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HTST Milk Processing: Evaluating the Thermal Lethality inside Plate Heat Exchangers

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Abstract: In the design of HTST processes, the lethality inside the plate heat exchanger and the heat loss at the holding tube are usually neglected. Thus, the thermal processing becomes more intensive than required and nutrient and sensorial losses may occur. In this work, the overall thermal lethality in milk pasteurization is evaluated by taking into account the lethality throughout the exchanger and the results are compared with the case that considers the lethality for the holding tube only.

Keywords: milk pasteurization, thermal lethality, plate heat exchangers, food process modeling.

1.Introduction

Plate heat exchangers (PHEs) are extensively used in the dairy industry for HTST (high temperature short time) pasteurization due to their excellent thermal characteristics, good flow distribution and flexibility for cleaning in place, disassembling and resizing. Usually the pasteurization process is designed by assuming that the thermal inactivation occurs exclusively inside the holding tube at constant pasteurization temperature. By neglecting the thermal inactivation that occurs inside the PHE and the temperature drop for the holding tube, the length of the tube may be overestimated and nutrient and sensorial losses may occur in practice. With the use of PHE simulation it is possible to obtain the temperature profiles in all of its channels and to further determine the extent of thermal inactivation throughout the pasteurizer. Moreover, the simulation results can be used to design more efficiently the pasteurization equipment so to ensure the inactivation of harmful microorganisms while preserving food nutrients and sensorial characteristics.

Since consumer demand for food products with lower costs, high quality and nutritive value is increasing, much research has been carried out to optimize the quality and safety of many processes, such as UHT (ultra high temperature) and HTST continuous processing of liquid foods [1]. Jung and Fryer [2] simulated the sterilization of liquid food products in tubular heat exchangers and concluded that the common safety margin used in the food industry leads to significant over-processing and unnecessary losses in product quality. Moreover, Grijspeerdt *et al.* [3] analyzed three commercial UHT milk treatment systems and verified through process simulation that they were over-designed with respect to bacterial inactivation.

In this work, the overall thermal lethality in milk pasteurization processing is evaluated taking also into account the lethality throughout the PHE and the results are compared with the lethality for the isothermal holding tube only. A rigorous

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thermal model of the PHE is applied for obtaining the temperature profiles along its channels.

2. Mathematical Modeling of the Pasteurization Process

The fundamental structure of the pasteurizer comprises the PHE, which is divided in three or more heat exchange sections, the heating and cooling circuits and the holding tube, as shown in the example of Figure 1.

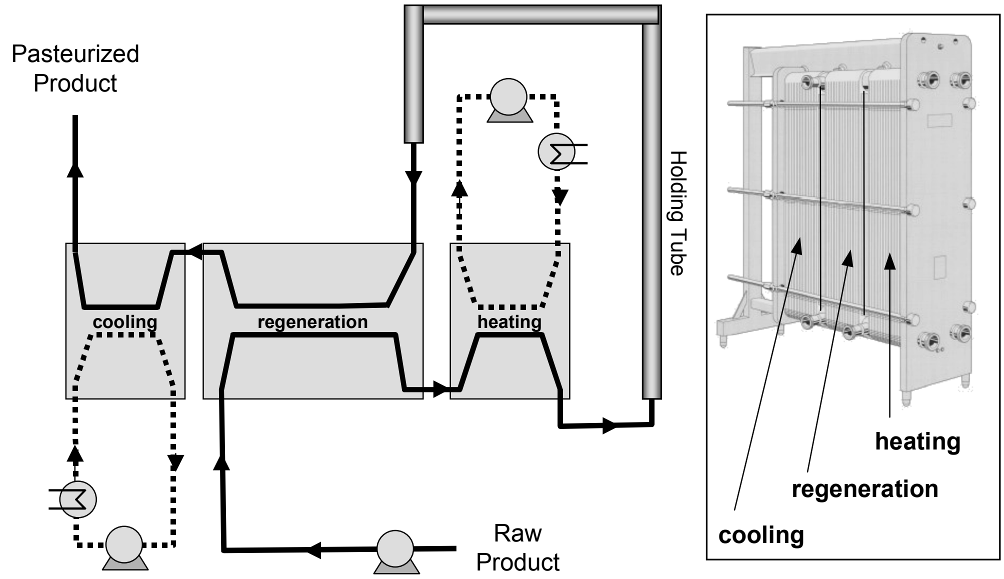

Figure 1: Schematic of the pasteurization unit and of the sections of the PHE.

