CONFIGURATION DESIGN FOR PLATE HEAT EXCHANGERS AND PASTEURIZERS: MATHEMATICAL MODELING AND OPTIMIZATION METHODS

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Abstract

The configuration of a plate heat exchanger comprises its number of plates, pass arrangement, location of the inlet and outlet connections and type of channel flow. The effective optimization of the configuration is a complex task since it is not possible to represent the mathematical model of the exchanger explicitly in the configuration elements. To overcome this limitation, the configuration is characterized by a set of six parameters and the model is developed in algorithmic form. The solution of the model provides the temperature profiles in all channels, pressure drops and distribution of the overall heat transfer coefficient along the exchanger. A simplified form of the model is tested and applied to the problem of configuration optimization for minimizing the operational and capital costs subject to constraints on the exchanger size and thermal and hydraulic performances. Specialized search procedures were developed, namely screening and branching, to obtain the optimal solution(s) with a very reduced number of exchanger evaluations. The screening was developed for the case of a single section exchanger, whereas the branching simultaneously optimizes the configurations of the regeneration, heating and cooling sections of the plate heat exchanger of a pasteurization unit.

Keywords

Plate Heat Exchanger, Pasteurization, Mathematical Modeling, Optimization, Design.

Introduction

Plate heat exchangers (PHEs) are widely used in dairy and food processing plants, chemical industries, power plants and central cooling systems (see Figure 1). Their design is very flexible; several flow patterns are possible depending on the configuration, which comprises the number of plates, pass arrangement, location of the inlet and outlet connections and type of channel flow. Moreover, in pasteurization units there may be multiple PHE sections, which can be configured independently in principle.

Due to the large number of possible configurations and variety of commercial plates, the design of PHEs is highly specialized. Manufacturers developed in-house design methods and, despite the large number of applications, rigorous design methods are not easily available in the literature, as are those for tubular exchangers. The available methods (Shah and Focke, 1988; Zaleski and Klepacka, 1992; Wang and Sundén, 2003) often have configuration limitations or rely on simplified forms of the thermal-hydraulic model, which limits their applicability.

The objective of this work is the development of a simulation model for generalized configurations and optimization methods for configuring the PHE targeting minimal capital and operational costs for single and multiple sections. This paper summarizes the results of

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several years of research on the configuration optimization of PHEs conducted at the University the São Paulo.

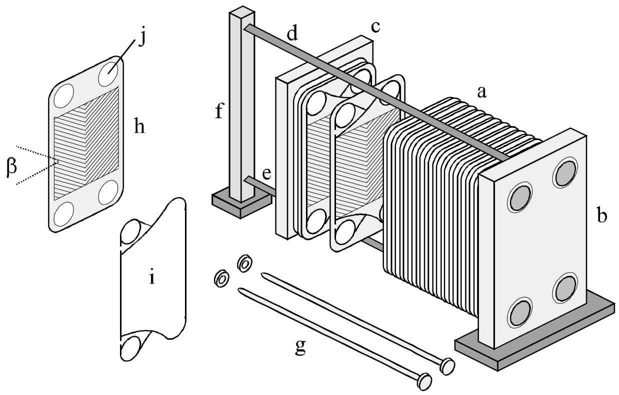

Figure 1. The PHE assemblage and parts: a) opened plate pack, b) fixed cover, c) moveable cover, d) upper carrying bar, e) lower carrying bar, f) support column, g) tightening bolts, h) corrugated plate, i) gasket, j) port

Configuration Characterization

The configuration of a PHE (or a section of a multisection PHE) is characterized by a set of six parameters: N_C is the number of channels; P^I and P^{II} are the number of passes at sides I and II respectively (side I: odd-numbered channels, side II: even-numbered channels); ϕ represents the feed connection relative location (see Figure 2); Y_h indicates the hot fluid location ($Y_h = 1$ if hot fluid at side I and $Y_h = 0$ otherwise); and Y_f indicates the type of channel flow ($Y_f = 1$ for diagonal channel flow and $Y_f = 0$ for vertical flow).

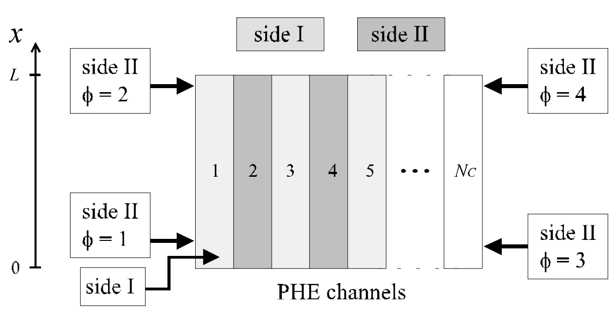

Figure 2. Definition for parameter ϕ

There may be equivalent configurations in terms of thermal and hydraulic performances and the identification of such configurations is important to avoid redundant evaluations when optimizing the PHE configuration. A methodology for the identification of equivalent configurations is presented by Gut and Pinto (2003a).

