CHEMICAL ENGINEERING TRANSACTIONS

VOL. 39, 2014

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Peng Yen Liew, Jun Yow Yong

ISBN 978-88-95608-30-3; **ISSN** 2283-9216 DOI:10.3303/CET1439052

PHEx: A Computational Tool for Plate Heat Exchangers Design Problems

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This paper presents a computational tool (PHEx) developed in Excel VBA for solving sizing and rating design problems involving Chevron type plate heat exchangers (PHE) with 1-pass-1-pass configuration. The rating methodology procedure used in the program is outlined, and a case study is presented with the purpose to show how the program can be used to develop sensitivity analysis to several dimensional parameters of PHE and to observe their effect on transferred heat and pressure drop.

1. Introduction

Heat exchangers have played an important role in industry processes for more than a century. Mainly they have been used to deliver and remove heat from process streams that need to be in certain temperature conditions, to meet process specifications. More lately, they have been extensively used to achieve better energy efficiency in industry, where heat recovery within the process helps to reduce utilities consumption with a direct impact in the economic health of companies.

A variety of heat exchangers can be employed for the mentioned purposes. Shell-and-tube type has been the most popular over the years, and the most often selected one. However, this situation has gradually changed, and PHE gained increased attention as viable cost-effective alternative. As a result, they are now commonly used in a wide range of chemical processes and other industrial applications.

In a PHE, both heat transfer rate and pressure drop are highly influenced by the plate geometry and the corrugation design. The plates between which the hot and cold fluids circulate alternately are thin metal sheets with a certain corrugation pattern that is produced by a stamping process. The physical characteristics of the corrugations influence the amount of transferred heat as well as plate rigidity and mechanical support due to multiple metal-to-metal contact points between adjacent plates.

Among the wide variety of corrugation patterns developed until now, the Chevron type have won more popularity in the last years and are commercialized by the most known companies of heat exchangers.

Contrary to other types of heat exchangers, like shell and tube heat exchangers, for which design data and methods are well known and easily available, PHE design is normally performed by manufacturers that use prediction models based on experimental data particular to the plates they sell. For that purpose, manufacturers developed their own computerized design procedures applicable to the PHE they produce (Kakaç and Liu, 2002) which cannot be generalized to other PHE.

Shah and Focke (1988) presented PHE solving methods for sizing and rating problems, which rely on experimental data obtained for specific plate characteristics, which is given in the form of the Colburn factor versus Reynolds number for heat transfer calculations and Fanning friction factor versus Reynolds number for hydraulic calculations. The experimental correlation data used by these authors was obtained by Focke et al. (1985) for specific plates. Other authors like Muley et al. (1999) developed heat transfer and pressure drop correlations for use in PHE, but most of these correlations cannot be generalized to give high degree of prediction ability. Manglik et al. (1996) compared the referred correlations, and found some discrepancies, that are originated in the geometric differences of the plates used by each author.

This paper presents PHEx, a computational tool based on Shah and Focke (1988) work, which embeds a step by step methodology that can be used to solve sizing and rating problems for 1-pass 1-pass PHE. Some simplifications were assumed, which means that these methods have some limitations in their

Please cite this article as: Palmeira J., Fernandes C., Matos H.A., Silva J., 2014, PHEx: a computational tool for plate heat exchangers design problems, Chemical Engineering Transactions, 39, 307-312 DOI:10.3303/CET1439052

application. At the same time, for solving design problems for specific model plates, the respective experimental correlations should be used in the developed program.

2. Chevron Plate Geometry

In **Error! Reference source not found.**, an illustration of a Chevron type plate is given. The plates have a rectangular shape and circular ports at each corner where the fluid enter and exit the volume between two plates. The space volume between two plates attached together is sealed by gaskets. Several geometrical parameters of plates can strongly influence the thermal-hydraulic performance of the PHE, like the fluid flow length, L, the channel wide, W, and Chevron angle, β. The diameter ports, D_p, should be projected to be as large as practical in order to keep the pressure drop in the inlet and outlet ports as low as possible.
When Chevron type plates are assembled in a stack, the corrugations of two adjacent plates are placed in opposite directions forming non-linear flow passages between the plates volume. As investigated by Dovic et al. (2009), the flux flow is basically composed by two flow components – the longitudinal which moves in a helix flow pattern in the main direction of the flow and the furrow component where the fluid follows the corrugation direction. The relative influence of these two components is determinant to the convective heat transfer coefficients, and consequently to the overall transfer heat.
The geometric parameter that the most influences transfer heat is the Chevron angle (β=1-θ), defined as the angle between the corrugation and a vertical line parallel to the flow. It should be noted that other authors as Gut and Pinto (2003) use a different definition. A plate with a high chevron angle offers a high heat transfer coefficient and high pressure drop, where a plate with low Chevron angle has lower heat transfer and lower pressure drop. Other geometric parameter that affects the performance of Chevron plates are the corrugation pitch, P_c. Most authors present the corrugation form as a perfect sinusoidal wave (Focke et al. 1985), however the waveform itself can have any intermediate shape from pure sinusoidal to pure triangular forms (Arsenyeva et al. 2013), being characterized by additional parameters like the radius of curvature and the straight length segment. Different values for these parameters will produce heat coefficients which will result in different overall performance of the PHE, even for plates where all other geometric characteristics are equal.
Because plates produced by different producers are unique with respect to their characteristics, this results that even plates with similar geometry (Chevron angle, height, wide) can show different heat transfer behaviour.

