PASTEURIZATION OF EGG YOLK IN PLATE HEAT EXCHANGERS: THERMOPHYSICAL PROPERTIES AND PROCESS SIMULATION

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Abstract
The thermophysical properties of liquid egg over a wide range of temperature is of utmost importance for evaluating, designing and modeling of heat treatment processes, such as pasteurization on plate heat exchangers. This paper presents empirical correlations to predict the specific heat, thermal conductivity and density of the egg yolk for a temperature range that is compatible with the industrial thermal processing of liquid egg (0 to 61 °C). Rheological parameters for the power-law model are as well correlated with the temperature for the egg yolk. The obtained correlations are used for the simulation of the egg yolk pasteurization process. A plate heat exchanger model for generalized configurations is applied to generate the temperature profiles in all the exchanger channels. The temperature profiles in the plate heat exchanger and in the holding tube are further used for the determination of the extension of the thermal inactivation of the process. With the simulation of the plate heat exchanger using reliable correlations for the thermophysical properties, it is possible to design more accurately the pasteurization equipment to ensure the inactivation of harmful microorganisms while preserving the food nutrients and characteristics.
1. Introduction

The egg industry represents an expressive segment of the food market, with a large supply of egg derivatives, such as dried, frozen and liquid egg-products that are used as ingredients in various food formulations. Approximately 30% of all eggs sold in the USA in 2002 were processed (American Egg Board, 2003), thus requiring shell cleaning and removal, filtering, blending, pasteurization and freezing or dehydration (ASHRAE, 1994). Pasteurization is a heat treatment process that aims the inactivation of harmful microorganisms and this process must be carefully designed to cause minimal damage to the lipoprotein components of the liquid food. For instance, the main function of pasteurization of liquid egg is to destroy Salmonella senftenberg but it should be observed that egg whites are more sensitive to high temperatures than whole eggs or yolk and can easily coagulate due to temperature rise (ASHRAE, 1994).

Understanding the thermophysical properties (TPP) of liquid egg yolk over a wide range of temperature and water content is of utmost importance to the egg-products industry since thermal treatment is applied in the processing plants. However, these data are very scarce in the literature. Density, specific heat, thermal conductivity, thermal diffusivity and rheological parameters are the major TPP required for evaluating, designing and modeling heat transfer processes, such as refrigeration, freezing, heating, pasteurization and drying.

Most works on thermal conductivity measurement of food products are concerned with solid materials. For liquids, the main source of experimental errors is the convection during measurements. In order to minimize uncertainties due to convection, Bellet et al. (1975) developed an apparatus based on a cell constituted of two coaxial cylinders, separated by a narrow space that is filled with the fluid sample. The thermal conductivity is obtained from the equations describing heat transfer in steady state conditions. Mathematical modeling of unsteady state operation allows for evaluation of the specific heat of the fluid employing the same device. This procedure is used in this work for experimentally obtaining the heat capacity and thermal conductivity of the egg yolk.

The experimental data is fitted and this paper presents simplified empirical correlations to predict the specific heat, thermal conductivity, rheological parameters for the power-law model and density of egg yolk at a temperature range that is compatible with the industrial thermal processing of liquid egg (0 to 61 °C).

The plate heat exchangers (PHEs) are extensively used for the pasteurization of liquid foods such as liquid egg because of their high thermal efficiency, good flow distribution and simple maintenance. A schematic diagram of the process is presented in Figure 1. It can be observed that the PHE has three distinct sections, namely: heating, cooling and regeneration, which can be assembled
side by side in the same frame using special connector plates. The cold raw product is preheated at the regeneration section before being heated up to the pasteurization temperature, $T_{pstr}$, at the heating section. Immediately after this section there is an insulated holding tube that is designed for the desired extent of inactivation. If the temperature of the product at the exit of the holding tube does not reach the required pasteurization temperature, the product stream must be diverted back to the raw product tank (the diversion line is not shown in Figure 1). At the regeneration section, the hot pasteurized product is used to pre-heat the incoming raw product before being cooled to a suitable storage temperature at the cooling section.

![Figure 1: Schematic of a three-section PHE used for pasteurization](image)

Usually the pasteurization process is designed by assuming that the thermal inactivation occurs exclusively inside the holding tube at a constant pasteurization temperature, $T_{pstr}$. By neglecting the thermal inactivation that occurs at the PHE sections, the length of the holding tube may be overestimated and thermal degradation or over-processing of the food can occur in practice. With the use of reliable correlations for the thermophysical properties in the thermal simulation of the plate heat exchanger it is possible to obtain the temperature profiles in all of its channels and to further determine the extent of process thermal inactivation throughout the PHE. 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.

In this work, the presented TPP correlations for the egg yolk are used for the simulation of a pasteurization process for obtaining the temperature profile of the egg yolk throughout the pasteurizer and evaluating the level of heat treatment. The distribution of the overall heat transfer
coefficient along the exchanger section is also obtained. Moreover, simplified forms of the mathematical model (assuming constant overall heat transfer coefficient and pure countercurrent flow conditions) are also used for simulating the process and the results compared.