The PHE model for generalized configurations presented by Gut and Pinto [4] is used to generate the temperature profiles in all the PHE channels. The model was developed for a single-section PHE assuming steady-state operation, no heat losses, constant overall heat transfer coefficient throughout the exchanger, one-dimensional incompressible plug-flow, no heat transfer in the direction of flow, uniform flow distribution through the channels of a pass, perfect mixture at the end of a pass and no phase-changes. Since the pasteurizer contains various sections, the model is first used to represent each section separately before generating the complete model of the pasteurizer. A section of the PHE is represented by a sequence of channels, numbered from 1 to the corresponding number of channels (N_C).

Based on the aforementioned assumptions, the energy balance applied to an arbitrary channel i of a section of the PHE yields eq.(1), where $T_i(x)$ is the temperature of the fluid inside channel i; x is the coordinate tangential to channel flow ($0 \le x \le L$); s_i indicates the direction of the flow inside channel i ($s_i = +1$ is the flow follows the x direction and $s_i = -1$ otherwise); U is the mean overall heat transfer coefficient (defined in eq.(2)); w is the channel width; Φ is the plate area enlargement factor; W_i is the mass flow rate inside channel i (obtained by dividing the flow rate by the corresponding number of channels per pass, N); and Cp_i is the specific heat of the fluid in channel i.

$$\frac{dT_i}{dx} = \frac{s_i \cdot U \cdot w \cdot \Phi}{W_i \cdot Cp_i} \cdot \left(T_{i-1} - 2 \cdot T_i + T_{i+1}\right) \quad , \qquad 1 \le i \le N_C \tag{1}$$

$$\frac{1}{U}=\frac{1}{h_{hot}}+\frac{1}{h_{cold}}+\frac{e_{plate}}{\lambda_{plate}}+R_{hot}+R_{cold} \tag{2}$$

Heat transfer correlations, such as $Nu=a\cdot Re^b\cdot Pr^c$, are required for obtaining the convective heat transfer coefficients inside the channels (h_{hot} and h_{cold}). Usual values for the empirical parameters *a*, *b* and *c* are supplied in the works of Shah and Focke [5] and Saunders [6]. If the fluid has non-Newtonian behavior, *Re* and *Pr* should be calculated using suitable generalized forms, such as the ones suggested by Gut and Pinto [4] for the power-law rheological model.

Boundary conditions for the temperatures of the channels are required in order to solve the system of differential equations generated from eq.(1). The boundary conditions represent the physical connection among the channels and passes. The three possible forms of boundary conditions are presented in Table 1.

Table 1: Thermal boundary conditions for the PHE modeling

Boundary Condition	Equation Form
Fluid inlet: the temperature at the entrance of the first pass is the same as the stream inlet temperature.	$T_i\big\|_{x=0 \text{ or } L}=T_{inlet} \quad , \quad i\in$ first pass
Change of pass: there is a perfect mixture of the fluid leaving the channels of a pass, before entering the next one.	$T_i\big\|_{x=0 \text{ or } L}=\frac{1}{N}\sum_{j\in \text{previous pass}}^{N} T_j\big\|_{x=0 \text{ or } L} \quad , \quad i\in$ current pass
Fluid outlet: the stream outlet temperature results from a perfect mixture of the fluid leaving the last pass.	$T_{outlet}=\frac{1}{N}\sum_{j\in \text{last pass}}^{N} T_j\big\|_{x=0 \text{ or } L}$

The mathematical modeling of the pasteurizer consists of the thermal modeling of the PHE sections, the boundary conditions that represent the connection among sections, the assumed temperature drop for the holding tube and the specifications for mass flow rates and inlet temperatures of the product, heating and cooling streams [7]. The model consists of a system of first order linear ordinary differential equations and algebraic equations, which can be solved by analytical or numerical methods, such as the method of finite differences. The main result is the product temperature profile inside the pasteurizer.

