ORIGINAL PAPER

Building a MATLAB applicaton for preliminary design and optimization of shell and tube heat exchangers

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Abstract

Designing shell and tube heat exchangers is a complex and time-consuming procedure. Since they are one of the most common process units in process industry, great effort should be made to improve their design and to facilitate the design procedure. Therefore, in this study, an easy-to-use MATLAB application for shell and tube heat exchanger preliminary design and optimization was developed. The application enables users to select operating parameters manually and test their effect on heat transfer area and pressure drop. Moreover, the application helps users to optimize the preliminary design, in terms of finding the minimal heat transfer area required to meet the process requirements. The validity of the application was tested on the example from the literature, where the heat transfer area was 61.91 m2. During the proposed optimization procedure, different parameter values were tested and an optimal combination of parameters was found within 5 seconds (for all combinations), resulting in the heat transfer area of 53.27 m2. The application has a great feature of displaying the impact of baffle cut value and baffle spacing on most important design parameters: heat transfer area, tube-side pressure drops and shell-side pressure drops. Also, new correlations were developed for the calculation of the Colburn heat transfer factor and friction factor as a function of Reynolds number and baffle cut value. Overall, the application has proven to be useful for the preliminary design of shell and tube heat exchangers, and can represent the foundation for the development of advanced heat exchanger design applications.

Keywords: shell and tube heat exchanger, MATLAB app, design optimization, Kern method

1. INTRODUCTION

The most common type of heat exchangers used in industry are shell and tube heat exchangers. Such exchangers are made up of a number of tubes in parallel and series through which one fluid travels and enclosed in a shell through which the other fluid is conducted (Perry 1999). A wide range of design alternates and operating conditions is obtainable with shell and tube exchangers, which makes them applicable in different areas of process industry (Couper 2012). The prime objective in the design of an exchanger is to determine the surface area required for the specified heat transfer rate using the temperature differences available. Many construction parameters can affect required surface area for heat exchange, for example: tube dimensions (length, inside and outside diame-

ter), tube pattern, heat exchanger head type, tube pitch, baffle spacing, baffle cut (Schlunder 1983), etc. The two main methods used in the design of shell and tube heat exchangers are Bell-Delaware and Kern methods, where the Kern method is simple to apply and is accurate enough for preliminary design calculations (Sinnott 2005). Since there are a lot of parameters that can be varied, finding optimal heat exchanger design (here we are talking about surface area as a goal function of our optimization problem) can be complex and time-consuming. Also, the design procedure has two iteration loops, one for the overall heat transfer coefficient, and one for testing if pressure drop is within specification (if not, construction adjustments have to be made). Most problems encountered in chemical engineering are very sophisticated and interdis-

ciplinary, and, because of that, they require the use of different software tools. MATLAB is one such tool that has been found suitable for implementing algorithms required in engineering, research, mathematics, and industrial operation-aid systems (Kalechman 2018; Yeo 2017). In recent years, MATLAB has developed a new feature called App Designer, which enables users to develop their own, easy-to-use applications. App Designer is an interactive environment introduced in version R2016a, which includes a fully integrated version of the MATLAB editor comprised of the design view and the code view of your app. The layout and code views are tightly linked so that the changes you make in one view immediately affect the other. A MATLAB app is a self-contained MATLAB program with a user interface that automates a task or calculation. This app can be shared in several ways: sharing MATLAB files directly, packaging your app, creating a Web app and creating a standalone desktop application. (MATLAB©App Building, 2019). So far not many papers have been published presenting this type of apps. However, it is shown that MATLAB App Designer can be used in process control, image analysis, modeling and simulation and sound processing (Quinones, Viana, Ochoa, , & and 2017; Raj, Rahman, & Anand 2016; Sardiñas-Fernández, García-Juárez, Zaldívar-Huerta, & Abril-García 2020; Wu et al. 2020). In this paper, App Designer was used to develop an app which can be used to perform preliminary design of a shell and tube heat exchanger and to optimize the preliminary design. This app enables the user to manually enter the thermophysical properties of fluids, the mass flow of a fluid of interest, the inlet and outlet temperatures, and to select values of different construction parameters. On the basis of those values, the app calculates important heat exchanger parameters (surface area, pressure drops, mean logarithm temperature difference, overall heat transfer coefficient, number of tubes). The app can be also used to optimize the preliminary design, regarding surface area for heat exchange, but this will be explained in the following sections.

