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Extending the Use of Welded Plate Heat Exchangers to Multi-Stream Applications

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Compabloc is a trademark of Alpha Laval and is one of the most efficient types of welded plate compact exchangers (WPHE). Their construction features and thermal performance make this technology suitable for application in a wide range of temperatures and pressures. This work focuses on the compabloc type of welded plate and presents a conceptual extension of the design to the case of multi-stream applications. WPHE units are finding wider application in heat recovery systems due to their construction features that enable them to operate at high temperatures and pressures. Besides, the corrugated surfaces employed by this type of units create high heat transfer performance at the expense of increased pressure drop which makes them transmit the required heat duty within a smaller exchanger size compared with conventional geometries. Their geometrical characteristics make it suitable for applications where more than two streams can meet their thermal duties within the same structure. This paper presents the design considerations for the use of compabloc exchangers that handle multiple streams. The multi-stream capabilities can be potentially used in the reduction of the number of heat exchanger units in heat recovery networks. The paper looks first at a thermohydraulic approach for the design of compabloc exchangers based on the full absorption of the pressure drop, then the methodology is extended to the case of multi-stream applications. The approach is demonstrated on a case study.

1. Introduction

Heat exchanger technologies such as the welded plate (WPHE) type represented by the commercially known Compabloc exchanger of Alpha Laval, are suitable for applications where not only high temperature and pressures prevail but also where high fouling is a serious problem as in the case of crude oil preheating trains (Andersson et al., 2009). The heat transfer surface of the WPHE heat exchanger consists of corrugated plates which create high turbulence and wall shear stress that, apart from increasing the heat transfer rate, tend to increase pressure drop. Additional benefits of using compabloc units are less complicated handling compared to conventional exchangers due to the smaller size required for the same duty, and smaller downtime for maintenance (Anipko et al., 2006). Further investigations on the use of compabloc heat exchangers in refinery applications show that better thermo-hydraulic performance is achieved when multi-passes are used (Tamakloe et al., 2013).

There are some critical features that must be kept in mind in the development of new exchanger technologies, for instance, from the mechanical point of view, the exchanger must have the mechanical strength to operate under a wide range of operating conditions, and from the thermal side, the unit should exhibit a large heat transfer coefficient and low pressure drop for a given fluid velocity. For instance, the fact that in WPHE the plates are welded instead of being sealed with polymer gaskets gives them the capacity to operate under a wide range of pressures and temperatures.

Cabezas-Gómez et al. (2012) developed a new cross flow arrangement for a single-phase unit and proposed an expression for the thermal effectiveness of the new unit. The new layout arrangement resulted in an improvement of the performance, particularly at large number of heat transfer units (Ntu). Such development finds its best application in large exchangers. Sammeta et al. (2011) analysed the performance of 9 different plate corrugations and derived a numerical model to determine thermal effectiveness-Ntu charts which are

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useful to determine the performance of such units under different operating conditions. These charts are valid for Ntu ranging from 0 to 6 and Reynolds's number 80 – 28,000 for constant heat capacity ratios, R.
The design and optimisation of compabloc heat exchangers was studied by Arsenyeva et al. (2016). The main targets in their approach were the selection of the corrugation pattern of the surfaces and at the adjustment of the number of passes. They proposed an optimisation model seeking to minimise fouling in crude preheat trains.
The construction of compabloc plate heat exchangers is such that the fluids flow in a crossflow arrangement in each pass. Cross flow arrangements exhibit poorer thermal behaviour than counter-current units; however, the linking of a cross flow unit with other cross flow units in series, making up an overall counter-current arrangement, is a practical way of improving the overall thermal performance of the unit. Such a structure is referred to as a complex assembly (Sammeta et al., 2011). The sizing of such units requires the determination of the correction factor of the logarithmic mean temperature difference (Picón-Núñez et al., 2014).
A multi-stream heat exchanger is a heat transfer device that takes advantage of the construction features of certain technologies that have the flexibility to accommodate more than three different streams within the same structure (Picón-Núñez et al., 2006). In principle, the use of multi-stream heat exchangers could reduce the complexity of existing heat recovery networks (Polley and Haslego, 2002). In this work, a methodology for the design of compabloc heat exchangers is presented; the approach is extended to consider the case of multi-stream applications.