Mathematical Modeling

The PHE modeling assumes 1) steady state operation, 2) no heat losses, 3) no phase-changes, 4) plug-flow inside channels and 5) uniform flow distribution. Under these assumptions, the energy balance for the fluid inside an arbitrary channel i (see Figure 3) yields Eq.(1).

$$\frac{dT_i}{dx} = \frac{s_i w \Phi U_{i-1}}{C_i}\left(T_{i-1} - T_i\right) + \frac{s_i w \Phi U_i}{C_i}\left(T_{i+1} - T_i\right) \tag{1}$$

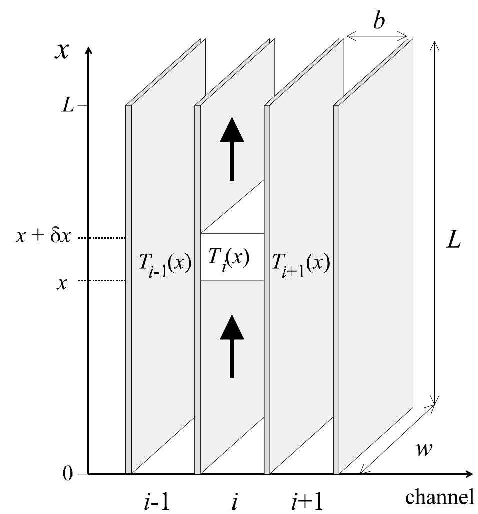

Figure 3. Control volume for derivation of energy balance in upward flow channel

In Eq.(1), T_i is the temperature inside channel i, x is the coordinate shown in Figure 3 (where L is the effective plate length and b is the mean channel gap), w is the effective plate width, Φ is the area enlargement factor, C_i is the channel heat capacity, U_i is the overall heat transfer coefficient between channels i and i+1 and $s_i = +1$ if the flow in channel i follows the direction of x or $s_i = -1$ otherwise. For obtaining U_i, correlations for the convective heat transfer inside the channels and fluid thermophysical properties are required (Raju and Bansal, 1983; Saunders, 1988). If the fluids present non-Newtonian behavior, generalized correlations for the power-law rheological model are available (Delplace and Leuliet, 1995).

While the pressure drop at sides I and II can be calculated with a simple algebraic correlation (Shah and Focke, 1988), the calculation of the outlet temperatures requires the solution of a non-linear system of differential (see Eq.(1)) and algebraic equations. This system can be reduced to a linear system of ordinary differential equations by assuming constant overall heat transfer coefficient, U. Gut and Pinto (2003a) verified that this assumption simplifies largely the thermal model and shows little influence over the main simulation results. Thus, this simplified model was selected for the solution of the configuration optimization problems further described.

Model Simulation and Validation

Associated with Eq.(1) is a boundary condition for the temperature in channel *i*, which, along with variables like s_i, depends on the PHE configuration. It was verified that it is not possible to derive a mathematical model that is explicitly a function of the configuration parameters. To overcome this limitation, the mathematical model of the PHE for generalized configurations was developed in the form of an "assembling algorithm" (Gut and Pinto, 2003a). For a given set of configuration parameters, plate specifications and process conditions, the algorithm builds and solves the associated system of equations using analytical or numerical methods. The main simulation results are the outlet temperatures, thermal effectiveness and pressure drops.

The simplified thermal model was experimentally validated using a FT-43 PHE (Armfield, Ringwood, UK) with 12 different configurations. When fitting the model for generalized configurations to experimental data, a certain lack of fit was obtained (see Figure 3) since the model does not account for flow maldistribution inside the PHE. This issue is not verified when fitting data obtained from a single configuration, as is frequently made (Kim et al., 1999; Muley et al., 1999), because the variation in flow distribution among runs is insignificant. It was verified that the estimated model parameters are associated with the configuration(s) experimentally tested and the corresponding flow distribution pattern(s). Consequently, consistent parameters or correlations for the heat transfer must be used when sizing or configuring a PHE.

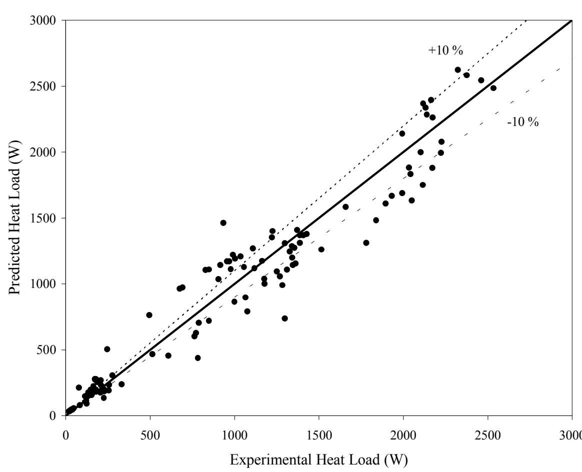

Figure 3. Predicted vs. Experimental heat loads for model fitting

Configuration Optimization

The Screening Method

The configuration optimization problem is formulated as the minimization of the operational and capital costs of the PHE, subject to constraints on the number of channels, pressure drops, velocities and thermal effectiveness. Because of the algorithmic form of the PHE thermal-hydraulic model, it is not possible to use mixed-integer non-linear programming (MINLP) techniques to solve the problem.

