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Optimal Design of Continuous Sterilization Processes with Plate Heat Exchangers

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Abstract

An optimization procedure is presented for configuration design of the plate heat exchanger sections of a plate pasteurizer subject to constraints on the equipment performance and operational limitations. The process mathematical model is presented for evaluating the unit thermo-hydraulic performance. Moreover, the extent of thermal processing inside the exchanger is determined. Both pasteurization costs and product thermal degradation are minimized using a structured search procedure that overcomes the limitations of representing the problem as a MINLP model. An example is presented for the design of a beer pasteurization unit.

Keywords: optimization, pasteurization, food processing, plate heat exchanger, design.

1. Introduction

The thermal processing of liquid foods targets the inactivation of harmful microorganisms and undesired enzymes that compromise food safety and product shelf life. Process conditions must be carefully selected so that the desired level of sterility is achieved with minimal deterioration of product quality. PHEs (plate heat exchangers) are widely employed for continuous pasteurization or sterilization because of their high thermal effectiveness, good fluid distribution and ease of sanitation.

Such thermal processing is commonly applied to liquid foods such as milk, fruit juices, liquid egg, purees or beer. The process involves four basic stages: heating, holding, heat regeneration and cooling. Design specifications assume that the thermal inactivation occurs exclusively at the holding stage under constant temperature. This conservative approach can lead to significant over-processing of the food product, resulting in unnecessary deterioration of its sensorial and nutritional quality.

Model-based optimization methods present potential for improving food processing through comprehensive process design. Modeling of a continuous sterilization process is non-trivial since it combines the thermo-hydraulic representation of the equipment with the thermal inactivation and quality deterioration kinetics. Moreover, liquid foods often present non-Newtonian behavior and are thermo-sensitive.

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In this work, an optimization technique is proposed for minimizing both the process costs and the thermal deterioration that takes place inside the PHE. The mathematical model of the plate pasteurizer is presented and the configuration of the PHE is characterized by a set of integer parameters, which are optimized subject to constraints on the equipment performance and operational limitations. A structured search procedure is proposed that overcomes the limitations of representing the optimization problem as a mixed integer non-linear programming (MINLP) problem.

2. Pasteurizer Model

2.1 Configuration characterization

A plate pasteurizer unit comprises basically the regeneration, heating and cooling sections of the PHE (assembled in the same frame using connector plates), the holding tube, the product pump and the heating and cooling circuits, as in Figure 1a. In principle, each section of the PHE can be configured independently. For characterizing the configuration of a PHE, six parameters are used: N_C (number of channels), P^I (number of passes at side I, which contains the odd-numbered channels), P^{II} (number of passes at side II, which contains the even-numbered channels), ϕ (determines the feed connection relative location, as in Figure 1b), Y_h ($Y_h = 1$ when the hot fluid is at side I and $Y_h = 0$ otherwise) and Y_f, ($Y_f = 1$ for diagonal flow inside the channels and $Y_f = 0$ for vertical flow, as in Figure 1c). More details presented in Gut and Pinto (2003a, b).

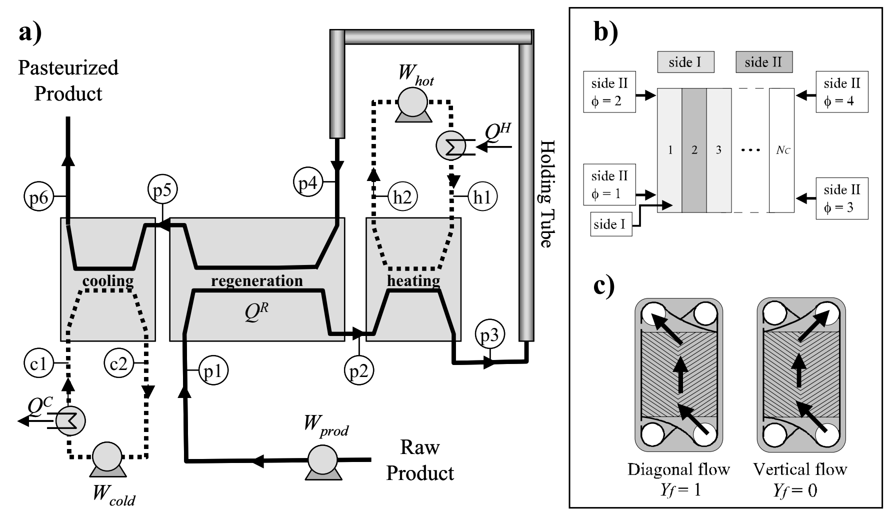

Figure 1. Schematic of a plate pasteurizer and PHE configuration parameters

2.2 Thermal Modeling

The heat loads for the regeneration, heating and cooling sections are defined in Eqs.(1a) to (1c), where C is the average heat capacity of the corresponding path.

