Using Computational Fluid Dynamics and Numerical Simulations to Analyze the Temperature and Flow of Liquid in a Can during Sterilization

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Abstract: *There is a big growing in the last two decades in using of mathematical modeling to analyze and predict the temperature distribution in the processing engineering. In this work, transient temperature and flow pattern profiles during natural convection heating of viscous liquid were simulated and predicted. The partial differential equations of energy, continuity and momentum were solved numerically for 2D case using a commercial Computational Fluid Dynamics (CFD) package (PHOENICS) version 3.5. All the physical properties of the liquid food used are assumed constant except for viscosity (temperature dependent) and density (Boussinesq approximation). Saturated steam at 121^oC was used as a heating medium. The measured temperature at the geometric center of the can was compared with that predicted numerically. The simulations show clearly the effect of the natural convection on the flow pattern as well as on the movement of the Slowest Heating Zone (SHZ).*

Keywords: computational fluid dynamics, thermal sterilization, natural convection

Notation

C_P Specific heat of liquid food [J kg^{-1} K^{-1}]
g Gravity acceleration [ms^{-2}]
k Thermal conductivity of heated liquid [W m^{-1} K^{-1}]
p Pressure [Pa]
r Radial position from centerline [m]
r_o Radius of the used can [m]
R Gas constant [kJ (kg mol)$^{-1}$ K^{-1}]
t Heating time [s]
T Temperature [°C]
T_w Wall temperature [°C]
T_{ref} Reference temperature [°C]
u Velocity in vertical (z) direction [ms^{-1}]
v Velocity in radial (r) direction [ms^{-1}]
z Vertical distance from the bottom [m]
β Thermal expansion coefficient [K^{-1}]
μ Apparent viscosity [Pa.s]
ρ Density [kg m^{-3}]
ρ_{ref} Reference density [kg m^{-3}]

1. Introduction

Thermal sterilization is one of the most effective means of preserving a large part of our food supply. In 1981, USA alone processed more than 16 billion kg of food products using approximately 37 billion containers (Kumar *et al.*, 1990). Thermal sterilization is still common, despite the significant advancement made in food preservation techniques. This is the reason of requiring estimates of heat transfer rates in order to obtain optimum processing conditions as well as to improve product quality. In many previous studies, only conduction was assumed in heat transfer, which is true only for solids. Natural convection occurs because of density differences within the liquid caused by temperature gradient. A number of heat transfer simulation studies have been done to model the sterilization process taking into account the effect of natural convection

(Kumar *et al.*, 1990; Data and Teiiexeria, 1987; Ghani *et al.*, 1999).

As mentioned above, only in recent years, Computational Fluid Dynamics technique has been applied for several applications in many different foods processing engineering. CFD models were developed to study and analyze the techniques applied to food industry, with comparison to some of the experiment (Scott and Richardson, 1997). In this work, a computational fluid dynamics software package, known as PHOENICS, is used to solve the governing partial differential equations, which is based on Finite Volume Method (FVM). The objective in this work is to analyze the natural convection current and its effect on the movement of the SHZ in a canned liquid food and compare the results with those measured.

2. Experimental

The experimental measurements were conducted for a single can filled with same canned liquid food used in theoretical study, using steam at 121^oC. The measurements of the can used in the study measurements were 0.036 m for radius and 0.106 m for its height. The can was sitting in an upright position and heated for 50 minutes for the whole sterilization process. The common practice in the canning industry is to measure the temperature at the geometric center of the can. However, we have shown previously (Ghani *et al.*, 1999) that SHZ never stays at the geometric center of the can even during the initial period of heating. A thermocouple probe 'TSC9601 Tracksence Temperature Probe" was placed at the bottom of the can. The "Tracksence Wireless Data Logging System" was used for the measurements, with the "Tracksence Interface Station.

3. Model Equations and Solution Procedure

Computational Grid Construction

A 2-D can with non-uniform grid system was used in the simulations with 3500 cells: 70 in the axial direction and 50 in the radial direction, with a finer grid near the wall. The heating of the can containing the liquid food was simulated for a total period of 3000s. It took 10 steps to achieve the first 200s of heating, and another 10 steps to reach 1000s and finally the rest of 30 steps for the total of 3000s of heating. This required 2.5 hr of CPU time on the UNIX IBM RS6000 workstations. "PHOENICS version 3.5", was used in the simulations. The PHOENICS package is based on finite volume method, and it is developed by Patankar and Spalding (1972). The details of this software can be found in the PHOENICS manuals, especially the PHOENICS Input Language (PIL) manual.

Physical Properties

Newtonian fluid approach is the common approach applied in most of the numerical studies. In reality the canned liquid food used are generally non-Newtonian. Because of the high viscosity of the liquid food used in the simulation, the shear rate would be low. Hence, the viscosity can be assumed independent of shear rate and the fluid will behave as a Newtonian fluid, which is valid for most liquid food materials (Steffe *et al*., 1986). In this study simulation, the viscosity was assumed function of temperature, following a second order polynomial. The coefficients of the polynomial were calculated from curve fitting to available measurements, and the properties of the liquid food used in this work simulations are: ρ =1050 kg m^{-3}, C_P = 3500 Jkg^{-1} K^{-1}, k = 0.554 Wm^{-1}K^{-1} and β = 0.0002 K^{-1}.

