Integrated lethality for the non-ideal flow of a pseudoplastic liquid food

V. Kechichian, C.C. Tadini, J.A.W. Gut*

University of Sao Paulo, Escola Politecnica, Dept of Chemical Engineering,
Sao Paulo, Brazil
jorgewgut@usp.br

Abstract

The analysis of the continuous thermal processing of a liquid food can be compromised by the common assumptions of isothermal ideal flow, instant heating and cooling steps and minimum residence time approach. In order to optimize safety, sensorial and nutritional attributes of the food, the thermal process should be modeled considering flow, heat transfer and kinetics principles. In this work, the thermal processing of a pseudoplastic (power-law) fluid in a tubular system is modeled taking into account the effective heat diffusion and mass diffusion in laminar flow, the reaction kinetics for microorganism or enzyme inactivation and quality attribute changes, as well as heat losses to the ambient. The model comprises differential equations for heat and mass balances applied to the heating and cooling sections (double-pipe heat exchangers) and the holding tube. Axial and radial components were discretized using finite difference methods and the model was solved using gPROMS (PSE). Main simulation results were the radial and axial distributions of temperature and concentration of microorganisms. The axial distribution of the integrated lethality (S-value) was also obtained for process evaluation. The model was successfully applied for the study of the pasteurization of soursop juice and the results are presented and discussed.

Introduction

The continuous thermal processing of liquid foods was developed to solve problems observed in the batch processing, such as low rate of heat penetration and long processing time to achieve the correct temperature needed to ensure the required lethality. The main advantages of continuous thermal processing, when compared to discontinuous processing, are: increasing production capacity, reduction of energy consumption and improvement in the sensorial characteristics of the final product due to lower processing temperature and time (Torres and Oliveira, 1998).

Pseudoplastic liquid foods like fruit juices and purées have a complex flow behavior and are often processed in heat exchangers in laminar flow. This way, the velocity profile, the residence time distribution and the temperature profile, regarding axial and radial domains, need to be considered for proper lethality evaluation and design of the thermal process (Gratão, 2006).

Despite these flow characteristics, the assumptions that are often used for the process design are: isothermal plug flow at the maximum velocity (minimum residence time), instant heating and cooling (the lethality takes place only in the holding tube) and no mass or heat dispersions or heat losses to the ambient. Since these assumptions lead to over-processing, they can guarantee product safety but undesired nutritional and sensorial changes of the product may occur (Jung and Fryer, 1999).

Nowadays, the demand for processed foods goes beyond basic requirements of food safety and assurance of shelf-life stability. Recent studies have been conducted to determine the most appropriate conditions of thermal processing in order to preserve sensorial and nutritional characteristics of the food product (Ditchfield *et al.*, 2006; Awuah *et al.*, 2007).

The objective of this work was to develop and test a mathematical model to simulate the continuous thermal processing of a pseudoplastic liquid food under non-ideal laminar flow in order to determine the integrated lethality and the temperature profile.

Materials and Methods

The mathematical model was developed considering a double-pipe heat exchanger composed by heating section, holding tube and cooling section. Differential mass and energy conservation equations were used in the mathematical modeling with appropriate boundary conditions for each control volume (Fogler, 2006). The variables were discretized using finite difference methods and the model was solved using gPROMS (Process System Enterprise, version 3.2) considering 400 axial points per section and 30 radial points for the variable discretization.

The non-Newtonian fluid (power-law) contains a general “component A” which follows first order thermal destruction kinetics. This general component could represent a microorganism, an enzyme activity or a nutrient concentration. The assumptions for this fluid modeling were as follows: incompressibility, developed laminar steady-state flow, radial diffusion of mass (component A), effective radial disffusin of heat, uniform physical properties in each section and negligible viscous dissipation.

The heating or cooling fluid flows in the heat exchnager annulus, counter-currently regarding the food product. For the simulations, hot and cold water were considered as fluid utilities for the heating and cooling sections, respectively. The assumptions for both were: incompressibility, developed turbulent flow (plug-flow), uniform physical properties in each section, thermal axial dispersion and negligible viscous dissipation.

The equipment exchanges heat with the ambient due to natural convection of the air. A layer of thermal insulation was considered and modeled for the holding tube, but the outer surface of the heating and cooling sections were in direct cointact with the ambient air.

The axial dimensionless domain, η, varied from 0 to 1 in the heating section, from 1 to 2 in the holding tube and from 2 to 3 in the cooling section. The radial dimensionless domain, present in the food product control volume, varied from 0 (tube center) to 1 (tube wall).