$$Q^R = C_{prod}^{p2-p1} \cdot \left(T_{p2} - T_{p1}\right) = C_{prod}^{p4-p5} \cdot \left(T_{p4} - T_{p5}\right) = \varepsilon^R \cdot \min\left(C_{prod}^{p2-p1}, C_{prod}^{p4-p5}\right) \cdot \left(T_{p4} - T_{p1}\right) \quad (1a)$$

$$Q^H = C_{prod}^{p2-p3} \cdot \left(T_{p3} - T_{p2}\right) = C_{heat}^{h1-h2} \cdot \left(T_{h1} - T_{h2}\right) = \varepsilon^H \cdot \min\left(C_{prod}^{p2-p3}, C_{heat}^{h1-h2}\right) \cdot \left(T_{h1} - T_{p2}\right) \quad (1b)$$

$$Q^C = C_{prod}^{p5-p6} \cdot \left(T_{p5} - T_{p6}\right) = C_{cool}^{c1-c2} \cdot \left(T_{c2} - T_{c1}\right) = \varepsilon^C \cdot \min\left(C_{prod}^{p5-p6}, C_{cool}^{c1-c2}\right) \cdot \left(T_{p5} - T_{c1}\right) \quad (1c)$$

In order to solve the system of equations in Eq.(1), the thermal effectiveness of the sections are required (ε^R, ε^H and ε^C). These can be obtained from the steady-state thermal model of the PHE, which is presented by Gut and Pinto (2003b) as a function of the configuration parameters and dimensionless thermal coefficients for sides I and II. Those coefficients can be determined for Newtonian and non-Newtonian fluids (power-law rheological model).

The thermal model solution, carried out by analytical or numerical methods, provides the temperature profiles for the PHE channels and ε. An alternative solution that does not require the solution of the PHE thermal model and provides reasonable accuracy is to assume pure counter-current flow conditions for obtaining ε, as described by Gut and Pinto (2003a).

An important parameter for pasteurization is the heat regeneration ratio, which is defined as $RR = Q^R/(Q^R+Q^H)$. Moreover, a temperature drop is assumed for the holding tube, so that $T_{p4} = T_{p3} - \Delta T_{drop}$.

2.3 Hydraulic Modeling

The pressure drop for either side of a PHE section is determined by Eq.(2), where f is the Fanning friction factor, L_P is the plate vertical length between centers of ports, ρ is the fluid density, D_e is the equivalent channel diameter, W is the mass flow rate, N is the number of channels per pass, $A_{channel}$ is the cross-sectional area for channel flow, A_{port} is the area of the plate orifice and g is the gravitational acceleration. The velocity inside a channel is $v = W/(N \cdot \rho \cdot A_{channel})$. The pressure drop of the product comprises the summation of the pressure drops along the fluid path, including the holding tube (the last term in Eq.(2) is accounted only once).

$$\Delta P = \frac{2 \cdot f \cdot L_P \cdot P \cdot \rho \cdot v^2}{D_e} + 1.4 \cdot \frac{P}{2 \cdot \rho}\left(\frac{W}{A_{port}}\right)^2 + \rho \cdot g \cdot L_P \quad (2)$$

2.4 Heat Treatment Modeling

The integrated lethality, F in Eq.(3), is used for evaluating the level of heat treatment of the process, where τ is the residence time, z is the Z-value for inactivation kinetics and T_{ref} is the reference temperature (Toledo, 1999). The solution of the pasteurizer model provides the temperature profiles inside the channels, which can be used in the second term of Eq.(3) for determining the integrated lethality for each PHE section.

$$F_{T_{ref}} = \int_0^{\tau} 10^{\frac{T(t)-T_{ref}}{z}} dt = \frac{z \cdot \tau}{\left(T_{i+1} - T_i\right) \cdot \ln(10)} \left(10^{\frac{T_{i+1}-T_{ref}}{z}} - 10^{\frac{T_i - T_{ref}}{z}}\right) \quad (3)$$

The integrated form on the right-hand side of Eq.(3) is valid for the assumption of linear temperature change. Hence, T_{p1} to T_{p6} can be used for obtaining the overall integrated lethality $F^{PHE} = F^{p1-p2} + F^{p2-p3} + F^{p4-p5} + F^{p5-p6}$.