The structure of this paper is as follows: first the experimental procedure and results are presented, leading to the empirical correlations for the TPP of the egg yolk. Further the mathematical model of the pasteurizer is presented and a simulation example of the pasteurization process is shown and the results are discussed.

2. Thermophysical Properties

2.1 Materials

The liquid egg yolk for this study was provided directly from the processing line of an egg breaking plant. The moisture content of the initial batch was determined in a vacuum oven (48 h, 333 K), resulting in 54.04 % of moisture (wet basis). The pH of the samples was measured by using a pHmeter (Marconi, São Paulo, Brazil) resulting a value of approximately 6.4. The egg yolk was stirred very slowly at room temperature for 3 min to reduce incorporation of air bubble and degassed in a centrifuge (Phoenix, São Paulo, Brazil).

2.2 Apparatus and Experimental Procedure

The density of the liquid egg products was determined by applying the pycnometric method (Constenla et al., 1989) in triplicate. The sample kept in a 25 ml standard volumetric pycnometer was weighed using an analytical balance with a given uncertainty of ± 0.0001 g (Mettler AB204, NY, USA). The pycnometer was previously calibrated with distilled water at each temperature studied.

Both heat capacity and thermal conductivity were determined using an equipment composed by a water thermostatic bath with a stability of ± 0.05 % (Marconi MA-184, São Paulo, Brazil) and a cylindrical cell with the liquid sample filling the annular space between two concentric cylinders. The cell was immersed in the thermostatic bath and cell calibration was performed using distilled water and glycerin. Details of this method, cell calibration and experimental tests can be found in Minim et al. (2002). The power input to the heater resistance was supplied by a laboratory DC power (Minipa MPS-3006D, São Paulo, Brazil) that allows to adjust the current with a stability of 0.05 %. An HP data logger model 75.000-B with an HP-IB interface and an HP PC running a data acquisition program monitored the temperatures with an accuracy of 0.6 K. Heat capacity was measured under unsteady state conditions and thermal conductivity under steady state conditions (Bellet et al., 1975).
Rheological measurements were carried out using a Rheotest 2.1 (MLW, Medingen, Germany) viscometer, Searle type, equipped with a coaxial cylinder sensor system (radii ratio: 1.04). A thermostatic bath was used to control the working temperature within the range of 277 to 333 K. The speed of the rotating cylinder varies from 0.028 to 243 rpm. The instrument can be operated at 44 different speeds, which are changed stepwise with a selector switch. Shear stress ($\sigma$) is obtained by multiplying torque readings by the viscometer constant, whereas shear rate ($\dot{\gamma}$) is obtained according to Krieger and Elrod (1953).

The performance of the viscometer was verified using two fluids with well known rheological properties: ethylene glycol and chlorobenzene, which present Newtonian behavior. Twenty-three repetitions were accomplished to determine the rheological properties of each fluid and at three working temperatures (–5, 10 and 70°C for ethylene glycol and –22, 0 and 20°C for chlorobenzene).

Fitted functions were obtained by using the nonlinear estimation procedure, from the software Statistica (StatSoft Inc., 1995). The suitability of the fitted functions was evaluated by the coefficient of determination ($R^2$), the significance level ($p$), and residual analysis.

### 2.3 Results and Discussion

Specific heat ($C_p$), thermal conductivity ($\lambda$), density ($\rho$) and rheological parameters ($K$, $n$) of egg yolk were obtained at eight selected temperatures varying from 0.4 to 60.8°C, adding up to 24 (triplicate) experimental values of each thermal property. The obtained data are presented in Tables 1 to 5.

**Table 1: Mass density of egg yolk**

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>$\rho$ (kg/m³)</th>
<th>$\bar{\rho}$ (kg/m³)</th>
<th>$\bar{\rho}$ (kg/m³)</th>
<th>$\bar{\rho}_\text{sd}$ (kg/m³)</th>
<th>$\bar{\rho}_\text{se}$ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1,133.1</td>
<td>1,133.2</td>
<td>1,133.4</td>
<td>1,133.2</td>
<td>0.170</td>
</tr>
<tr>
<td>8.9</td>
<td>1,132.6</td>
<td>1,132.4</td>
<td>1,132.7</td>
<td>1,132.6</td>
<td>0.174</td>
</tr>
<tr>
<td>20.3</td>
<td>1,132.0</td>
<td>1,132.4</td>
<td>1,131.9</td>
<td>1,132.1</td>
<td>0.295</td>
</tr>
<tr>
<td>28.4</td>
<td>1,131.5</td>
<td>1,131.6</td>
<td>1,131.6</td>
<td>1,131.6</td>
<td>0.065</td>
</tr>
<tr>
<td>37.8</td>
<td>1,131.0</td>
<td>1,131.1</td>
<td>1,130.8</td>
<td>1,131.0</td>
<td>0.139</td>
</tr>
<tr>
<td>48.2</td>
<td>1,130.4</td>
<td>1,130.1</td>
<td>1,130.7</td>
<td>1,130.4</td>
<td>0.339</td>
</tr>
<tr>
<td>55.2</td>
<td>1,130.0</td>
<td>1,130.2</td>
<td>1,129.6</td>
<td>1,130.0</td>
<td>0.305</td>
</tr>
<tr>
<td>60.8</td>
<td>1,129.7</td>
<td>1,129.8</td>
<td>1,129.9</td>
<td>1,129.8</td>
<td>0.112</td>
</tr>
</tbody>
</table>
Experimental values of density shown in Table 1 presented a very weak temperature dependence. Linear functions, dependent on temperature were investigated in order to correlate experimental data. The best fit, resulting in a $R^2$ value of 0.991, is given by eq.(1),