The integrated lethality or F-value, denoted by *F* in eq.(3), is employed for evaluating the level of heat treatment of the process [8]. The F-value can be considered to be the holding time at a given reference temperature T_{ref} (assuming instant heating and cooling) to which the whole process is equivalent, thus it can be used to compare different processes [9]. In eq.(3), *z* is the Z-value for the inactivation kinetics (defined as the temperature change required to change the D-value by a factor of 10, where the D-value is the time required to obtain a 90 % inactivation at constant temperature) and *t* is the time for a batch process or the residence time for a continuous process.

$$F_{T_{ref}}=\int_0^t L_t(\mathrm{t})\,dt=\int_0^t 10^{\frac{T(t)-T_{ref}}{z}}\,dt \tag{3}$$

The temperature profiles in the plate heat exchanger channels and in the holding tube obtained from the pasteurizer model are further used for obtaining the temperature-time distribution of the product in the pasteurizer, $T(t)$, and the F-value is then calculated through eq.(3). In this work, plug flow is assumed in the pasteurizer for the calculations.

Example of Application

The proposed pasteurizer model was applied for the evaluation of a HTST milk pasteurization process. The number of channels and pass-arrangement of the three PHE sections, as well as the inlet conditions of the streams are presented in Table 2. The main dimensions of the PHE are similar those of the exchanger Q030 RKS-10 [10] and the heat transfer and friction factor correlation supplied by Sauders [6] for chevron plates with corrugation inclination angle of 45° were used. The holding tube (nominal diameter: 2” sanitary, length: 7.6 m) was sized for a residence time of 16 s at 72 °C in turbulent flow. A temperature drop of 2 °C is assumed for the holding tube, as in Landfeld *et al.* [11].

Table 2: Configuration of the PHE sections and inlet conditions of the streams [7]

Section	N_C	Hot side	Cold side
Regeneration	96	24×2	24×2
Heating	16	4×2	2×4
Cooling	12	3×2	3×2

Inlet	W (kg/h)	T (°C)
Milk (13% t.s.)	3,000	5
Hot Water	4,500	80
Cold Water	5,500	2

An appropriate finite difference method was applied for the solution of the pasteurizer model using the software gPROMS [12]. The obtained temperature profiles inside the PHE channels were used for generating the milk temperature-time distribution shown in Figure 2 (the horizontal flow inside the PHE was neglected because of the small thickness of the plates and channels).