3. Rating design methodology

Although PHEx is applicable for solving rating and sizing problems, we focus only in the first type. The solution of a rating problem results in the knowledge of heat load, outlet temperatures and pressure drop for each side of PHE. For that, it is necessary to provide information about the fluid flow rates, inlet temperatures and allowable pressure drops for a completely specified plate heat exchanger, where heat transfer surface area, flow arrangement, and flow passage dimensions are already known.
This solving c is normally used to verify vendor's specification for a required heat duty, or to evaluate the performance of an existing PHE for different working conditions from those used in the design. A flowchart with step by step calculus procedure adapted from Shaw and Focke (1988) work and implemented in PHEx is presented in Figure 2.

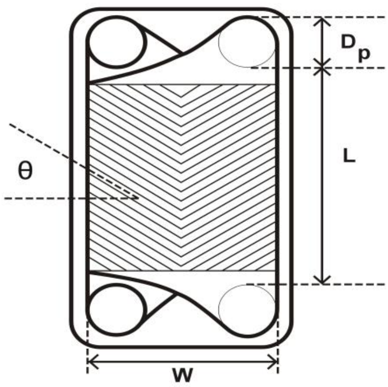


Figure 1: Chevron plate geometry

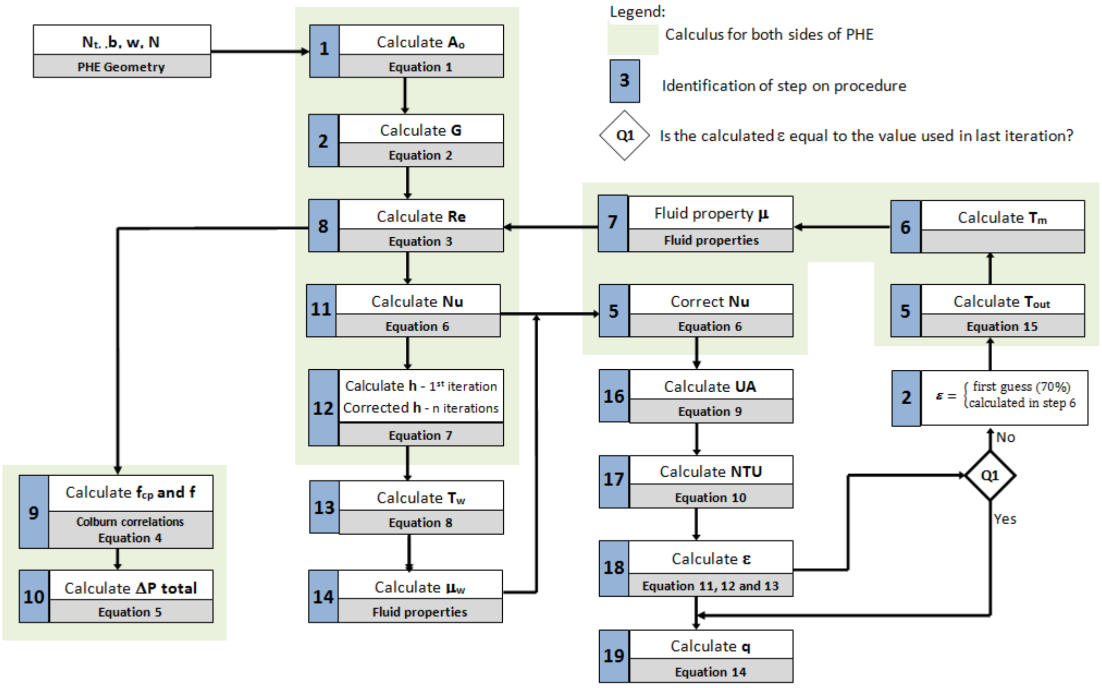
4. Software Description

Based on Shah methodology, a computational tool was created in Excel VBA for solving sizing and rating problems. All the solving steps were implemented in several Excel worksheets, however the user is faced only with a friendly interface where input data is asked and output data is provided. The software interface is composed by an initial introduction page (Figure 3) where the user can choose to solve a sizing or rating problem.