Equation 1 was incorporated in the model to represent the velocity profile of a non-Newtonian fluid (power-law model) flowing under laminar regime in a circular section tube (Toledo, 1999):

$$v_{product} = \bar{v}_{product} \left(\frac{3n+1}{n+1} \right) \left(1 - x^{\frac{n+1}{n}} \right) \tag{1}$$

where: n = flow behavior index (dimensionless), $v_{product}$ = product velocity ($m \cdot s^{-1}$), $\bar{v}_{product}$ = average product velocity ($m \cdot s^{-1}$) and x = radial domain (dimensionless).

Equation 2 was used for the evaluation of the effect of the thermal processing on the product according to the number of decimal reductions of component A, S_{value} (Toledo, 1999).

$$S_{value} = \log\left(\frac{C_{Ao}}{C_A} \right) \tag{2}$$

where: C_A = flow-average concentration of component A (mixing cup), C_{A0} = inlet concentration of A and S_{value} = number of decimal reductions (dimensionless).

Regarding the dispersion of heat and of component A through the product, it was considered that the radial mass Peclet number was equal to the radial thermal Peclet number.

Results and Discussion

To test the simulation model, the thermal processing of 18 ºBrix soursop juice (pseudoplastic fluid) with a flow rate of 18 L h^{-1} was studied. The thermal inactivation of yeast and molds ($D_{82.2ºC}$ = 0.57 s, z = temperature gradient to reduce D by a factor of 10 = 7 ºC) was used to evaluate the process lethality. It was considered a small-scale heat exchanger with the following dimensions: internal diameter of 4.5 mm and each section with 5 m length (heating, holding tube and cooling).

The inlet temperature of the hot water was set to obtain a flow-average product temperature of 74 ºC at the end of the holding tube (process parameter). The thermo-physical properties (density, specific heat and thermal conductivity) and rheological properties (consistency index and flow behavior index) of the food product were defined using appropriate equations considering the estimated average temperature in the specific section of the heat exchanger. It was admitted that the Peclet number (radial and axial) for the soursop juice was 2000 and the Peclet number (axial) for the heating and cooling water was 1300 in all simulation cases.

Figure 1 shows the obtained temperature profile of the soursop juice in the heating section (tube center and tube wall). Due to the laminar regime and rheological properties, the tube center takes longer to have its temperature increased than the tube wall. For instance, halfway through the heating section (η = 0.5), the temperature at the center and at the tube wall is 59 ºC and 74 ºC, respectively.

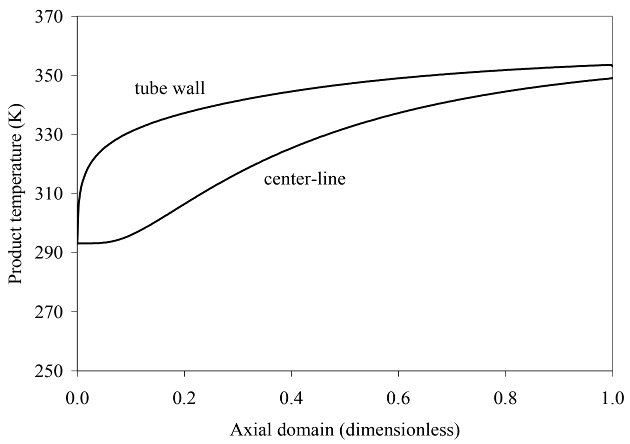

Figure 1. Axial profile of the food product temperature in the heating section

Since the thermal destruction rate is strongly temperature dependent, the concentration of yeasts and molds is higher at the center of the tube than at the wall as shown in Figure 2. Halfway through the heating section (2.5 m) the concentration of micro-organisms at the center of the tube decreased to approximately half of the initial value. Regarding the tube wall, the same concentration was only achieved at 3.3 m of the heating section.

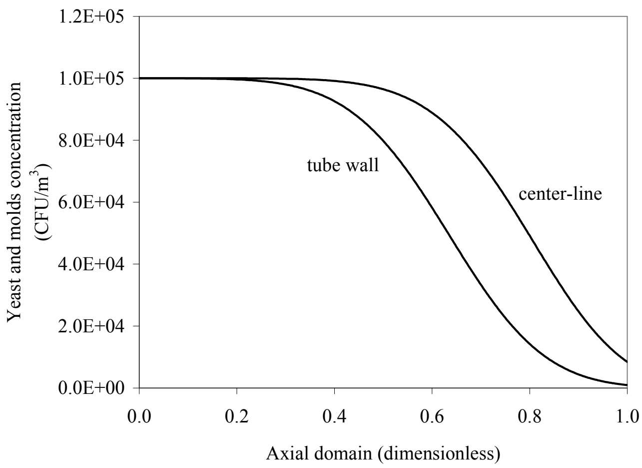

Figure 2. Axial profile of the concentration of yeast and molds in the heating section

Figure 3 illustrates the effect of considering the dispersions (mass and thermal) and the heat losses to the ambient in the simulation results regarding the center-line temperature. When the dispersions are neglected, the radial heat transfer rate is low and it takes longer to heat or cool the product than when the dispersions are taken into account. When heat losses are neglected, the required inlet temperature of the hot water is lower; therefore, the product wall temperature is also lower.