For determining the residence time for a side of a PHE section, plug-flow inside the channels is assumed and the vertical and horizontal paths along the plate pack are considered, as in Eq.(4). The effective lengths of the vertical and horizontal paths are defined in Eq.(5a) and (5b), where e is the plate thickness and b is the mean channel gap. In Eq.(5b), $\psi = 0$ for sides I and II when N_C is even, $\psi = +1$ for side II with odd N_C and $\psi = -1$ for side I with odd N_C.

$$\tau = \left(L_{vert} \cdot A_{channel} + L_{horiz} \cdot A_{port}\right) \cdot \left(\rho / W\right) \tag{4}$$

$$L_{vert} = P \cdot N \cdot L_P \tag{5a}$$

$$L_{horiz} = \left[2 \cdot P \cdot (2 \cdot N - 1) + \psi\right] \cdot (e + b) + e \tag{5b}$$

3. Configuration Optimization

The objective of the optimization problem is to simultaneously configure the multiple PHE sections of the plate pasteurizer that minimize both pasteurization costs (described in the next section) and product quality deterioration. The quality goal is the minimization of the heat treatment that occurs inside the PHE, F^{PHE}, which is desired to take place only inside the holding tube.

The problem of cost minimization for multiple section PHEs is presented by Gut and Pinto (2003a), where the optimization constraints are grouped in three categories: design constraints (representing the physical connection among plates and sections), thermal performance constraints (bounds on T_{p4}, T_{p6}, ε^R and RR) and hydraulic performance constraints (bounds on ΔP and v). Moreover, the problem is also subject to the pasteurizer thermo-hydraulic model. The optimization variables are the configuration parameters of each PHE section, which yields a very large number of possible combinations, e.g. $9.2 \cdot 10^{11}$ alternatives for $N_C^{total} \leq 100$.

Since each PHE configuration determines a unique set of thermal and hydraulic boundary conditions, the generalized mathematical model cannot be represented in algebraic form, and consequently it is not possible to use mixed-integer nonlinear programming (MINLP) techniques (Gut and Pinto, 2003b). To overcome this limitation, a branching procedure is proposed, where the optimization variables are arranged on a tree structure and the constraints are applied at each level as criteria for node generation. A structured search algorithm enumerates the feasible region of the problem with a much reduced number of exchanger evaluations (the reduction is of several orders of magnitude in comparison to an exhaustive enumeration procedure). Once the feasible region is obtained through the branching method, quality constraints can be further applied and the optimization criteria are used to select the best candidates and locate all optimal and near-optimal elements, as is shown in the next section.

4. Optimization Example: Beer Pasteurization

The proposed optimization method is applied for the configuration design of a PHE for continuous pasteurization of 3200 L/h of beer. The temperature program was defined according to Dymond (1997) with a required pasteurization effect of 15 P.U.s at 70 ºC, which is equivalent to $F_{70°C} = 32$ s (1 Pasteurization Unit corresponds to $F_{60°C} = 1$ min). The utility streams are: 4500 kg/h hot water at 74 ºC and 5500 kg/h cold water at 2 ºC. Plates are stainless steel, 45º chevron, with main dimensions similar to PHE Quasar Q030 RKS-10 (APV, 2000): $A_{plate} = 0.30$ m²/plate, $e = 0.07$ cm, b = 0.37 cm, D_e

= 0.643 cm, L_P = 72 cm, A_{port} = 78.5 cm^2, $A_{channel}$ = 15.5 cm^2 and Y_f = 1. Holding tube is sanitary 2½" with estimated ΔP_{tube} = 0.1 psi and ΔT_{drop} = 1 ºC.

The Nusselt and friction factor correlations were obtained from Saunders (1988) and fouling factors from Marriott (1971). Thermophysical properties of beer are taken from Telis-Romero et al. (2004) and those of water from Gut and Pinto (2003b). Countercurrent flow was assumed for the PHE thermal model and linear temperature variations are considered for lethality calculation.

The total number of channels must lie in the range $6 \le N_C^{total} \le 140$. The lower bound for channel flow velocity is v^{min} = 0.1 m/s. The minimum thermal effectiveness and heat recovery ratio allowed of the regeneration section are $\varepsilon^{R,min}$ = 80 % and RR^{min} = 0.90, respectively. The process temperature constraints are $70 \le T_{p4}$ and $T_{p6} \le 3$ °C, whereas the pressure drop constraints are as follows: $\Delta P_{beer} \le 35$ psi, $5 \le \Delta P_{heat} \le 17$ psi and $5 \le \Delta P_{cool} \le 20$ psi.