For sizing problems, the user must define all parameters of PHE, namely plate height, width, thickness, spacing, thermal conductivity, chevron angle and maximum allowed pressure drop for both sides. For each side of PHE, the user must also select the fluid from the available database which will provide information about specific heat, viscosity, thermal conductivity and density. If the fluid to be considered is not available, the program offers the possibility to add new fluids to database. Additionally, fluid inlet temperatures, flow rate and the desired outlet temperature for one of the fluids must be provided.

The sizing problem output will be the required number of plates and area, the effective transfer heat and pressure drop for each side.

For solving rating problems, the same information must be provided, except the outlet temperature of one of the streams and maximum allowed pressure drop for both sides. Instead, the number of plates must be provided and the program will calculate the transferred heat as well the effective pressure drop.



Nº	Equation Formula	Nº	Equation Formula
1	$A_o = b\, L_w (N_t + 1/2\, N)$	9	$\frac{1}{UA} = \frac{1}{h_h A} + \frac{1}{h_{s,h} A} + \frac{a}{k_w A_w} + \frac{1}{h_{s,c} A} + \frac{1}{h_c A}$
2	$G = W / A_o$	10	$NTU = UA / C_{min}$
3	$Re = G\ D_e / \mu$	11	$P_1 = \frac{1 - exp[-NTU(1 - R_1)]}{1 - R_1 exp[-NTU(1 - R_1)]} = \frac{T_{1,in} - T_{1,out}}{T_{1,in} - T_{2,in}}$
4	$f = f_{cp} (\mu_w / \mu_m)^m$	12	$R_1 = C_1 / C_2$
5	$\Delta P = \frac{1.5\ G^2 N}{2 g_c\, \rho_i} + \left[\frac{4\ f\ L\ G^2}{2 g_c\, D_e} \left(\frac{1}{\rho}\right)_m + \left(\frac{1}{\rho_o} - \frac{1}{\rho_i}\right) \frac{G^2}{g_c} \right] \pm \left(\frac{\rho_m\ g\ L}{g_c}\right)$	13	$\varepsilon = \begin{cases} P_1 & for\ \ C_1 = C_{min} \\ P_1 / C^* & for\ \ C_1 = C_{max} \end{cases}$
6	$Nu = j\ Re\ Pr^{\ 1/3}$	14	$q = \varepsilon C_{min} (T_{h,i} - T_{c,i})$
7	$h = Nu\ k / D_e$	15	$q = c_{p,h} W_h (T_{h,o} - T_{h,i}) = c_{p,c} W_c (T_{c,i} - T_{c,o})$
8	$T_w = \frac{T_h + [(R_h + R_{s,h})/(R_c + R_{s,c})] T_c}{1 + [(R_h + R_{s,h})/(R_c + R_{s,c})]}$		

Figure 2: Flowchart for solving rating type problems with corresponding equation formula