2. Multi-stream arrangement

A compabloc heat exchanger consists of stacks of corrugated plates which constitute the heat transfer core of the unit. The separation between the plates, which are welded to one another, form the channels for fluid flow. Inside the unit, streams flow in crossflow fashion either in single or multiple passes. There are many possible flow array combinations in a compabloc exchanger. In the case of multi-pass arrangements, the system is arranged overall in counter-flow fashion for maximum thermal performance. Figure 1 shows different flow pass arrangements that are possible in a compabloc unit. The construction characteristics of the compabloc exchanger make it suitable for the processing of more than two units within the same frame. This feature could, in principle, represent the capability for multi-stream applications. Figure 2 shows a basic diagram where a single hot stream H1, exchanges heat with two cold streams C1 and C2. Subject to layout restrictions, the heat recovery network of Figure 3a shows two possible multi-stream applications out of the various options in the network. Figure 3b shows that the number of units has been reduced from 7 to 4.

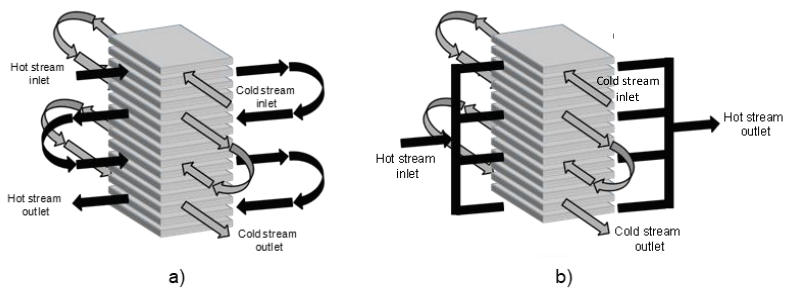


Figure 1: Basic construction features of a compabloc heat exchanger. Different flow arrangements: a) four passes on both streams, b) one pass on hot stream and four passes on cold stream.

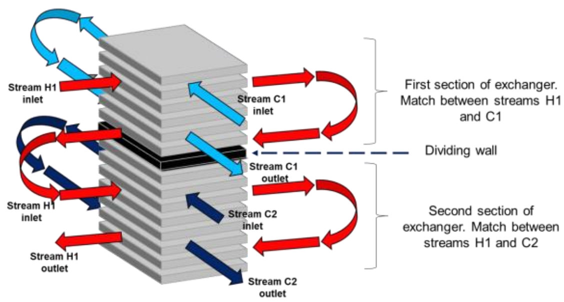


Figure 2: Schematic of a compabloc exchanger handling three process streams.

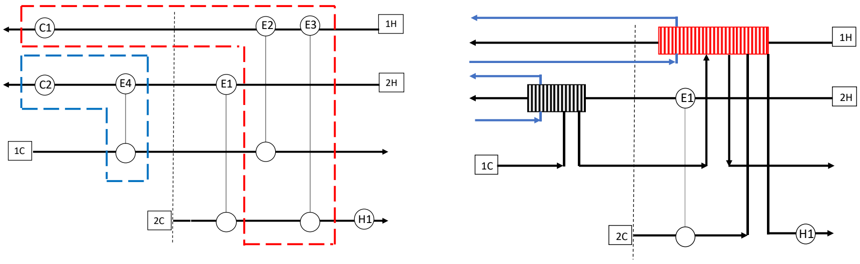
3. Design considerations

The strategy for the design of compabloc multi-stream heat exchangers is composed of two main steps. In the first, the dimensions of the plate are selected from the viable commercial dimensions. The selection is based on the pressure drops allocated to the streams. The stream that has been assigned the lower pressure drop determines the required plate dimensions. All other streams must conform to the given dimensions but the number of passages is a function of the heat duty. The final design will give a block with the same type of plate and the total height being the summation of the different units that are to be brought together into the same frame. The sizing definition of a compabloc heat exchanger involves the definition of the following geometrical features: the plate size (length), the height or number of plates, the number of passes per stream and the number of plates per pass. The sizing of a heat exchanger proceeds after the calculation of each of the terms of the design equation:

$$A = \frac{Q}{U\ F\ \Delta T_{lm}} \tag{1}$$

$$U = 1 \Big/ \frac{1}{h_1} + \frac{1}{h_2} + \frac{\tau}{k_W} \tag{2}$$

Where Q is the heat duty, ΔT_{lm} is the logarithmic mean temperature difference, U is the overall heat transfer coefficient expressed for clean conditions in Eq(2), and F is the correction factor of the log mean temperature difference. The terms h_1 and h_2 refer to the heat transfer coefficient of stream 1 and 2, τ is the thickness of the separating wall and k_w is the thermal conductivity of the material of construction.



a) b)

Figure 3: Potential strategy for the simplification of a heat recovery network: a) simplified heat recovery network, b) use of compabloc multi-stream exchangers.

In this work, the correction factor of the logarithmic mean temperature difference is obtained from (Kays and London, 1984):

$$F = \frac{Ntu_{counter\text{-}current}}{Ntu_{other\,arrangement}} \tag{3}$$

The term $Ntu_{\text{other arrangement}}$ refers to the number of heat transfer units of an arrangement different from counter-current and $Ntu_{\text{countercurrent}}$ refers to the number of heat transfer units if the arrangement is counter-current. For a given design problem, the overall thermal effectiveness (ε) can be determined from the inlet and outlet temperatures. For example, for a case where the hot stream experiences the largest change in temperature compared to the cold stream, the thermal effectiveness can be expressed as:

$$\varepsilon = \frac{\left(T_{h\,in} - T_{h\,out}\right)}{\left(T_{h\,in} - T_{C\,in}\right)} \tag{4}$$

The thermal effectiveness as a function of *Ntu* and *C* for a counter-current arrangement is calculated from:

$$\varepsilon = \frac{1 - e^{-Ntu(1-C)}}{1 - C\ e^{-Ntu(1-C)}} \tag{5}$$

The overall thermal effectiveness ($\varepsilon_{overall}$) of a heat exchanger exhibiting the same number of passes on each stream (Figure 1a), is:

$$\varepsilon_{overall} = \left[\left(1 - \varepsilon_p C \Big/ 1 - \varepsilon_p \right)^n - 1 \right] \Big/ \left[\left(1 - \varepsilon_p C \Big/ 1 - \varepsilon_p \right)^n - C \right] \tag{6}$$

Where C is the ratio of the mass flow rate-heat capacity of the for a given number of passes (n) and ε_p is the thermal effectiveness per pass. From the equation of the thermal effectiveness of the single cross flow exchanger, Eq(7), the Ntu_{pass} is obtained.

$$\varepsilon_p = 1 - e^{\left[(1/C) Ntu_{pass}^{0.22} \left\{ e^{\left[-C \left(Ntu_{pass}^{0.78} \right) \right] - 1} \right\} \right]} \tag{7}$$

Then the total number of heat transfer units for the four-pass cross flow arrangement is:

$$Ntu_{otherarrangemen} = n\ Ntu_{pass} \tag{8}$$

The number of thermal plates in a compabloc unit is calculated from the overall heat transfer area and the surface area per plate. The number of channels equals the number of thermal plates plus 1. The pressure drop (ΔP) across the unit can be determined from:

$$\Delta P = 2nfWG^2 / \rho d_h \tag{9}$$

Where n is the number of passes, G is the mass flow rate per unit area, W is the length of the plate, f is the friction factor and ρ is the density. The value of G is determined from:

$$G = m / A_C \tag{10}$$

And d_h is the hydraulic diameter given by:

$$d_h = 2\delta / \varphi \tag{11}$$

Where δ, is the spacing between plates and φ is the factor of elongation. The cross-sectional area (Ac) to fully absorb the specified pressure drop can be determined from Eq(12):

$$A_c = \left[\frac{2xm^{(2-y)} \mu^y nW}{d_h^{(1+y)} \rho \Delta P} \right]^{1/(2-y)} \tag{12}$$