2. MATERIAL AND METHODS

The mentioned app was developed in MATLAB (The MathWorks Inc., License Number 1108951) by means of the App Designer feature. In order to obtain a proper optimal design, it was necessary to perform two-parameter curve fitting. For this procedure, MATLAB *Curve fitting toolbox* was used, where the data was fitted to a custom equation. In order to obtain this data (friction factor and heat transfer factor as a function of baffle cut and Reynolds number), the images of corresponding diagrams were analyzed by means of a free online software called WebPlotDigitizer – a Web-based tool for extraction of data from

plots, images, and maps. The Kern method was used to determine a preliminary design of a shell and tube heat exchanger.

3. RESULTS AND DISCUSSION

3.1. Shell – side heat transfer factor and shell – side friction factor

In order to calculate the overall heat transfer coefficient, it is necessary to calculate shell- and tube- side heat transfer coefficients, as well as to know the values of fouling factors and tube's thermal conductivity. Heat transfer coefficients on both sides of a tube can be calculated from the following equation:

$$Nu = j_h \cdot \mathrm{Re} \cdot \mathrm{Pr}^{1/3} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14} \qquad (1)$$

Where N_u represents Nusselt number, R_e – Reynolds number, P_r – Prandtl number, μ and μ_w are the fluid's viscosities at the mean fluid temperature and at the wall temperature, respectively, and j_h is the heat transfer factor. This factor is a function of Reynolds number and L/do ratio (for tube-side heat transfer, where L represents the length of a tube, and do represents the outer diameter of a tube) and it is a function of Reynolds number and baffle cut (for shell-side heat transfer). For tube-side heat transfer, correlations can be easily found in the literature (Đorđević et al. 2018), while in the case of shell-side heat transfer, correlations can only be found for 15, 25, 35 and 45% baffle cut. A graphical representation of these correlations can be found in Chemical Engineering Design, Section 12, page 673 (here referred to as Graph 1) (Sinnott 2005). Since baffle cut can have different values from those previously stated, it was necessary to obtain a unified correlation of the heat transfer factor as a function of Reynolds number and baffle cut. Graph 1 was analyzed in order to obtain data, and two-parameter curve fitting was performed. Since all correlations for individual baffle cut percentages are in the form of:

$$j_h = a \cdot \mathrm{Re}^b \qquad (2)$$

in order to obtain an overall correlation, a similar form was proposed:

$$j_h = a \cdot \mathrm{Re}^b \cdot BC^c \qquad (3)$$

where BC represents baffle cut value (this equation should be used for baffle cut values from 0.15 to 0.45). The data was separated into two groups, one for the Reynolds number higher than 300 and one for the Reynolds number lower than 300. The fitting results are shown in Table 1.

Table 1. Fitting results for heat transfer factor unified correlation.

	Re<300	Re>300
a	0.4889	0.2842
b	-0.5813	-0.4753
c	-0.2856	-0.3139
R^2	0.9997	0.9994

The same procedure was implemented for the shell-side friction factor. Shell-side pressure drop can be calculated from the following equation:

$$\Delta P_s = 8 \cdot j_f \cdot \left(\frac{D_s}{d_e}\right) \cdot \left(\frac{L}{l_B}\right) \cdot \frac{\rho \cdot u_s^2}{2} \cdot \left(\frac{\mu}{\mu_w}\right)^{-0.14} \quad (4)$$

where D_s represents shell diameter, d_e – equivalent diameter, L – tube length, l_b – baffle spacing, ρ – fluid density, u_s – fluid mean velocity, and j_f – a dimensionless friction factor, which is a function of Reynolds number and baffle cut. In the literature, correlations can be only found for baffle cut percentages of 15, 25, 35 and 45. A graphical representation of these correlations can be found in Chemical Engineering Design, Section 12, page 674 (hereby referred to as Graph 2) (Sinnott 2005). Since baffle cut can have different values those previously stated, it was necessary to obtain a unified correlation of friction factor as a function of Reynolds number and baffle cut.