Since the optimization variables, N_C, P^I, P^{II}, ϕ, Y_h and Y_f, are discrete, an exhaustive enumeration procedure would locate the optimal solution(s). However, this procedure would demand a large computational time. Instead, a specialized search procedure is proposed to obtain the feasible region of the problem and locate the optimal solution(s). In this "screening method", the constraints are successively applied to eliminate infeasible solutions (and also sub-optimal feasible solutions when minimizing the number of channels) with a very reduced number of exchanger evaluations. Examples show that the screening method demands only 5% of the pressure-drop/velocity calculations and 1% of the thermal simulations that those required in an exhaustive enumeration. Moreover, it locates all the optimal solutions instead of a single optimum. The algorithm for the method is presented by Gut and Pinto (2004) with a detailed optimization example.

The Branching Method

PHEs used for pasteurization processes contains at least three heat exchange sections mounted in the same frame: heating, cooling and regeneration. The configuration of each section could be, a priori, independently optimized using the screening method. However, this would generate a poor solution because unrealistic assumptions regarding the process integration would be required. Therefore, it is desired to optimize the three sections simultaneously targeting minimal annual pasteurization costs.

The optimization variables are the configuration parameters of the three sections and the constraints can be arranged in three groups: 1) thermal performance constraints, regarding the safety of the product and the regeneration of heat, 2) hydraulic performance constraints, regarding fouling and pressure drop, and 3) design constraints, regarding the physical connection among sections.

In Figure 4, the cumulative number of possible configurations is related to the maximum number of plates supported by the PHE. It is clear that the dimension of the optimization problem for the three-section PHE is much larger than that of a single section.

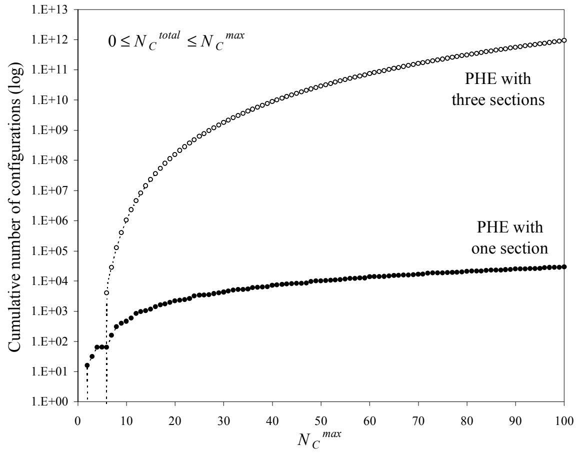

Figure 4. Cumulative number of configurations for different problems

A branching procedure is proposed to solve the optimization problem. As in the screening method, constraints are successively applied to eliminate infeasible elements until the feasible region is obtained; however, the search strategy is different. The main optimization variables are organized as the tree structure shown in Figure 5, where the superscripts *R*, *H* and *C* stand for regeneration, heating and cooling sections, respectively.

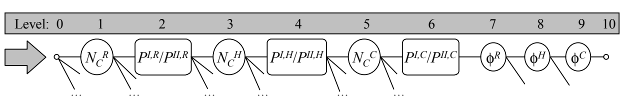

Figure 5. Tree structure for the branching

Starting from the lowest level of the tree, a node is generated in the following level only if a certain set of constraints is satisfied, respecting the bounds on the optimization variables. The enumeration of the tree (with a "depth first" strategy) by the branching method obtains the feasible region of the problem with a very reduced number of section evaluations. The objective function is then used for ordering the elements, thus locating all optima and also the near-optimal solutions.

The algorithm for the method is presented by Gut and Pinto (2003b) with an example of optimization for a HTST (high temperature short time) pasteurization of milk. In this example, the number of possible configurations is $4.55 \cdot 10^{12}$. Nevertheless, only 177,560 pressure-drop/velocity calculations and 154 thermal simulations were required for obtaining the optimal solution. Moreover, inspection of the near-optimal solutions revealed one configuration with assemblage advantages unavailable in the optimal solution.

Conclusions

The configuration of a PHE is represented by a set of six parameters and a mathematical model for generalized configurations was developed in algorithmic form. This model automatizes the simulation of different configurations and thus can be used for optimizing the PHE configuration targeting minimal operational and capital costs. The screening method is proposed for this task. This method is a specialized search procedure that obtains the feasible region of the problem and locates all optimal and near-optimal solutions. For the case of a PHE with three sections used for pasteurization, a branching method is proposed for the simultaneous optimization of the sections. Both optimization methods require a very reduced number of exchanger evaluations in comparison with an exhaustive enumeration procedure.

Acknowledgments

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