The parcel of the pasteurization cost dependent on the PHE configuration, PC ($/yr), is obtained through Eq.(6), with cost coefficients according to Wang and Sundén (2003). $PP = W \cdot \Delta P/\rho$ is the pumping power (Watts) and Q is the heat load (Watts).

$$PC = 110 \cdot \left(N_C^{total} - 1\right)^{0.85} + 0.17 \cdot \left(PP_{beer} + PP_{heat} + PP_{cool}\right) + 0.13 \cdot \left(Q^H + Q^C\right) \qquad (6)$$

The branching method is used for enumerating the feasible region of the problem, which contains 10750 elements out of a universe of $4.55 \cdot 10^{12}$ defined by the bounds on N_C (number of calculations: $1.8 \cdot 10^5$ for ΔP and $2.4 \cdot 10^4$ for ε). Applying an additional quality constraint, $T_{p4} \le 72.5$ ºC, the number of feasible elements is reduced to 4988, which are shown in Figure 2a. PC and F^{PHE} (T_{ref} = 70 ºC) were calculated for each feasible element and the results are in Figure 2b. The Z-value z = 6.9 ºC for the beer micro-flora presented by Dymond (1997) was used in Eq.(3) for evaluating F^{PHE}.

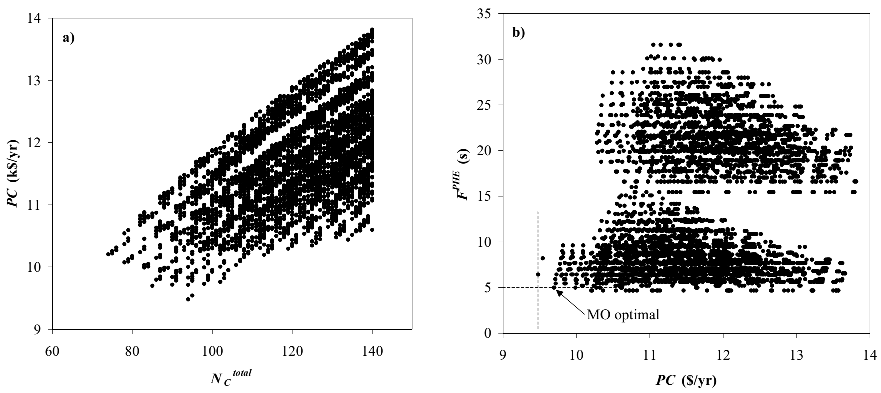

Figure 2. a) Feasible region of the problem, b) Pareto chart for multi-objective optimization

The peculiar shape in Figure 2b is due to the configuration of the heating section. Given the process conditions and constraints, only six numbers of channels are feasible for this section: 5, 6, 7, 16, 17 and 20. The first three yield low F^{PHE} values whereas the last three yield high F^{PHE} values. Since the main contribution to F^{PHE} is from the heating section, this explains the formation of two main regions in Figure 2b.

The optimal element for minimum cost is a single PHE with 94 channels, PC = 9480 \$/yr and F^{PHE} = 6.43 s. However, when minimizing F^{PHE}, multiple optima (40 elements) are obtained with F^{PHE} = 4.67 s and $10203 \leq PC \leq 13571$ \$/yr, as can be seen in Figure 2b. The difference among these elements resides solely on the configuration of the cooling section, which has an insignificant influence on F^{PHE}.

The solutions for lowest cost and lowest integrated lethality are located on the lower left corner of the dispersion in Figure 2b. Since the problem does not have opposing objectives, it is simple to locate a solution near the ideal unfeasible solution of the multi-objective (MO) problem: PC = 9480 \$/yr and F^{PHE} = 4.67 s. This selected solution has 85 channels, PC = 9698 \$/yr and F^{PHE} = 4.98 s. The configurations of the PHE sections are: Regeneration, $N_C = 64$, $P^I = 16$, $P^{II} = 16$, $Y_h = 0$, $\phi = 3$; Heating, $N_C = 5$, $P^I = 3$, $P^{II} = 2$, $Y_h = 0$, $\phi = 4$; Cooling: $N_C = 16$, $P^I = 2$, $P^{II} = 4$, $Y_h = 1$, $\phi = 4$. With this improved design, the length of the holding tube can be reduced by 15 % if the lethality inside the PHE is accounted for.

5. Conclusions

A branching optimization technique was presented for the configuration design of the PHE sections of a plate pasteurizer. A structured search procedure enumerates the feasible region with a very reduced number of process evaluations and locates all optimal and near-optimal solutions according criteria on process costs and/or product quality. For further design of the holding tube, the model presented by Jung and Fryer (1999) can be applied for non-Newtonian laminar flow, since it takes into account the radial lethality distribution.

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