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Experimental Determination of Fluid-particle Convective Heat Transfer in Particulate Food Processing

Eksperimentalno određivanje prijenosa topline konvekcijom u sustavu fluid-čestica pri proizvodnji hrane

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Summary

The design of continuous sterilization of particulate foods is limited by the impossiblity of monitoring particle temperature during the continuous process, by the difficulty of solving the differential equations of conductive heat transfer within the particles and, finally, by the uncertainty in estimating the convective heat transfer coefficient between fluid and particle.

In this work, the differential equations for heat transfer are solved by means of a numerical method based on a finite difference discretization scheme.

The heat transfer coefficient is estimated using an experimental set-up consisting of a cubic tomato particle immobilized in a tubular pilot plant. Particle temperatures of heated tomato juice at different flow rates and concentration are measured by means of thermocouples and calculated using the numerical method: a best fitting procedure between experimental and calculated data gives then the optimal coefficient values.

Sažetak

Projektiranje uređaja za kontinuiranu sterilizaciju pojedinih vrsta hrane značajno je otežano zbog: nemogućnosti praćenja temperature čestice tijekom procesa, poteškoćom rješavanja diferencijalnih jednadžbi kondukcijskog prijenosa topline unutar čestice, kao i nesigurnošću određivanja koeficijenta prijenosa topline konvekcijom između fluida i čestice.

U ovom su radu diferencijalne jednadžbe prijenosa topline riješene numerički primjenom metode diskretne sheme konačnih razlika.

Koeficijent prijenosa topline određen je eksperimentalno na pokusnom uređaju. U cijev kroz koju protječe sok od rajčice smještena je čestica rajčice kockastog oblika. S pomoću termopara mjerene su temperature čestice rajčice pri različitoj brzini tečenja i koncentraciji zagrijanog soka. Postupkom najboljeg slaganja eksperimentalnih i izračunanih podataka dobivene su optimalne vrijednosti koeficijenta prijenosa topline.

Introduction

In the food industry, the design of an optimal thermal treatment from both microbial and quality point of view, requires the exact knowledge of the thermal history of the product during the process.

For particulate foods (liquids which contain particles larger than 5 mm, such as tomato pulp, fruit dices or salads and jams), the experimental monitoring of temperature distribution within the particles suspended in a liquid flowing through the plant is not possible.

Therefore the thermal history of each particle must be predicted mathematically, solving the partial differential equations (PDE) which describe the conductive heat transfer within a three-dimensional particle, where the temperature is a function of both space and time. An analytical solution to this PDE set is not possible using conventioanl integrating procedures because of the time dependent convective boundary conditions at the fluid-particle interface. Consequently, the best method is the mathematical modelling of heat transfer, solving the PDE set by means of numerical methods, followed by a biological validation of calculated lethality.

In addition, the modelling procedure is strictly related to the knowledge of the physical parameters which influence the heat transfer process. In particular, the convective heat transfer coefficient between the fluid and the particle h_{fp}, is a very difficult parameter to estimate, because of its complex dependence on fluid transport properties and fluid-particle interface fluidodynamics. The use of an infinite value of h_{fp} in the mathematical model (i.e. the neglecting of resistance to heat transfer between liquid and particle surface), allows predicted particle temperature profiles higher than the true ones. Consequently, the processing time is underestimated and the microbiological safety could not be achieved *(1)*. On the contrary, assuming that the particles and the fluid flow with an identical velocity through the system, yields a conservative estimate of h_{fp} that may cause unacceptable product quality degradation *(2,3)*.

The interest of researchers is now focused on the development of several and original techniques to determine the value of h_{fp} in the different industrial processing conditions as exactly as possible *(4–8)*.

Experimental

In this work, in order to solve the PDE equations for heat transfer, a computer program based on a finite difference discretization scheme was developed *(9–11)*. Each suspended particle was approximated as a cube-shaped particle having uniform dimension. The cube was subdivided into a finite number of small »subcubes« by setting up a three-dimensional grid of discrete nodes. Energy balances were then written within control volumes centred on any node, obtaining a set of nodal algebraic equations; for the interior nodes, the temperature increment between the time steps was due to conductive heat transfer from all the adjacent nodes, while for the fluid-particle boundary nodes the convective contributions of surrounding fluid elements were considered as well. Finally, the resulting system of equations was solved by means of an iterative explicit algorithm of calculus.

For the experimental determination of h_{fp}, a tubular pilot plant was used. It consisted of a heating tube (internal diameter = 6 cm; length = 7 m) surrounded by a jacket where steam was continuously condensing and a holding tube (internal diameter = 6 cm; length = 7 m). Within this plant, a 2 cm side tomato cube was immobilised while tomato juice was continuously flowing.

Several experiments were performed using different process conditions and measuring the temperatures of fluid and both particle surface and centre by means of thermocouples (T type). The different process parameters where then inserted into the mathematical model that was solved iteratively using different values of h_{fp} until the sum of squared deviations between the experimental and calculated temperature profiles for a chosen h_{fp} was minimized.