Graph 2 was analyzed in order to obtain data, and two-parameter curve fitting was performed. Since all correlations for individual baffle cut percentages are in the form of:

$$j_f = a \cdot \mathrm{Re}^b \quad (5)$$

in order to obtain an overall correlation, a similar form was proposed:

$$j_f = a \cdot \mathrm{Re}^b \cdot BC^c \quad (6)$$

where BC represents baffle cut value (this equation should be used for baffle cut values from 0.15 to 0.45). In order to obtain more accurate results, the data was separated into three groups according to different boundary values of the Reynolds number. The fitting results are shown in Table 2.

Table 2. Fitting results for friction factor unified correlation.

	Re<300	300<Re<2000	Re>2000
A	9.0140	0.1582	0.0995
B	-0.9712	-0.2259	-0.1649
C	-0.7150	-0.5969	-0.6210
R2	0.9990	0.9876	0.9931

3.2. Application design and results

This application consists of two tabs, one of which is used for manual design and the other for optimization. The layout of the first tab (*Manual design* tab) is shown in Figure 1.

This app is designed for problems where mass flow value of one fluid (fluid of interest – Fluid 1) is known, and that value should be typed in the field *Mass flow of fluid 1*. The inlet and outlet temperatures as well as thermophysical properties of the fluids can be defined in *Temperature* panel and *Fluid properties at mean temperature* panel, respectively. Next, the user should decide which fluid flows through the tubes, by entering a fluid number into the field labeled *Tube-side fluid*. In the *Tubes* panel, the user can manually define the construction of tube bundle (the outer and inner diameter of a tube, tube length, tube thermal conductivity, tube arrangement, and head type). Under the *Shell* panel, the user should type in the baffle cut value, and select the baffle spacing (baffle spacing D_c or l_b is usually given in respect to the shell diameter – D_s; in that way, the inserted number shows how many times the shell diameter is larger than the baffle spacing). Table 1 provides information about expected overall heat transfer coefficient values for different systems, which was obtained from *Chemical Engineering Design*, Section 12, page 637 (Sinnott 2005). In addition, Table 2 provides information about expected fouling factor values for different fluids, which was also obtained from *Chemical Engineering Design*, Section 12, page 640 (Sinnott 2005). The user can specify if shell-side and tube-side numbers of passes are set manually in the Set number of passes manually panel. Calculation is performed by clicking on the *Calculate* button and the results are displayed in the fields below. The results include heat transfer area, heat transfer coefficient, mean temperature difference, number of tubes, shell and bundle diameter, tube-side and shell-side numbers of passes, tube-side and shell-side pressure drops and baffle spacing. The Question marks button next to a certain option or a field gives the user additional information and tips when selecting a parameter value. The layout of the second tab (*Optimization* tab) is shown in Figure 2.

In order to optimize the preliminary design of our heat exchanger, the user needs to click on the button *Optimize*. The optimization procedure consists of a simple combination of different values of exchanger parameters, i.e., selected parameters obtain different values in each set of calculation, all results are saved, and the combination which results in a minimal heat transfer area (with pressure drop requirements met), represents the optimal design. The variable parameters are the following: outer diameter of a tube (three values – the current i.e. manually selected value, the first larger value and the first
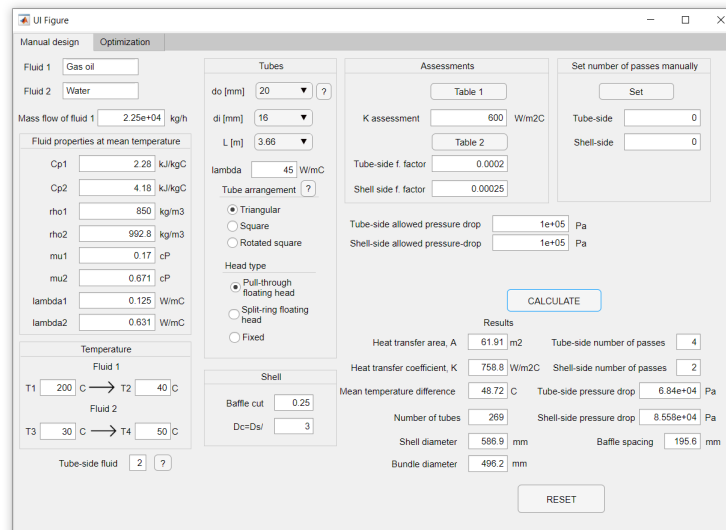
Figure 1. Manual design application tab.