The number of plates is:

$$N_{hydraulic\ plates} = \frac{1}{(W\delta)} \left[\frac{2xm^{(2-y)} \mu^y nW}{d_h^{(1+y)} \rho \Delta P} \right]^{1/(2-y)} \tag{13}$$

Where W is the plate length. Typical plate dimensions are in the range between 0.2 and 2.2 m. On the thermal side, once the heat transfer surface area (A) is determined from Eq(1), the number of thermal plates ($N_{thermal\ plates}$) is computed from the surface area of the plate (A_{plate}) as:

$$N_{thermalplates} = A / A_{plate} \tag{14}$$

$$A_{plate} = W^2 / \varphi \tag{15}$$

4. Heat transfer performance

The thermal design of single-phase heat exchangers in complex assembly requires that a close attention be given to the determination of the heat transfer coefficients on both stream sides as well as the determination of the correction factor of the logarithmic temperature difference. According to Hesselgreaves (2001), the type of plate used in compabloc units exhibit a like performance to the type of plates used in plate and frame units. Typical heat transfer and friction correlations for plate and frame surfaces are expressed in the form:

$$Nu = a\,\mathrm{Re}^{b}\,\mathrm{Pr}^{0.4}\left(\mu/\mu_{w}\right)^{0.14} \tag{16}$$

$$f = x\,\mathrm{Re}^{-y} \tag{17}$$

Where *Re* is the Reynolds number and *Pr* the Prandtl number. The values of coefficients and exponents of Eq(16) and Eq(17) have been reported for various surface types by Arsenyeva et al. (2011). These values are used in this work.

5. Case study

To demonstrate the proposed approach for multi-stream compabloc unit, the operating conditions and physical properties of a three-stream problem, composed of one hot and two cols streams, is presented in Table 1. The match between stream H1 and stream C1 (exchanger 1) transfers 1,491 kW, and the match between stream H1 and stream C2 (exchangers 2) transfers 1,278 kW. The schematic of the heat recovery problem is depicted in Figure 4. The plate dimension chosen for the design of exchanger 1 is also chosen as the basis for the design of exchanger 2 that becomes the section of the multi-stream unit. The rationale being that for the two exchangers to fit in the same structure, they must have the same plate dimension. At this stage, the design considers only the possibility of both streams having the same number of passes. The plate dimensions are plate width: 0.9 m; plate thickness: 2 mm; plate spacing: 5 mm; plate elongation: 1.15 and number of passes: 4. The values of a, b x and y of Eq(16) and Eq(17) are: 0.265, 07, 10.7 and 0.07. The results of the design exercise are presented in Table 2.

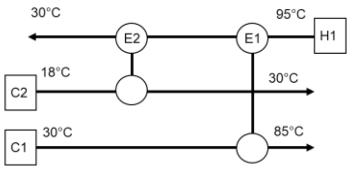


Figure 4: Schematic of the heat recovery problem for the design of a multi-stream compabloc exchanger.

Table 1: Physical properties and operating conditions of three-stream problem

	H1	C1	C2
Mass flow rate (kg/s)	15.0	10.95	25.35
Inlet temperature (°C)	95	30	18
Outlet temperature (°C)	30	85	30
Pressure drop (Pa)	35,000	35,000	50,000
Density (kg/m^3)	750	961.8	995
Heat capacity (J/kg °C)	2,840	3,180	4,200
Viscosity (Pa· s)	0.0008	0.00166	0.00089
Thermal conductivity (W/m °C)	0.19	0.66	0.59

Table 2: Design results of the three stream compabloc exchanger

	Exchanger 1	Exchanger 2
Correction factor (F)	0.946	0.946
Thermal conductivity of material (W/m °C)	80	
Exchanger surface area (m^2)	108.35	72.62
Overall heat transfer coefficient (W/m^2°C)	798.74	946.61
Heat load (kW)	1,491	1,278
Total number of channels	118	78
Exchanger height (m)	0.821	0.704
Pressure drop hot stream (Pa)	24,454.7	19,491.7
Pressure drop cold stream (Pa)	10,968.5	41,563.2
Multi-stream exchanger dimensions		
Width (m)	0.9	
Height (m)	1.52	