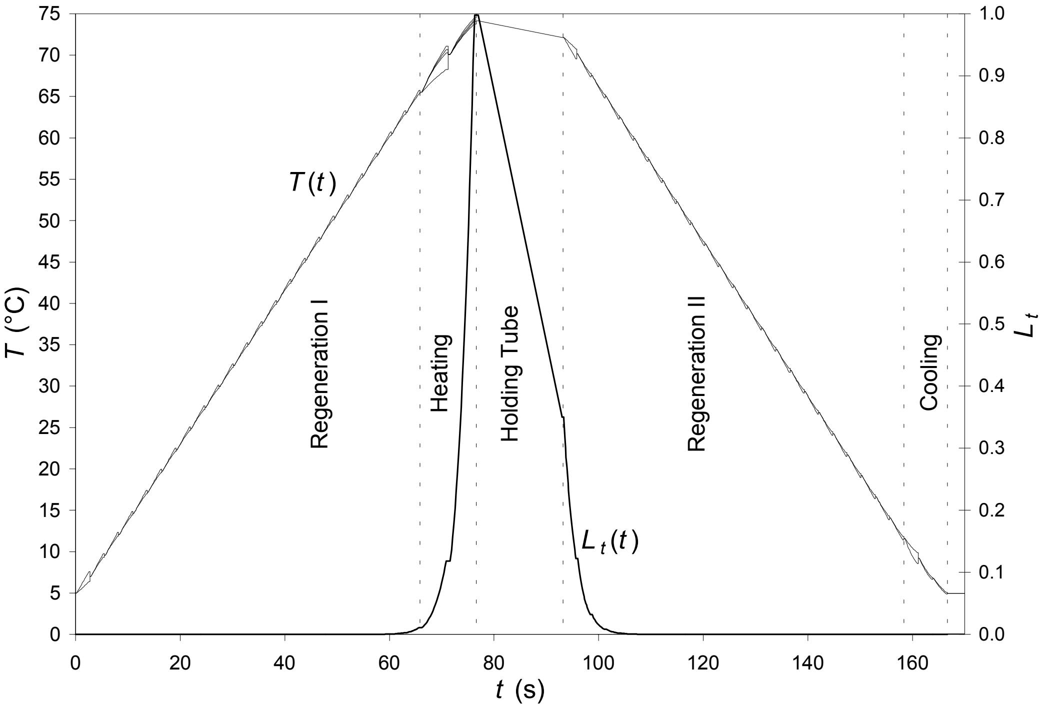

Figure 2: Milk temperature and lethality profiles for the example

The process lethality was evaluated considering the thermal inactivation of *Coxiella burnetti* with z = 4.4 °C [13] and the obtained lethality profile is presented in Figure 2, where the temperature at the entrance of the holding tube is considered as reference, T_{ref} = 74.14 °C. The integrated lethality, obtained numerically, is $F_{72°C}$ = 45.7 s, whereas the lethality for the holding tube only, assuming isothermal conditions for the outlet temperature of 72.14 °C, is $F_{72°C}$ = 17.2 s (details in Table 3). For this example, the actual lethality is more than twice the required value for *Coxiella burnetti* because the holding tube was sized neglecting the thermal inactivation inside the PHE and the temperature drop in the holding tube. As a consequence, unnecessary deterioration of nutrients and sensorial quality occur and also energy is wasted at the heating and cooling circuits. Moreover, cheese production yield may be affected. For the given process conditions, one tenth of the holding tube would be enough to achieve the desired level of heat treatment, $F_{72°C}$ = 16 s.

Table 3: Integrated lethality inside the pasteurizer for the example

Section	Accumulated $F_{72°C}$ (s)	Individual Contribution on F (%)
Regeneration section I	0.07	0.2
Heating section	8.74	19.0
Holding Tube	43.14	75.3
Regeneration section II	45.67	5.5
Cooling Section	45.67	0.0
Total	45.7	100

Conclusions

The mathematical modeling of the a HTST milk pasteurizer, comprising a multi-section PHE, holding tube and heating and cooling circuits, was presented. The resulting model consists of a system of first order linear ordinary differential equations and algebraic equations, which can be solved by analytical or numerical methods. The simulation results are used for obtaining the temperature-time distribution of the milk stream, which is applied for evaluating the level of heat treatment of the process. An example of application is presented and it is verified that the length of the holding tube is overdesigned because its original design did not account for the thermal inactivation inside the PHE and the temperature drop in the holding tube. Process simulation showed to be an important tool for designing more efficiently the pasteurization equipment so to ensure the inactivation of harmful microorganisms while preserving food nutrients and sensorial characteristics and also reducing operational costs.

Nomenclature

a	model parameter
b	model parameter
Cp	specific heat (J/kg·K)
c	model parameter
D_e	channel equivalent diameter, $2 \cdot d/\Phi$ (m)
d	mean channel gap (m)
e	thickness (m)
F_{Tref}	integrated lethality or F-value at T_{ref} (s)
h	convective heat transfer coef. (W/m^2·°C)
L	effective plate length (m)
L_t	thermal lethality
N	number of channels per pass
N_C	number of channels
Nu	Nusselt number, $h \cdot D_e/k$
Pr	Prandtl number, $Cp \cdot \mu/k$
Q	heat load (W)
Re	Reynolds number, $D_e \cdot v \cdot \rho/\mu$
R	fouling factor (m^2·°C/W)
s_i	channel i flow direction parameter
T	temperature (°C)
t	time (s)
U	overall heat transfer coef. (W/m^2·°C)
v	velocity inside the channel (m/s)
W	mass flow rate (kg/s)
W_i	mass flow rate inside channel i (kg/s)
w	channel width (m)
x	plate length coordinate (m)
z	Z-value (°C)

Greek Symbols

λ	thermal conductivity (W/m·°C)
μ	viscosity (Pa·s)
ρ	density (kg/m^3)
Φ	plate area enlargement factor

Subscripts

cold	cold side of a PHE section
hot	hot side of a PHE section
inlet	stream inlet
outlet	stream outlet
plate	plate
ref	reference

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