smaller value), inner diameter of a tube (all available inner diameters for a given outside diameter), tube length (three values – the current i.e. manually selected value, the first larger value and the first smaller value), tube arrangement (all three tube arrangements are varied), baffle cut (values from 0.15 to 0.45 with a 0.01 step) and baffle spacing (seven values – manually selected value of D_s/D_c ratio, three larger ratio values and three smaller ratio values – the starting ratio was increased and decreased by 0.5, 1.0 and 1.5). This gives a total of 23436 combinations. All results are saved and the one with minimal heat transfer area and suitable pressure drop is displayed in the fields placed below the *Optimization* button. Also, all results are saved as an Excel file in the current MATLAB directory. For a selected outer diameter, inner diameter, tube length and tube arrangement, by clicking on a *Plot* button, three dependencies are displayed: heat transfer area as a function of baffle spacing and baffle cut (*Surface plot*), tube-side pressure drop as a function of baffle cut and baffle spacing (*Tube-side pressure drop plot*) and shell-side pressure drop as a function of baffle cut and baffle spacing (*Shell-side pressure drop plot*). To test the validity of our code and application, one example for design calculation was used. This example is given in the book *Chemical Engineering Design*, Section 12.9.3, Example 12.2 (Sinnott 2005). The problem involves cooling of gas oil from 200°C to 40°C with water, which enters the exchanger at 30°C and leaves at 50°C. The mass flow of oil is 22500 kg/h. To illustrate the manual design method, the following parameters were used: tube outer diameter of 20 mm, tube inner diameter of 16 mm, tube length of 3.66 m, triangle tube arrangement with a pull-through floating head, baffle cut of 25% and D_s/D_c ratio of 3. For

the same example, the optimization procedure was performed and the results are shown in Table 3.

Table 3. Results of a manual preliminary design calculation and optimization procedure

	Manual calculation	Optimization
A, m^2	61.91	53.27
K, $W \cdot m^{-2} \cdot K^{-1}$	758.8	878.4
ΔT_m, °C	48.72	48.72
N_t	269	434
D_s, mm	586.9	582.0
D_b, mm	496.2	489.4
n_t	4	4
n_s	2	2
ΔP_t, Pa	44150	68400
ΔP_s, Pa	85580	95850
l_b, mm	195.6	194
Tube arrangement	Triangular	Triangular
Baffle cut, %	0.25	0.17
L, m	3.66	2.44
d_o, mm	20	16
d_i, mm	16	13

In the previous table, N_t stands for number of tubes, D_b for bundle diameter, n_t and n_s for number of passes on tube-side and shell-side, respectively, and ΔP_t and ΔP_s stand for pressure drop on tube-side and shell-side, respectively. All calculations were performed for tube pitch of $1.25d_o$. The wall temperature viscosity correction factor $(mu/mu_w)^{-0.14}$ was neglected in all calculations, which is a common procedure in preliminary design. Time consumption for the optimization process was approximately
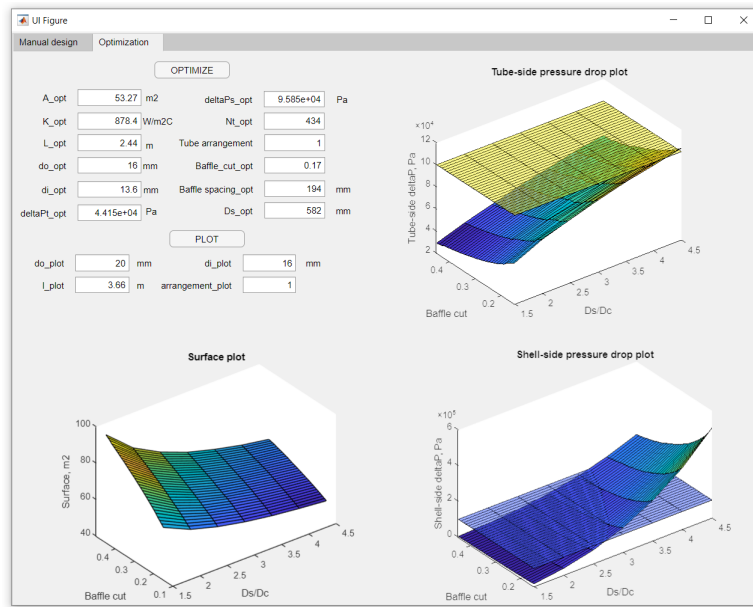
Figure 2. Optimization application tab.