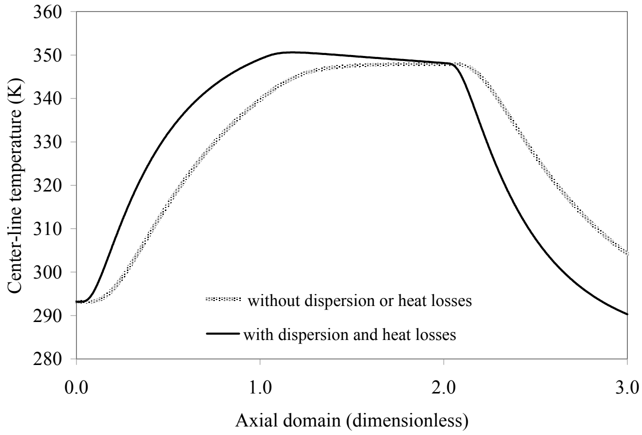

Figure 3. Effect of the model assumptions on the center-line temperature

Figure 4 shows the effect of the model assumptions on S_{value}. When it was considered that the process was isothermal with plug flow at maximum velocity with the lethality only in the holding tube, the S_{value} was the smallest. On the other hand, taking into account the dispersions, heat losses and velocity profile in all sections of the heat exchanger, the S_{value} was strongly affected. A holding tube with approximately 19 m (instead of 5 m) would be necessary to obtain an S_{value} of 5.74 if it was considered that the process was isothermal at the maximum velocity with only the holding tube. The longer time that the soursop juice should need to be submitted to high temperature would impact negatively in its sensorial and nutritional characteristics.

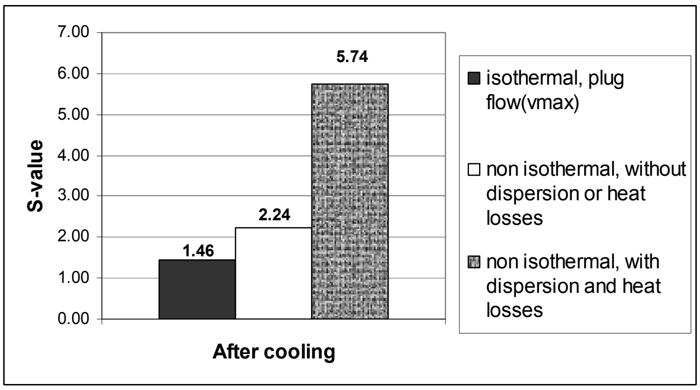

Figure 4. Effect of model assumptions on the number of decimal reductions S_{value}

The separate effects of the thermal and mass dispersions assumptions on the distributed lethality can be analyzed in Figure 5. When just thermal dispersion was considered, the yeast and molds did not disperse radially and the effect of the temperature on the average concentration of the micro-organisms was lower (S_{value} at the end of cooling section = 4.36) than when all the assumptions were taken into account (S_{value} at the end of cooling = 5.74). Since the heat transfer rate is lower when only mass dispersion and the thermal condutivity (instead of effective thermal conductivity) are considered, it was necessary to increase the inlet hot water temperature. Consequently, the S_{value} was highest for this case (S_{value} at the end of cooling = 6.02).

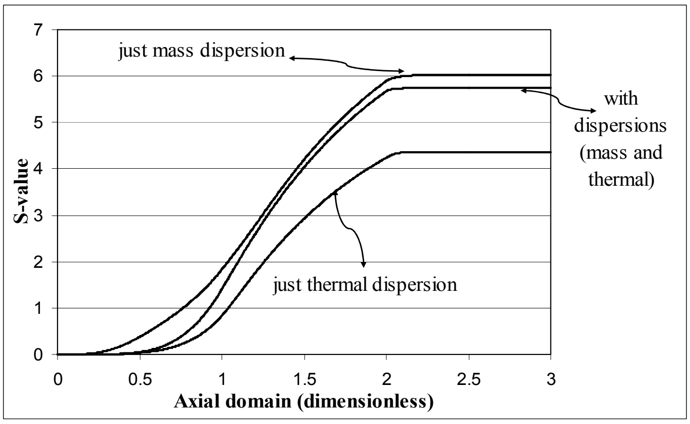

Figure 5. The effect of considering mass or thermal dispersions on S_{value} (based on the average concentration)

Figure 6 presents the effect of the product flow rate on S_{value}. It can be seen that, the higher the flow rate of the soursop juice, the lower is the S_{value}, even considering that the inlet temperature of hot water was 1 ºC higher in the case of the higher flow rate. This can be justified by the fact that the faster the flow the shorter the time that the fluid is exposed to high temperature.