6. Conclusions

This paper shows the development of a design methodology for the sizing of compabloc heat exchangers. The methodology stems from the design principle of maximisation of the pressure drop. This objective can be achieved provided the plates were available at any width. However, plates are available only in standard dimensions so, full pressure drop absorption cannot effectively be achieved. Despite of this, the approach is still valid and leads the designer to find the plate dimension that absorbs the highest pressure drop without surpassing the established limit. The design approach presented in this work applies to conventional two-stream applications but, it is extended to look at the possibility of incorporating, in the same unit, a second or even a third exchanger. This gives rise to extending the compabloc geometry to fit multi-stream applications. There is a limit to the number of exchanger blocks that can be fit together in a single frame. The limitation is the total height of the resulting unit.

A basic assumption for the development of this work is that the expressions to determine the thermohydraulic performance of the heat transfer surfaces are readily available. This may not be case for a special surface corrugation. Since the main flow arrangement in a compabloc heat exchanger is crossflow, the number of passes is an effective means of increasing the overall thermal effectiveness of the exchanger. Consideration of the number of passes gives rise to more complex flow arrangements since in some cases, it is only one of the streams that need to increase its velocity. The work considers these other situations has not been included due to space limitations in this work.

References

Andersson E., Quah J., Polley G.T., 2009, Experience in the application of compabloc in refinery preheat trains and first analysis of data from an operational unit, Proceedings of International Conference on Heat Exchanger Fouling and Cleaning VIII, Eds. Muller-Steinhagen H., Malayeri M. R., Watkinson A. P., Schaladming, Austria, 29-43.

Anipko O. B., Kapustenko P. A., Gogenko A. L., Arsenyeva O. P., Perevertaylenko A. Y., 2006, Fouling of Compabloc type plate heat exchangers in technological processes of distilleries and nitric acid production. CHISA 2006, 17th International Congress of Chemical and Process Engineering, Prague, Czech Republic, 1062.

Arsenyeva O. P., Tovazhnyansky L. L., Kapustenko P.O., Khavin G. L., 2011, Optimal design of plate-and-frame heat exchangers for efficient heat recovery in process industries, Energy, 36, 4588-4598.

Arsenyeva, O. P., Tovazhnyanskyy, L. L., Kapustenko, P. O., Khavin, G. L., Yuzbashyan, A. P., Arsenyev P. Y., 2016. Two Types of Welded Plate Heat Exchangers for Efficient Heat Recovery in Industry. Applied Thermal Engineering, 105, 763–773.

Cabezas-Gómez L., Aparecido-Navarro H., Sáiz-Jabardo J. M., De Morais Hanriot S., Brasil M. C., 2012, Analysis of a new cross flow heat exchanger flow arrangement-Extension to several rows, International Journal of Thermal Sciences, 55, 122-132.

Hesselgreaves, J E., 2001, Compact heat exchangers selection design and operation, Elsevier Science and Technology books, Oxford, UK, 52-53.

Kays W. M., London A. L., 1984, Compact Heat Exchangers, 3rd ed., McGraw-Hill, New York, United States, 23.

Picón-Núñez M., Martínez-Rodríguez G., López-Robles J.L., 2006, Alternative design approach for multipass and multi-stream plate heat exchangers for use in heat recovery systems, Heat Transfer Engineering, 27, 6, 12-21.

Picón-Núñez M., Rodríguez-Ibarra J. E., Alvarado-Briones B., 2014, Design of heat exchangers in complex arrangements for use in preheat trains, Chemical Engineering Transactions, 39, 301-306.

Polley, G. T., Haslego C., 2002, Compact heat exchangers, Part 2: Using plate heat exchangers in heat recovery networks, Chemical Engineering Progress, 98, 10, 48-51.

Sammeta H., Ponnusamy K., Majid M. A., Dheenathayalan K., 2011, Effectiveness charts for counter flow corrugated plate heat exchanger, Simulation Modelling Practice and Theory, 19, 777–784.

Tamakloe E. K., Polley G. T., Picón-Núñez M., 2013, Design of Compabloc exchangers to mitigate refinery fouling, Applied Thermal Engineering, 60, 441-448.