Variation of the density with temperature is usually expressed (Adrian 1993) as:

$$\rho = \rho_{ref}[1 - \beta(T - T_{ref})] \qquad (1)$$

In this work, the density is assumed as a constant in the governing equations except in the buoyancy term (Boussinesq approximation), where equation (1) is used to describe the variation of density with temperature.

Assumptions Used in the Numerical Simulation

The following assumptions were used to simplify the case problem used in this study, which are:
1) Axisymmetry which reduces the problem from 3-D to 2-D;
2) Heat generation due to viscous dissipation is negligible (Mills, 1995);
3) Boussinesq approximation for variation of density with temperature;
4) Physical properties such as specific heat C_p, thermal conductivity k, and volume expansion coefficient β are assumed constants;
5) No-slip condition assumption at the inside wall of the can is assumed;
6) The condensing steam at outer surface of can maintain at constant temperature condition;
7) Because of the low thermal resistance of the can wall, the thermal boundary conditions are applied to liquid boundaries rather than the outer boundaries of the can (Ghani *et al*., 1999).

Governing Equations and Boundary Conditions

The partial differential equations governing natural convection motion in a cylindrical space are the Navier-Stokes equations in cylindrical coordinates (Bird *et al*., 1976) as shown below:

Continuity equation

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v) + \frac{\partial}{\partial z}(\rho u) = o \qquad (2)$$

Energy conservation

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial r} + u\frac{\partial T}{\partial Z} = \frac{k}{\rho C_p}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right] \quad (3)$$

Momentum equation in the vertical direction

$$\rho\left(\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial r} + u\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) + \frac{\partial^2 u}{\partial z^2}\right] + \rho g$$

$$(4)$$

Momentum equation in the radial direction

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r} + u\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial r} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv)\right) + \frac{\partial^2 v}{\partial z^2}\right]$$

$$(5)$$

The boundary conditions used were:

At the can boundary,
$$r = R \quad T = T_w, u = 0, v = 0, \text{ for } 0 \leq z \leq H \quad (6)$$

At the bottom of the can, z = 0,
$$T = T_w, u = 0, v = 0, \text{ for } 0 \leq r \leq R \qquad (7)$$

At symmetry, r = 0,
$$\frac{\partial T}{\partial r} = 0, \frac{\partial u}{\partial r} = 0, v = 0, \text{ for } 0 \leq z \leq H \quad (8)$$

At the top of the can, z = H
$$\frac{\partial T}{\partial z} = 0 \quad u = 0, v = 0, \text{ for } 0 \leq r \leq R \qquad (9)$$

Initially the fluid is at rest and is at a uniform temperature
$$T = T_i, u = 0, v = 0 \quad at \quad 0 \leq r \leq R, 0 \leq z \leq H \quad (10)$$

The above set of governing equations can be used for a variety of flow situations in liquids and gases. The most important parameters that specify the desired solution amongst many solutions is the boundary and the initial conditions. For a good convergence of the numerical solution to these governing partial differential equations, it is necessary to apply a proper under-relaxation or an over relaxation.

4. Result and Discussion

Figure 1 shows the streamline and the velocity vector of the flow in a can heated by a condensing steam. The figure

shows very clearly, the influence of natural convection on the flow pattern and on the movement of the SHZ (i e. the location of the lowest temperature at a given time), which is pushed toward the bottom of the can.