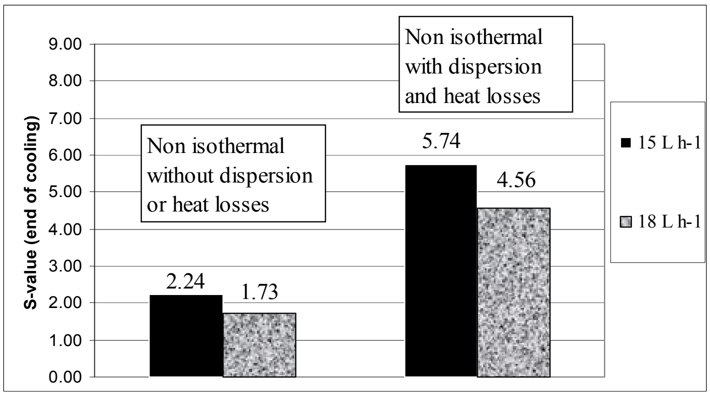

Figure 6. The impact of the food product flow rate on S_{value} (end of cooling section)

The effect of the soursop soluble solids content on S_{value} was evaluated and the results are shown in Figure 7. When the food product has 12 ºBrix, the required inlet temperature of hot water was 1 ºC lower than when the concentration was 18 ºBrix, probably due to the higher heat transfer rate for the less concentrated fluid. For the same concentration, the S_{value} was approximately 2.5 times higher when the dispersion (mass and thermal) and heat losses are considered in the modeling than when they are neglected.

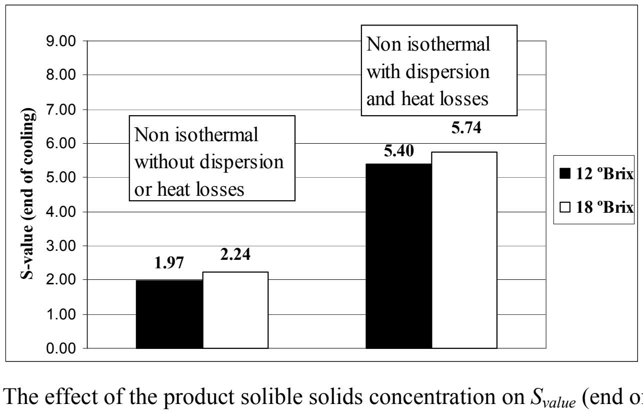

Figure 7. The effect of the product solible solids concentration on S_{value} (end of cooling)

Conclusions

A mathematical model was developed to simulate the thermal processing of a viscous non-Newtonian fluid in a tubular heat exchanger. Thermal and mass dispersions, as well as heat loses do the ambient, were considered in the model. The model was tested for the study case of soursop juice and it was possible to determine the temperature and the lethality distributions throughout the equipment. The effect of the model assumptions on the simulation results was analyzed and a large difference was obtained in comparison with the conventional model of isothermal flow at maximum velocity. The effect of the product flow rate and soluble solids concentration were also studied. As consumer demands for products with better sensorial and nutritional characteristics is increasing, proper models are required for process design and evaluation in order to guarantee the product safety with minimal processing and maximum nutrient and sensorial retention.

References

Awuah, G. B.; Ramaswamy, H. S. & Economides, A. 2007. Thermal processing and quality: Principles and overview. *Chemical Engineering and Processing*, 46, p. 584-602.

Ditchfield C.; Tadini C. C.; Singh, R. K. & Toledo, R. T. 2006. Velocity and temperature profiles, heat transfer coefficients and residence time distribution of a temperature dependent Herschel-Bulkley fluid in a tubular heat exchanger. *Journal of Food Engineering*, 76, p. 632-638.

Fogler, H. S. 2006. *Elements of Chemical Reaction Engineering*. 4.ed. NJ Prentice Hall PTR.

Gratão, A. C. A; Silveira Jr., S. & Telis-Romero, J. 2006. Laminar forced convection to a pseudoplastic fluid food in circular and annular ducts. *International Communication in Heat and Mass Transfer*, 33, p. 451-457.

Jung, A. & Fryer, P. J. 1999. Optimizing the quality of safe food: computational modeling of a continuous sterilization process. *Chemical Engineering Science*, 54(6), p. 717-730.

Toledo, R. T. 1999. *Fundamentals of Food Process Engineering*. 2.ed. New York: Chapman & Hall.

Torres, A. P. & Oliveira, F. A. R., 1998. Residence time distribution studies in continuous thermal processing of liquid foods: a review. *Journal of Food Engineering*, 36, p. 1-30.