$$\rho = 1133.19 - 0.06 \cdot T$$ (1)

where $\rho$ is the density of egg yolk, in kg/m$^3$ and $T$ is the temperature in °C.

Temperature increase generates higher values of specific heat. Experimental data could be well correlated by a linear function of temperature given by eq.(2), which resulted in a coefficient of determination ($R^2$) of 0.993,

$$C_p = 2629.05 + 2.39 \cdot T$$ (2)

where $C_p$ is the specific heat in J/kg·°C and $T$ in °C. The correlation obtained was similar to that presented by Telis-Romero et al. (1998) for orange juice. Table 2 shows the experimental values of specific heat.

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>$C_p$ (J/kg·°C)</th>
<th>$\bar{C}_p$ (J/kg·°C)</th>
<th>$\overline{C}_p$ (J/kg·°C)</th>
<th>$sd$ (J/kg·°C)</th>
<th>$se$ (J/kg·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>2,629.9</td>
<td>2,627.8</td>
<td>2,629.9</td>
<td>2.115</td>
<td>1.221</td>
</tr>
<tr>
<td>8.9</td>
<td>2,650.3</td>
<td>2,646.5</td>
<td>2,650.1</td>
<td>3.496</td>
<td>2.018</td>
</tr>
<tr>
<td>20.3</td>
<td>2,677.7</td>
<td>2,681.3</td>
<td>2,679.2</td>
<td>1.863</td>
<td>1.076</td>
</tr>
<tr>
<td>28.4</td>
<td>2,697.1</td>
<td>2,694.9</td>
<td>2,696.0</td>
<td>1.101</td>
<td>0.635</td>
</tr>
<tr>
<td>37.8</td>
<td>2,719.7</td>
<td>2,717.5</td>
<td>2,718.6</td>
<td>1.110</td>
<td>0.641</td>
</tr>
<tr>
<td>48.2</td>
<td>2,744.6</td>
<td>2,740.1</td>
<td>2,742.7</td>
<td>2.387</td>
<td>1.378</td>
</tr>
<tr>
<td>55.2</td>
<td>2,761.4</td>
<td>2,765.2</td>
<td>2,761.9</td>
<td>3.017</td>
<td>1.742</td>
</tr>
<tr>
<td>60.8</td>
<td>2,774.9</td>
<td>2,772.6</td>
<td>2,774.5</td>
<td>1.718</td>
<td>0.992</td>
</tr>
</tbody>
</table>

The effect of temperature on the experimental values for thermal conductivity was not so well defined. Nevertheless, a linear dependence on temperature, represented by eq.(3), could well adjust the data with a $R^2$ value of 0.988,
\[ \lambda = 0.390 + 4 \cdot 10^{-4} \cdot T \]  

(3)

where \( \lambda \) is the thermal conductivity in W/m\(^\circ\)C. Table 3 shows the experimental values of thermal conductivity.

### Table 3: Thermal conductivity of egg yolk

<table>
<thead>
<tr>
<th>( T ) (°C)</th>
<th>( \lambda ) (W/m(^\circ)C)</th>
<th>( \lambda ) (W/m(^\circ)C)</th>
<th>( \lambda ) (W/m(^\circ)C)</th>
<th>( \bar{\lambda} ) (W/m(^\circ)C)</th>
<th>( sd ) (W/m(^\circ)C)</th>
<th>( se ) (W/m(^\circ)C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.391</td>
<td>0.389</td>
<td>0.391</td>
<td>0.390</td>
<td>0.0009</td>
<td>0.0005</td>
</tr>
<tr>
<td>8.9</td>
<td>0.387</td>
<td>0.385</td>
<td>0.387</td>
<td>0.386</td>
<td>0.0014</td>
<td>0.0008</td>
</tr>
<tr>
<td>20.3</td>
<td>0.383</td>
<td>0.385</td>
<td>0.383</td>
<td>0.384</td>
<td>0.0012</td>
<td>0.0007</td>
</tr>
<tr>
<td>28.4</td>
<td>0.379</td>
<td>0.378</td>
<td>0.379</td>
<td>0.379</td>
<td>0.0009</td>
<td>0.0005</td>
</tr>
<tr>
<td>37.8</td>
<td>0.376</td>
<td>0.374</td>
<td>0.376</td>
<td>0.375</td>
<td>0.0008</td>
<td>0.0005</td>
</tr>
<tr>
<td>48.2</td>
<td>0.371</td>
<td>0.369</td>
<td>0.371</td>
<td>0.370</td>
<td>0.0015</td>
<td>0.0009</td>
</tr>
<tr>
<td>55.2</td>
<td>0.369</td>
<td>0.371</td>
<td>0.369</td>
<td>0.369</td>
<td>0.0012</td>
<td>0.0007</td>
</tr>
<tr>
<td>60.8</td>
<td>0.366</td>
<td>0.365</td>
<td>0.367</td>
<td>0.366</td>
<td>0.0008</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Rheograms of egg yolk for temperatures ranging from 273.4 to 333.8 K were obtained. The egg yolk exhibited non-Newtonian behavior. This could be attributed mainly due to the presence of phosphate and lipo-proteins and other complex molecules. According to Damodaran (1996), high-molecular-weight soluble polymers such as these proteins greatly increase viscosity even at very low concentrations.