In this first research step, experiments were carried out using a tomato cube (2 cm side) and tomato juices at three different concentrations (6, 12, 18 %) and four mass flow rates, at the temperature of 50 °C.

Rheological measurements were performed by means of a rotational viscometer with coaxial cylinders, carrying out steady-shear tests at shear rate varying from 0 to 200 s^{-1}.

Results and Discussion

The value of h_{fp} within each product, increases at increasing fluid flow rate (Fig. 1), because a higher fluid velocity means a more efficient convective heat transfer.

In order to simplify the interpretation of results regarding the effect of fluid rheology on convective heat transfer coefficient values, a mean apparent viscosity was introduced, defined as the ratio of the integral, over the tube cross-sectional area, of fluid velocity multiplied by apparent viscosity to the integral of fluid velocity over the same tube cross-section *(12)*.

Fig. 2. shows the global decrease of h_{fp} with apparent viscosity, as the concentration increases from the juice to sauce up to tomato paste. This depends on the growing dissipation of energy due to viscous stresses of fluid that transfers the heat to the particle surface. But, within each product, h_{fp} decreases with the increase of apparent mean viscosity, because such increase contains in itself a reduction in the fluid flow rate.

$$\mathrm{Nu} = \frac{h_{fp} D_p}{k_f} \qquad \mathrm{Re} = \frac{\rho_f V^{2-n} D_p^n}{2^{n-3} k \left(\frac{3n+1}{n}\right)^n}$$

$$\mathrm{Pr} = \frac{2^{n-3} k \left(\frac{3n+1}{n}\right)^n c_{pf} \left(\frac{D_p}{V}\right)^{1-n}}{k_f}$$

For the best correlation, dimensional analysis was used, grouping in generalised non-dimensional numbers (the Nusselt number Nu, Reynolds number Re, Prandtl number Pr) the properties that influence the phenomenon *(12)*.

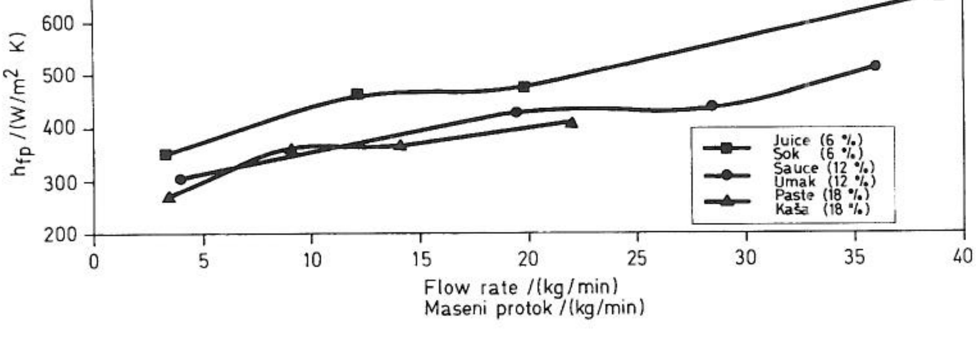

Fig. 1. Estimated values of h_{fp} vs. fluid mass flow rate for the tested products
Slika 1. Odnos između h_{fp}-vrijednosti i brzine masenog protoka ispitivanih proizvoda

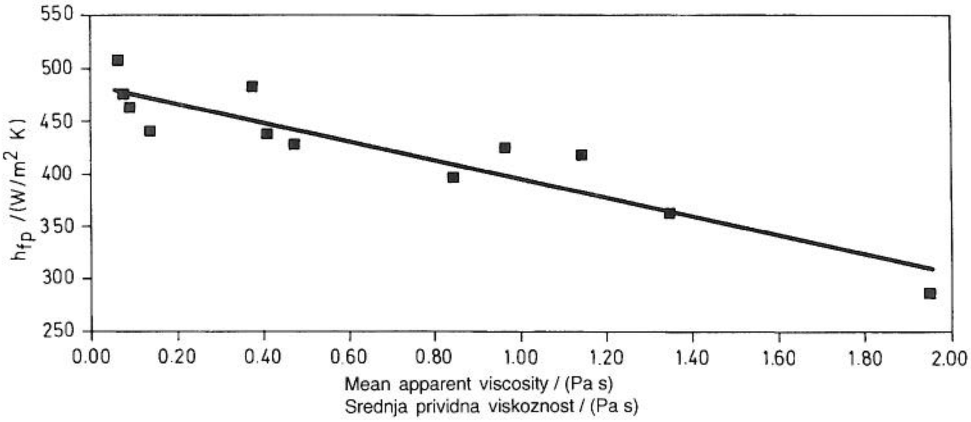

Fig. 2. Estimated values of h_{fp} vs. fluid mean apparent viscosity

Slika 2. Odnos između h_{fp}-vrijednosti i srednje prividne viskoznosti tekućine

Since these numbers were introduced for motion around spheres, D_p is the equivalent diameter of the sphere having the same surface/volume ratio of the cube, while V is the fluid linear velocity; fluid thermophysical properties (density ρ_f, specific heat c_{pf}, thermal conductivity k_f) were obtained from the correlations re-