Stagnant zones
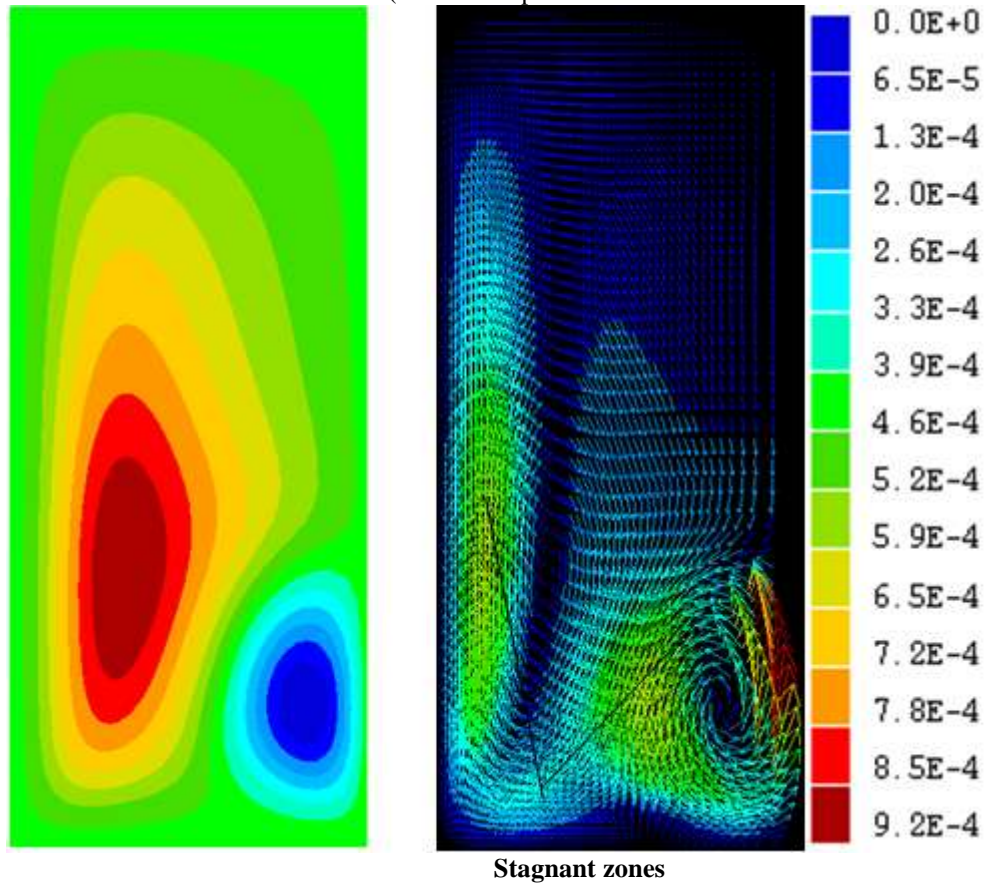
Figure 1: Streamline and velocity vector for liquid food in a can heated by a condensing steam after 20m. The right-hand side of each figure is the center line.

Figures 2(a) and 2(b), shows the temperature distribution during two heating periods of 1 min and 40 is presented in the form of isotherms in Figures 2(a) and 2(b).
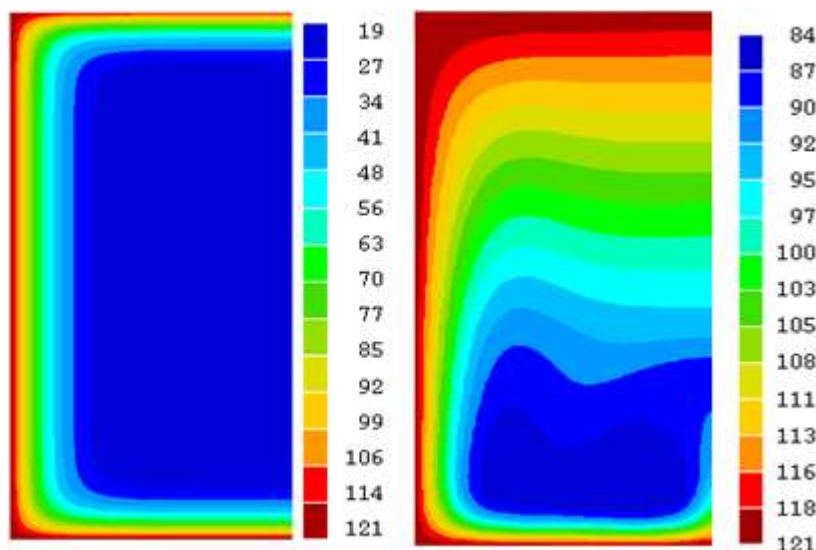
Figure 2: Temperature contours in a can filled with liquid food and heated by condensing steam after periods of (a) 1min; (b) 40min.

The isotherms at early stage of heating (t=60s) are almost identical to pure conduction heating but as heating progress, the isotherms is seen to be strongly influenced by convection. The Slowest Heating Zone in the can is not a stationary point in the liquid undergoing convection heating. Its location is not at the geometric center of the can as for the case of conduction heating. As heating progresses, it's migrating from the geometric center to the heel of the can and towards the wall as shown clearly in Figure 2(b). Traditionally, the movement of the Slowest Heating Zone is

a critical parameter in the thermal process designs. The liquid and thus the bacterial spores carried with it at this location are exposed to less heating treatment than other locations of the product. The streamline of the flow in Figure 1 shows very clearly, the effect of secondary flow on the shape of the Slowest Heating Zone

A comparison between the experimental works for the measured temperature at the geometric center of the can is compared with the theoretical works obtained from the computer simulations. It shows that, the calculated temperature at the center of the can is higher than those measured experimentally. This is expected due to the strong effect of the temperature probe, which leads in the reduction of the convection current in the can, due to its big size. This suggests that, the presence of the thermocouple probe has reduced the convection current in the can.

5. Conclusions

Transient temperature and fluid flow profiles during natural convection heating of viscous liquid in a cylindrical can have been simulated and studied by solving the governing equations for energy conservation, continuity, and momentum using finite volume method of solution. A computational fluid dynamics software package (PHOENICS) was used in the computations. The results of the simulations show that bat the early stage of heating; the Slowest Heating Zone covers the whole cross sectional area of the can, while it migrates towards the bottom of the can at later stages of heating. The results of the simulations were compared with those obtained by the experimental measurements.

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