Flow curves could be well fitted by the Ostwald-De Waele model, in the range of temperatures from 273.4 to 333.8 K. The consistency index (\( K \)) and the flow behavior index (\( n \)) were determined. These rheological parameters are presented in Tables 4 and 5 respectively. The behavior index showed values varying from 0.840 to 0.874, indicating that in this range of temperature the egg yolk presents pseudoplastic (shear thinning) behavior in nature. The consistency index varied from 0.10 to 2.26 Pa\( \cdot \)s\(^n\) and, in the same way as the Newtonian viscosity, decreased with higher temperature.
Table 4: Consistency index of egg yolk*

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>$K$ (Pa·s$^n$)</th>
<th>$K$ (Pa·s$^n$)</th>
<th>$K$ (Pa·s$^n$)</th>
<th>$\overline{K}$ (Pa·s$^n$)</th>
<th>$sd$ (Pa·s$^n$)</th>
<th>$se$ (Pa·s$^n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>2.26</td>
<td>2.28</td>
<td>2.23</td>
<td>2.26</td>
<td>0.025</td>
<td>0.015</td>
</tr>
<tr>
<td>8.9</td>
<td>1.24</td>
<td>1.26</td>
<td>1.21</td>
<td>1.24</td>
<td>0.025</td>
<td>0.015</td>
</tr>
<tr>
<td>20.3</td>
<td>0.59</td>
<td>0.59</td>
<td>0.60</td>
<td>0.59</td>
<td>0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>28.4</td>
<td>0.36</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>37.8</td>
<td>0.21</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>48.2</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>55.2</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60.8</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Valid for shear rates between 70.2 to 512.4 s$^{-1}$

Table 5: Behavior index of egg yolk*

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>$n$ (-)</th>
<th>$n$ (-)</th>
<th>$n$ (-)</th>
<th>$\overline{n}$ (-)</th>
<th>$sd$ (-)</th>
<th>$se$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.842</td>
<td>0.847</td>
<td>0.831</td>
<td>0.840</td>
<td>0.009</td>
<td>0.005</td>
</tr>
<tr>
<td>8.9</td>
<td>0.847</td>
<td>0.855</td>
<td>0.827</td>
<td>0.843</td>
<td>0.015</td>
<td>0.008</td>
</tr>
<tr>
<td>20.3</td>
<td>0.854</td>
<td>0.857</td>
<td>0.873</td>
<td>0.861</td>
<td>0.010</td>
<td>0.006</td>
</tr>
<tr>
<td>28.4</td>
<td>0.859</td>
<td>0.856</td>
<td>0.847</td>
<td>0.854</td>
<td>0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>37.8</td>
<td>0.864</td>
<td>0.861</td>
<td>0.853</td>
<td>0.859</td>
<td>0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>48.2</td>
<td>0.870</td>
<td>0.867</td>
<td>0.846</td>
<td>0.861</td>
<td>0.013</td>
<td>0.007</td>
</tr>
<tr>
<td>55.2</td>
<td>0.874</td>
<td>0.868</td>
<td>0.894</td>
<td>0.878</td>
<td>0.013</td>
<td>0.008</td>
</tr>
<tr>
<td>60.8</td>
<td>0.877</td>
<td>0.880</td>
<td>0.865</td>
<td>0.874</td>
<td>0.008</td>
<td>0.004</td>
</tr>
</tbody>
</table>

*Valid for shear rates between 70.2 to 512.4 s$^{-1}$

The flow parameters $K$ and $n$ could also be correlated to the temperature, resulting in eqs.(4) and (5), respectively. The function represented by eq.(4) was able to adjust the experimental data with determination coefficient ($R^2$) of 0.990. In spite of the function for the behavior index presenting $R^2 = 0.919$, the dependence of temperature for this parameter must be considered.

