vs pressure drop (TVPD) diagram*

In the proposed TVPD diagram, the major difference compared to the SRTGD is the y-axis. The relative heat capacity flowrate (ΔCP) is replaced by the relative pressure drop. The height of each rectangle means the relative pressure drop of each heat exchanger. The larger height indicates a higher pressure drop, which requires more energy from the pumps or compressors to pressurise the fluid or gas in the stream. Other main

characteristics are similar to the SRTGD. From the view of the temperature, hot stream temperatures are shifted by subtracting $\Delta T_{min}$ from their actual temperatures. The links that connect to two blocks still indicate if the heat transfer is feasible or not. If the slope is positive, which means it is feasible to implement the heat exchanger. The allowable working temperature ranges for several types of heat exchangers are also illustrated in this diagram, which helps the designer to select the suitable heat exchanger type that satisfies the temperature requirement.
Through this tool, it is easy to identify both the HEN retrofit plan as well as the energy demand for pressurisation. For example, when proposing the retrofit plan of the HEN in Figure 1, both the shell-and-tube heat exchanger (Figure 2) and PHE (Figure 3) can be used as the temperature requirement can be satisfied, but they have different pressure drops. Usually, PHE has a higher pressure drop as higher friction due to construction. So the next step would be the detailed calculation considering the investment cost, the energy cost for pressurising, and the benefit from the heat recovery.

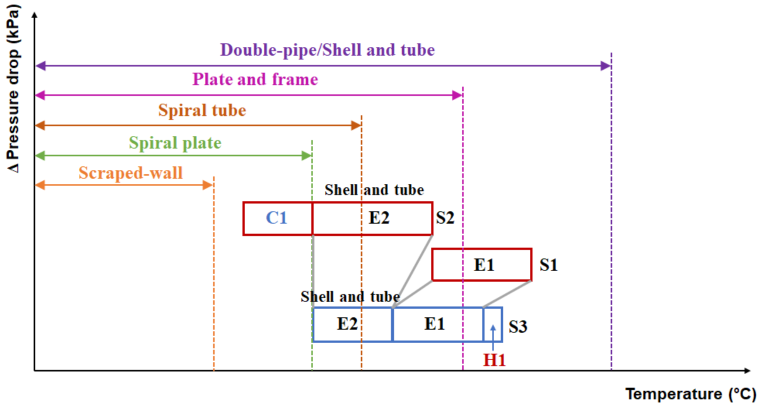


*Figure 2: A retrofit option with the use of a shell-and-tube heat exchanger*

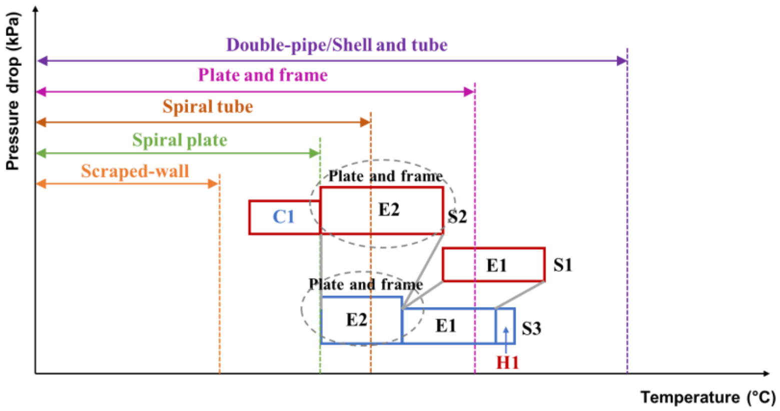


*Figure 3: A retrofit option with the use of a plate heat exchanger*

## 3. Conclusions

This paper presents a framework for the HEN retrofit. The main tool is the proposed Temperature vs Pressure drop (TVPD) diagram, which shows the insight of energy targeting, the temperature range of heat exchangers, and the pressure drop. The methods of pressure drop calculation for the PHE and shell-and-tube heat exchanger are provided. One of the most important justifications is the total annualised cost, which could quantitively evaluate which retrofit plan should be selected. However, due to the page limit of the paper, the detailed calculation procedure would be given in the extended version, together with a practical case study to show the implementation of the proposed method.

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