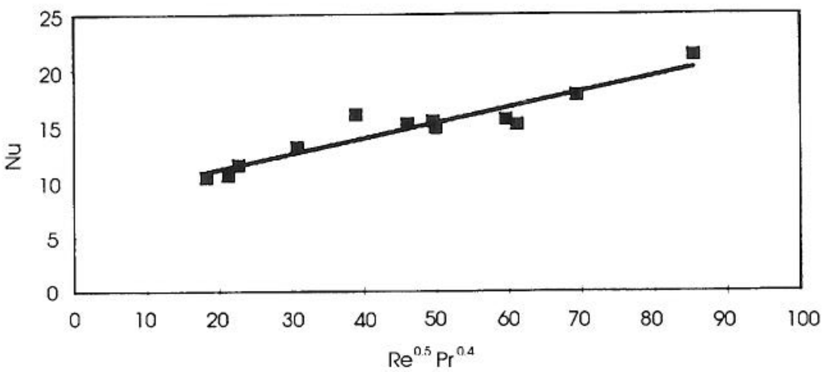

Fig. 3. Correlation among Nu, Re and Pr numbers

Slika 3. Korelacija između Nu, Re i Pr-vrijednosti

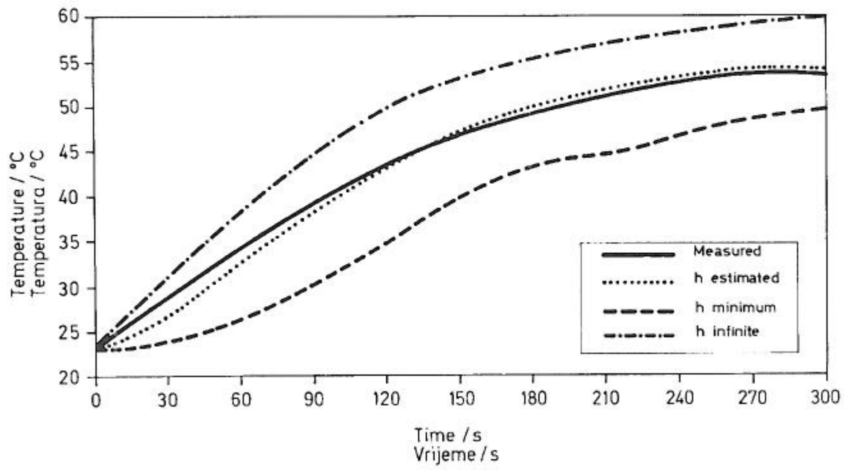

Fig. 4. Example of particle center temperature profiles: experimental data and predicted values using different procedures

Slika 4. Primjer temperaturnih profila u središtu čestice: eksperimentalni podaci i predvidive vrijednosti dobivene različitim postupcima ported in the literature; the consistency index k and flow index n come out from modelling of rheological data.

A three-variable non linear regression (Nu = f(Re, Pr)) was carried out and, for the best resulting model, parameters were estimated by least squares method. The following relationship was found:

$$Nu = 8.274 + 0.139\ Re^{0.5}\ Pr^{0.4}$$

Fig. 3. shows Nu versus $Re^{0.5}Pr^{0.4}$ with regression straight line; correlation coefficient is rather good and residua are not too high.

The obtained correlation model is very similar to those proposed in the literature *(13)*, except the value of Nu at relative velocity = 0 and Re = 0, condition at which the literature models estimate Nu = 2. The main reason for this discrepancy may be the fact that the classical models were obtained for motion of Newtonian fluid around spheres, whilst in this work Non-Newtonian fluids and cubic particle were considered. Another possible factor may be the contribution of the free convection that the classical models neglect altogether, but at limit conditions of absence of relative motion could be not negligible.

Fig. 4. shows an example of the temperature profiles at the center of the particle as calculated using h_{fp} value estimated by the described procedure, in comparison with those obtained by using the hypothesis of h_{fp} infinite and h_{fp} minimum. The agreement between calculated and experimental values is quite satisfactory and certainly better than that obtained by the two assumptions previously discussed.

Conclusions

It was demonstrated that the technique used to determine the value of h_{fp} may be a correct one but it is affected by various constraints associated with the heat channelling through the measuring thermocouple and mislocation of thermocouple within the particle. In addition, the real motion of the particles is influenced by particle-particle interactions, collisions against the pipe walls, radial migration and rotations that modify the heat transfer but are very difficult to be considered in the mathematical model.

In the following phases of the research, the whole set of variables affecting h_{fp} will be investigated, obtaining a complete set of experimental data that will be used to correlate h_{fp} with these variables. The models so found will be then inserted into the computer program in order to allow it to calculate the temperature profiles within the particles and to predict the lethal effect of a thermal treatment starting only from the process conditions.

This approach, together with the determination and modelling of residence time distribution of particles within the plant, may be one of the keys for a successfull application of aseptic technology to particulate foods.

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