$$K = 7.686 \cdot 10^{-9} \cdot \exp \left( \frac{E_a}{R \cdot (T + 273.15)} \right)$$ (4)
\[ n = 0.277 \cdot (T + 273.15)^{0.198} \]  

(5)

In eqs.(4) and (5), the terms corresponding to the effect of temperature on the rheological properties are similar to Arrhenius-type equations (eq.(4)), permitting the calculation of the activation energy for flow \( (E_a) \). The activation energies obtained for the egg yolk were of \( E_a = 44,314.45 \) J/mol in the case of the consistency index (eq.(4)). Their magnitudes are comparable with values reported by Telis-Romero et al. (2001) for coffee extract and by Vélez-Ruiz and Barbosa-Cánovas (1998) for concentrated milk. High values of activation energy mean that there is a large effect of temperature on the considered parameter (Holdsworth, 1971).

The flow parameters estimated with eqs.(4) and (5) exhibited good agreement with experimental values. The relative error between observed and predicted values, calculated according to eq.(6) presented an average value of 8.44 %, with a maximum of 19.16 %, for \( K \) and an average value of 0.115 %, with a maximum of 0.309 %, for \( n \). The obtained parameters are also in fair agreement with the values of \( K \) and \( n \) reported by Landfeld et al. (2002) for the egg yolk, particularly for the temperature of approximately 45 °C.

\[
\Delta \% error = 100 \cdot \left| \frac{\text{observed} - \text{predicted}}{\text{observed}} \right|
\]

(6)

Values of the standard deviation \( (sd) \) and standard error \( (se) \) included in Tables 1 to 5 were calculated by eqs.(7a) and (7b) respectively, where \( y_i \) is the value of each measurement, \( \bar{y} \) is the mean value and \( m \) is the number of measurements.

\[
sd = \sqrt{\frac{\sum_{i=1}^{m} (y_i - \bar{y})^2}{(m-1)}}
\]

(7a)

\[
se = \frac{sd}{\sqrt{m}}
\]

(7b)
3. Pasteurization Process

3.1 Mathematical modeling

As shown in Figure 1, the fundamental structure of the pasteurizer comprises the three sections of the PHE, the heating and cooling circuits and the holding tube. The distributed-U model for the PHE presented by Gut and Pinto (2003a) is used to generate the temperature profiles in all the exchanger channels and the distribution of the overall heat exchanger coefficient throughout the three sections of the PHE. The model was developed for a single-section PHE assuming steady-state operation, no heat losses, one-dimensional incompressible plug-flow inside the channels, no heat transfer in the direction of flow, uniform distribution of the flow through the channels of a pass, perfect mixture at the end of a pass and no phase-changes. Since the pasteurizer contains three sections, the model is first used to represent each section separately and then the complete model of the pasteurizer is generated. 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 aforementioned assumptions, the energy balance applied to an arbitrary channel \( i \) of the exchanger yields eq.(8), where \( T_i(x) \) is the temperature of the fluid inside channel \( i \); \( x \) is the coordinate tangential to the flow in the channels \( (0 \leq x \leq L) \); \( s_i \) indicates the direction of the flow inside channel \( i \) \((s_i = +1 \text{ is the flow follows the } x \text{ direction and } s_i = -1 \text{ otherwise})\); \( w \) is the channel width; \( \Phi \) 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 \( C_p_i(x) \) is the specific heat of the fluid in channel \( i \).

\[
\frac{dT_i}{dx} = \frac{s_i \cdot w \cdot \Phi}{W_i \cdot C_p_i} \left[ U_{i+1} \cdot (T_{i+1} - T_i) + U_i \cdot (T_{i+1} - T_i) \right] , \quad 1 \leq i \leq N_C \quad (8)
\]

The variable \( U_i(x) \) is the overall heat transfer coefficient between channels \( i \) and \( i+1 \), as defined in eq.(9), where \( h_i(x) \) is the convective heat transfer coefficient inside channel \( i \); \( e_{\text{plate}} \) is the plate thickness; \( \lambda_{\text{plate}} \) is the thermal conductivity of the plate; and \( R_{f\text{hot}} \) and \( R_{f\text{cold}} \) are the hot and cold side fouling factors. Note that \( U_0 = 0 \) and \( U_{N_C} = 0 \) when eq.(8) is applied to the first and last channels respectively.

\[
\frac{1}{U_i} = \frac{1}{h_i} + \frac{1}{h_{i+1}} + \frac{e_{\text{plate}}}{\lambda_{\text{plate}}} + R_{f\text{hot}} + R_{f\text{cold}} , \quad 1 \leq i \leq (N_C - 1) \quad (9)
\]
For obtaining the convective heat transfer coefficient, correlations such as the one presented in eq.(10) are required. Usual values for the empirical parameters $a_1$, $a_2$ and $a_3$ are supplied in the works of Shah and Focke (1988), Saunders (1988) and Mehrabian et al. (2000).

$$Nu_i = a_i \cdot Re_i^{a_i} \cdot Pr_i^{a_i}$$  \hspace{1cm} (10)