5 seconds (23436 combinations). As it was previously stated, this app has an option of plotting heat transfer area and pressure drops as a function of baffle spacing and baffle cut value. As an example, the following construction parameter values were used: tube outside diameter of 20 mm, tube inside diameter of 16 mm, tube length of 3.66 m and triangular tube arrangement.
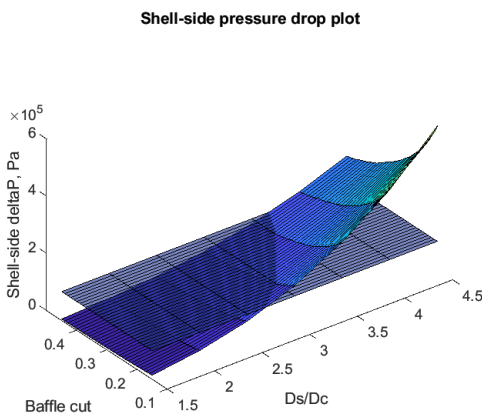

Figure 3. Shell-side pressure drop plot.

Transparent surface plots on pressure drop diagrams represent the allowed pressure drop in the corresponding part of a heat exchanger (transparent-yellow for tube-side allowed pressure drop and transparent-blue for shell-side allowed pressure drop).

Figure 4. Tube-side pressure drop plot.

Figure 5. Heat transfer area plot.

4. CONCLUSIONS

Designing a shell and tube heat exchanger is a complex and time consuming procedure. Since shell and tube heat exchangers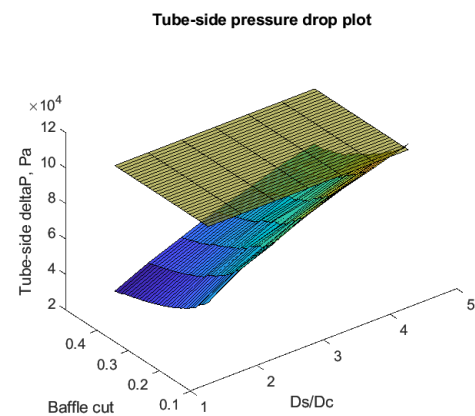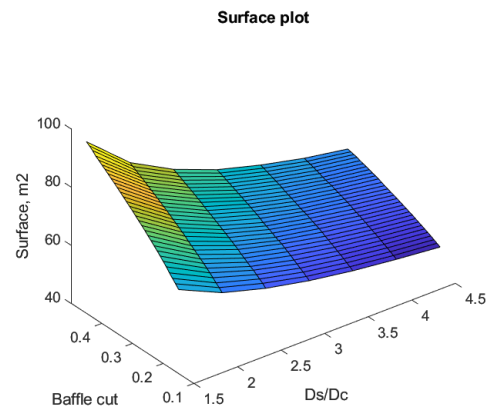 are one of the most common process units, great effort should be made to improve their design. In this paper, a new MATLAB application was presented,

which can be used to perform a preliminary design calculation of a shell and tube heat exchanger, and to optimize that preliminary design, as regards finding the minimal heat transfer area required to meet the process requirements. One example from the literature was selected, which was used to test the validity of our app and our code. The next step in the development of this app will be implementing economic analysis i.e., the cost optimization of the heat exchanger. This app was proven to be fast, useful, and user-friendly. Even though it only covers the preliminary design, it can be a useful tool for chemical engineers, since it can provide the close-to-optimal design parameters very quickly. This type of application can be used in many different areas of chemical engineering, but so far there have not been many publications regarding its applicability in this area. Great effort could and should be made, therefore, to present this tool to chemical engineers, in order to improve their efficiency in everyday tasks.

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