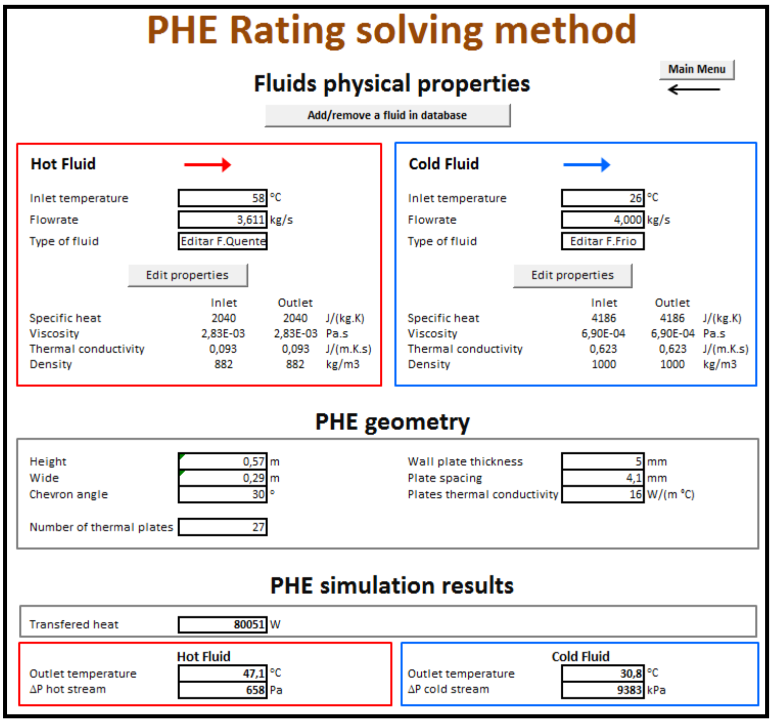


Figure 3: PHEx windows for solving rating problems

The experimental correlation data used in PHEx is based in published data (Focke et al. 1985) for specific plate geometry. Any solution of rating and sizing problems that use different kind of plates, it will require a modification of the software application in order to allow the use of specific experimental data for those plates, which could be provided by manufacturers or investigated in laboratory.
An example of the use of this software for solving a rating problem is provided in the next chapter.

5. Case Study

In this chapter, we will be present an example of the use of PHEx to solve a rating problem and to perform a set of sensitivity analysis of several dimensional parameters of the PHE. The case study corresponds to a PHE to be implemented in a biodiesel production process in order to recover energy within the process.

5.1 Problem statement

An energy analysis to a biodiesel production process concluded that the installation of a new heat exchanger would allow a significant energy recovery between two process streams. The PHE to be implemented should allow a heat duty of 44,200 W, which represents a cooling of the hot stream to 52 ℃. Using the rating mode of PHEx, both stream properties were introduced in the program together with a PHE setup according with Table 1. The results from simulated PHE are presented in

Table 2.

Table 1: Fluid and PHE characteristics

Fluid characteristics	Hot side	Cold side	PHE characteristics	
Fluid	Biodiesel	Water	Chevron angle - β (degrees)	30°
Mass flow rate (kg/h)	13,000	1,730	Wall plate thickness (mm)	5
Inlet temperature (°C)	58	26	Plate spacing (mm)	4.1
Density (kg/m^3)	882	1,000	Plate thermal conductivity (W/m°C)	16
Mass specific heat (J/(kg.K))	2,040	4,186	Plate height (m)	0,57
Thermal conductivity (W/(m.K))	0,093	0,623	Plate width (m)	0,29
Viscosity (mPas)	2,830	0,690	Number of thermal plates	27
Max. pressure drop (kPa)	30	30		

Table 2: Fluid and PHE characteristics

	Hot side	Cold side
Outlet temperature (°C)	Biodiesel	Water
Pressure drop (kPa)	0,6	5,8
Transfer heat (kW)	44899	

5.2 Sensitivity analysis

With the following sensitivity analysis, it is intended to show the utility of the software application to characterize the influence of important parameters in the overall PHE performance. The parameters analysed were the total transfer area (that result from the number of plates introduced), the Chevron angle, the plate spacing between two consecutive plates, and the cold fluid flowrate where the value can change overtime. For each study, the used PHE/fluid characteristics values are presented in Table 1, except the parameter that is being studied.

The data presented in Figure 4a, quantifies the pressure drop decreasing for both fluids as well the heat transfer increasing with total heat transfer area. Due to hot fluid characteristics, in particular the high viscosity and high mass flow, the pressure drop of this fluid is more sensible to total transfer area than the cold fluid. In this analysis, it was initially established that the hot side is the critical pressure side and for this reason it was assumed that the hot fluid is entering in the top side and the cold fluid in the down side of the PHE. The pressure drop of hot side assumes negative values for areas above 5 m^2 which means that the pressure rise due to fluid elevation (which corresponds to a negative pressure drop) is higher than pressure drop attributed to plate passages and manifolds. With respect to the variation of transfer heat with total area, as it was expected, the first parameter increase with the second.