If the fluid has non-Newtonian behavior, $Re_i(x)$ and $Pr_i(x)$ should be calculated using the generalized viscosity ($\mu_g$) defined in eq.(11a) for the power-law reological model, where the velocity inside the channel ($\nu$) is given by eq.(12). The definition of the geometric parameters $\upsilon$ and $\xi$ is presented by Delplace and Leuliet (1995) for cylindrical ducts of arbitrary cross-section, including the PHE channel. Since the power-law parameters $n$ and $K$ are valid for a certain range of shear rate, eq.(11b) is important to evaluate the shear rate at the plate wall, $\dot{\gamma}_{wall}$, and thus validate the PHE simulation results.

$$\mu_g = K \cdot \xi^{-n} \cdot \left( \frac{\nu}{D_e} \right)^{n-1} \cdot \frac{\upsilon \cdot n + 1}{(\upsilon + 1) \cdot n}$$ \hspace{1cm} (11a)

$$\dot{\gamma}_{wall} = \xi \cdot \left( \frac{\upsilon}{D_e} \right) \cdot \frac{\upsilon \cdot n + 1}{(\upsilon + 1) \cdot n}$$ \hspace{1cm} (11b)

$$\nu = \frac{W}{N \cdot b \cdot w \cdot \rho}$$ \hspace{1cm} (12)

Boundary conditions for the temperatures of the channels are required in order to solve the system of differential equations generated from eq.(8). The boundary conditions represent the physical connection among the channels and passes. The three possible boundary condition equations are presented in Table 6.
Table 6: Thermal boundary conditions for the PHE modeling

<table>
<thead>
<tr>
<th>Boundary Condition</th>
<th>Equation Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid inlet: the temperature at the entrance of the first pass is the same as the stream inlet temperature.</td>
<td>$T_i</td>
</tr>
<tr>
<td>Change of pass: there is a perfect mixture of the fluid leaving the channels of a pass, before entering the next one.</td>
<td>$T_i</td>
</tr>
<tr>
<td>Fluid outlet: the stream outlet temperature results from a perfect mixture of the fluid leaving the last pass.</td>
<td>$T_{\text{outlet}} = \frac{1}{N} \sum_{j=\text{last pass}}^N T_j</td>
</tr>
</tbody>
</table>

In summary, the distributed-U mathematical thermal modeling of a section of the PHE is defined by eq.(8) (channel fluid temperature), eq.(9) (overall heat transfer coefficient), the equations in Table 6 (boundary conditions), eq.(10) for the hot and cold sides and the equations for the temperature dependence of the physical properties of the fluids: $Cp_i(T_i(x)), \lambda_i(T_i(x)), K_i(T_i(x))$ and $n_i(T_i(x))$ for $1 \leq i \leq N$. Note that average values for the fluid densities ($\rho_{\text{hot}}$ and $\rho_{\text{cold}}$) are required for the hot and cold streams since incompressible flow is assumed. It can be verified in Table 1 that the density of the egg yolk has a weak dependence on the temperature, with a variation of only 0.3% for the temperature range of 0 and 61°C.

The mathematical modeling of the pasteurizer consists of the thermal modeling of the three sections, the temperature boundary conditions to represent the connection among sections and the specifications for mass flow rates and inlet temperatures of the product, heating and cooling streams. Since the holding tube is thermally isolated, the heat losses are neglected. The model consists of a non-linear system of differential and algebraic equations, which needs to be solved by numerical methods, such as the method of finite differences.

3.2 Thermal treatment criteria

The integrated lethality or F-value, $F$ in eq.(13), is employed for evaluating the level of heat treatment of a process. The F-value can be considered to be the holding time at a given reference temperature $T_{\text{ref}}$ (assuming instant heating and cooling) to which the whole process is equivalent, thus it can be used to compare different processes (Toledo, 1999; Lewis, 2000). In eq.(13), $z$ 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.

\[
F_{T_{\text{ref}}} = \int_0^t L_t \, dt = \int_0^\frac{T(t) - T_{\text{ref}}}{\tau} \, dt
\]  

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 distribution of the product in the pasteurizer, \( T(t) \). The F-value is then calculated through eq.(13). In this work, plug flow is assumed in the pasteurizer for the calculations. A experimental study on the residence time distribution of the egg yolk inside the pasteurizer is presented in the work of Landfeldt (2002).

### 3.3 Simulation example

The thermophysical properties for the egg yolk presented in this work are used for the simulation of a pasteurizer for evaluating the level of heat treatment of the process. The process conditions are shown in Figure 2 and the PHE with SS-304 flat plates presented by Sharifi et al. (1995) is considered for this application. The parameters for the heat transfer correlation in eq.(10) are \( a_1 = 1.35 \), \( a_2 = 0.36 \) and \( a_3 = 0.33 \) (Sharifi et al., 1995). The PHE was configured using the optimization procedure developed by Gut and Pinto (2003b) targeting a pasteurization temperature of 60 °C and a storage temperature of 5 °C.