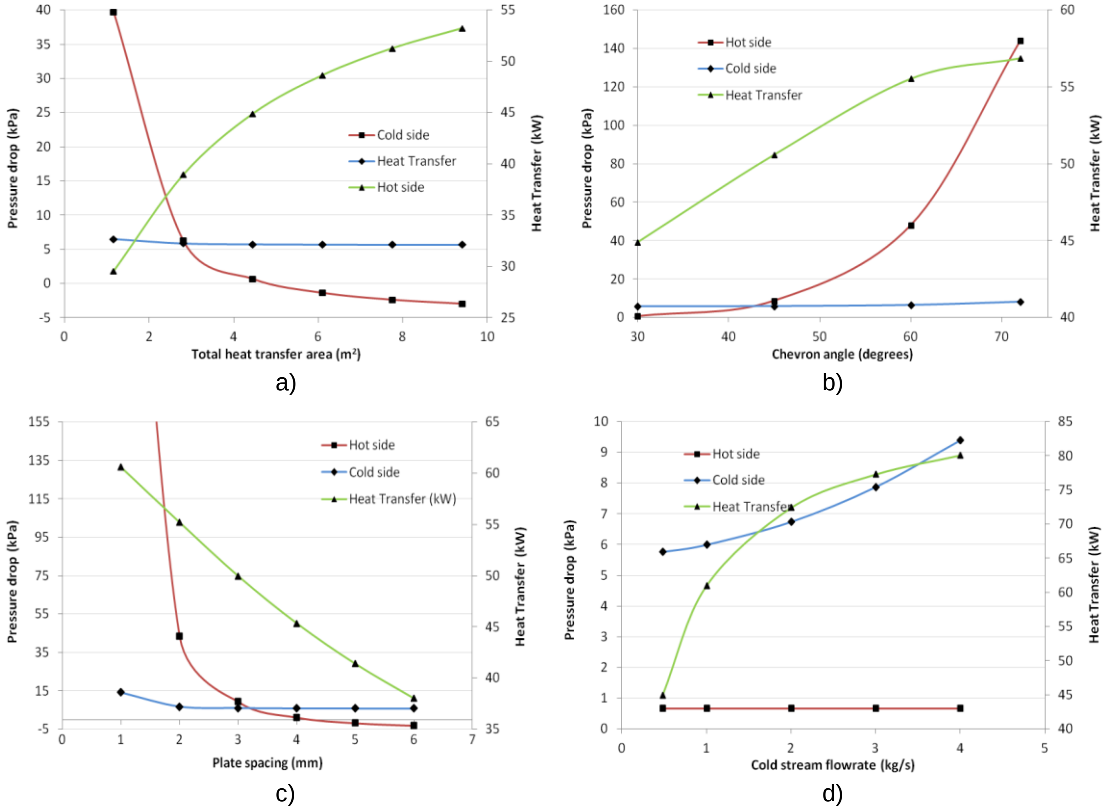


Figure 4: Pressure drop and heat transfer with: a) total heat transfer area, b) Chevron angle, c) plate spacing, and d) cold stream flowrate.

The Chevron angle is one of the geometric parameters that most influence the heat transfer and pressure drop, as it can be observed in Figure 4b. Increasing the Chevron angle will increment significantly the transferred energy. In this case the increase is approximately 40 % when it goes from 30° to 72°. With

respect to the pressure drop, the Chevron angle also affect considerably the pressure drop on the hot side and it is almost negligible in the cold side. The reason for this is mainly attributed to high viscosity and flow rate of the hot fluid.
The plate spacing affects the overall performance because influences the free flow area of fluids, which in turn affects the fluid velocities. In Figure 4c we can observe that the plate spacing can influence greatly the not only the transferred heat but also the pressure drop of fluids (which is evident in this case for hot fluid). We could say that low values of plate spacing are favourable to heat transfer, but for values below 3 mm the pressure drop of hot fluid increases greatly.
This problem is considering a heat exchanger for heat recover between two process streams, so flowrates are determined by the process. In this study we want to evaluate what would be the PHE performance if the cold fluid flowrate suffers considerable variation. As presented in Figure 4d, an increase in cold fluid flow rate affects considerably the exchanged heat between the two fluids. The value almost duplicate when going from 0.5 kg/s to 5 kg/s. The influence is also positive when analysing the cold fluid pressure drop. As expected, the influence in hot fluid pressure drop is negligible.

6. Conclusions

The sizing and rating design problems differ in nature, so different input data must be given and different output data will be obtained. Although solving these types of problems involve several steps including iteration processes, once the solving method is implemented in a programming tool, obtaining a solution is quite easy. With this in mind, we presented PHEx, a computational tool that can be used to solve design problems related to Plate Heat Exchangers.
The PHEx was design in Excel software, which facilitates is use because of the easy access to this last software by everyone. The PHEx application have well identified fields for data input and data output. The fact that implements, simultaneously, rating and sizing methodologies, can be used to solve the great majority of PHE problems. The program can only solve a specific problem, but also it constitutes an important tool in order to perform sensitivity analysis to PHE whether they are still in a project phase or they are already working.
When using PHEx to solve PHE problems, care must be taken in using accurate experimental correlation data for the plate geometries that will be considered. The experimental correlation data used in PHEx is specific for a certain plate characteristics and cannot be used for other plates. For correct results, when considering design problems for a certain PHE manufacturer the correspondent experimental correlation data must be provided in PHEx application.
Because PHE are the preferred types of heat exchangers in many applications it is important have a design tool to predict PHE characteristics for a certain application. The developed program PHEx, complemented with economic data about plate costs provided by manufacturers, can be of great help to estimate PHE costs.

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