Fouling factors for water \((1.7 \cdot 10^{-5} \, \text{m}^2\cdot\text{°C}/\text{W} \) for cold water and \(3.4 \cdot 10^{-5} \, \text{m}^2\cdot\text{°C}/\text{W} \) for cold water) were obtained from Marriott (1971), whereas for the egg yolk the values presented by Lalande et al. (1979) for the pasteurization of milk were considered \( (9 \cdot 10^{-4} \, \text{m}^2\cdot\text{°C}/\text{W} \) in the heating section and \(3 \cdot 10^{-4} \, \text{m}^2\cdot\text{°C}/\text{W} \) for the other sections). The correlations for the physical properties of the water were taken from Gut and Pinto (2003a). The Z-Value of *Salmonella senftenberg* in liquid egg was obtained from Mañas et al. (2003): \( z = 5.2 \, \text{°C} \). Since the plates are flat, the geometrical parameters for parallel plates, \( \nu = 2 \) and \( \xi = 12 \), are used for calculating \( \mu_g \) and \( \dot{\gamma}_{\text{wall}} \) with eqs.(11a) and (11b). The obtained values of \( \dot{\gamma}_{\text{wall}} \) fall in the range of validity of the rheological parameter correlations in eqs.(4) and (5), which is \( 70.2 \leq \dot{\gamma} \leq 512.4 \, \text{s}^{-1} \). A temperature drop of 1.0 °C is assumed for the holding tube, which has a holding time of 3.5 min.
The distributed-U mathematical model of the pasteurizer was solved through the solver gPROMS v.2.11 (Process Systems Enterprise, 2002) using a second order centered finite differences method with 20 intervals in the plate length for representing the profiles. The discretized model contains 13,362 variables and algebraic equations. The simulation time was 14 s on a 450 MHz / 512 Mb-RAM personal computer. The obtained temperature profile for the egg yolk is presented in Figure 3, as well as the distribution of the lethality throughout the PHE. It can be seen that the lethality in the heating and regeneration sections is significant. It is also possible to note that the temperature profile in the regeneration section is almost linear, confirming the prediction of Lewis and Heppell (2000) for regeneration sections with high heat recovery ratio \( RR \approx \frac{(T_2-T_1)}{(T_3-T_1)} = 78.3 \% \). The obtained overall heat transfer coefficient profiles are shown in Figure 4 for the three sections of the PHE and the obtained integrated lethality is \( F_{60^\circ C} = 5.53 \) min.
Figure 3: Temperature profile and lethality for the egg yolk in the pasteurizer

Figure 4: Distribution of the overall heat transfer coefficient throughout the PHE

Alternately, the simulation of the pasteurizer was conducted assuming:
1) Constant overall heat transfer coefficients for the PHE sections: the average physical properties are calculated as the arithmetical mean between inlet and outlet conditions of each stream. This
assumption greatly simplifies the solution of the system of differential equations represented by eq.(8), which becomes linear.

2) Pure countercurrent flow conditions: the average heat transfer coefficients are used for obtaining the thermal efficiency of the sections for these ideal conditions and thus \( T_2 \) to \( T_6 \) can be calculated (please refer to Rohsenow et al., 1998). The temperature profile in the pasteurizer is assumed linear for calculating the lethality.

The main results obtained by these three mathematical models are presented in Table 7. The variation of the obtained temperatures \( T_2 \) to \( T_6 \) is not very significant, taking into consideration that \( T_4 \) (outlet of the holding tube) and \( T_6 \) (outlet of the cooling section) are the most important temperatures obtained from simulation. However, the F-value is very sensitive to the temperature profile \( T(t) \) and a poor solution was obtained from the pure countercurrent flow model in comparison with the distributed-U model. Since assuming a constant overall heat transfer coefficient simplifies greatly the solution of the mathematical model, this approach is recommended for the simulation of PHEs, as verified by Gut and Pinto (2003a).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distributed-U model</th>
<th>Constant-U model</th>
<th>Pure counter-current flow model</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_2 ) (°C)</td>
<td>49.16</td>
<td>48.01</td>
<td>48.34</td>
</tr>
<tr>
<td>( T_3 ) (°C)</td>
<td>61.42</td>
<td>61.08</td>
<td>61.26</td>
</tr>
<tr>
<td>( T_4 ) (°C)</td>
<td>60.42</td>
<td>60.08</td>
<td>60.26</td>
</tr>
<tr>
<td>( T_5 ) (°C)</td>
<td>16.71</td>
<td>17.54</td>
<td>17.38</td>
</tr>
<tr>
<td>( T_6 ) (°C)</td>
<td>4.48</td>
<td>4.60</td>
<td>4.45</td>
</tr>
<tr>
<td>( U_R ) (W/m·°C)</td>
<td>see Figure 4</td>
<td>756</td>
<td>756</td>
</tr>
<tr>
<td>( U_H ) (W/m·°C)</td>
<td>see Figure 4</td>
<td>864</td>
<td>864</td>
</tr>
<tr>
<td>( U_C ) (W/m·°C)</td>
<td>see Figure 4</td>
<td>1196</td>
<td>1195</td>
</tr>
<tr>
<td>( F_{60°C} ) (min)</td>
<td>5.53</td>
<td>4.75</td>
<td>5.86</td>
</tr>
</tbody>
</table>

With the simulation of the pasteurizer, a more realistic F-value can be obtained for the process. In this case, \( F_{60°C} = 5.53 \) min was obtained for this process which was originally designed for \( F_{60°C} = 3.50 \) min.
4. Conclusions

Empirical correlations for calculating the specific heat, thermal conductivity, rheological parameters for the power-law model and density of egg yolk at a temperature range that is compatible with the industrial thermal processing of liquid egg (0 to 61 °C) were presented. These correlations are of utmost importance for the design of processing plants.

The obtained correlations were used for the simulation of the pasteurization process of the egg yolk using a distributed-U model. The obtained temperature profile was used for evaluating the level of heat treatment of the process, in comparison with the design specifications. It was verified that the assumption of constant overall heat transfer coefficient for the sections of the plate heat exchanger simplifies greatly the mathematical solution of the model without compromising the main simulation results (inlet and outlet temperatures of the exchanger sections). However, a significant variation was observed on the F-value when simplifying the mathematical model of the pasteurizer.

Acknowledgments

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Nomenclature

\[
\begin{align*}
A_{plate} & \quad \text{plate effective heat transfer area, } A_{plate} = L \cdot w \cdot \Phi \ (m^2) \\
a_i & \quad \text{model parameter (dimensionless)} \\
b & \quad \text{mean channel gap (m)} \\
Cp & \quad \text{specific heat at constant pressure (J/kg·K)} \\
D_e & \quad \text{equivalent diameter of channel, } D_e = 2 \cdot b / \Phi \ (m) \\
E_a & \quad \text{activation energy for flow (J/mol)} \\
e_{plate} & \quad \text{plate thickness (m)} \\
F & \quad \text{integrated lethality or F-value (s)} \\
h_i & \quad \text{convective heat transfer coefficient inside channel } i \ (W/m\cdot°C) \\
K & \quad \text{consistency index, power-law model (Pa·s^n)} \\
L & \quad \text{effective plate length for heat transfer (m)} \\
Lt & \quad \text{thermal lethality (dimensionless)} \\
m & \quad \text{number of measurements} \\
N & \quad \text{number of channels per pass} \\
n & \quad \text{flow behavior index, power-law model (dimensionless)}
\end{align*}
\]
Nu  Nusselt number, \( Nu = h \cdot D_e / \lambda \) (dimensionless)

\( P \)  number of passes

\( Pr \)  Prandtl number, \( Pr = C_p \cdot \mu / \lambda \) (dimensionless)

\( Q \)  heat load (W)

\( R \)  universal gas constant, \( R = 8.31451 \) J/mol·K

\( R^2 \)  coefficient of determination

\( Re \)  Reynolds number, \( Re = D_e \cdot v \cdot \rho / \mu \) (dimensionless)

\( Rf \)  fouling factor (m²·°C/W)

\( RR \)  heat recovery ratio (%)

\( sd \)  standard deviation

\( se \)  standard error

\( s_i \)  channel i flow direction parameter, \( (s_i = +1 \text{ or } -1) \)

\( T \)  temperature (°C)

\( t \)  time (s)

\( U_i \)  overall heat transfer coefficient between channels \( i \) and \( i+1 \) (W/m²·°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)

\( x \)  coordinate tangential to the flow in the channels (m)

\( y \)  experimental measurement

\( \bar{y} \)  arithmetic mean of the measurements

\( z \)  \( Z \)-value, thermal inactivation parameter (°C)

Greek Symbols

\( \dot{\gamma} \)  shear rate (s⁻¹)

\( \dot{\gamma}_{wall} \)  shear rate at plate wall (s⁻¹)

\( \eta \)  dimensionless coordinate for the plate length (dimensionless)

\( \lambda \)  thermal conductivity (W/m·°C)

\( \lambda_{plate} \)  thermal conductivity of the plate (W/m·°C)

\( \mu_g \)  generalized viscosity for power-law model (Pa·s)

\( \xi \)  duct geometrical parameter (dimensionless)
\( \rho \)  density (kg/m\(^3\))
\( \nu \)  duct geometrical parameter (dimensionless)
\( \Phi \)  plate area enlargement factor (dimensionless)

**Subscripts**
- \( C \)  cooling section
- \( cold \)  cold side of PHE section
- \( cool \)  cooling fluid
- \( H \)  heating section
- \( heat \)  heating fluid
- \( hot \)  hot side of PHE section
- \( R \)  regeneration section
- \( ref \)  reference

**Superscripts**
- \( max \)  maximum value
- \( min \)  minimum value

**References**


