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# Numerical simulation of natural convection heating of canned food by computational fluid dynamics

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**Abstract**

Natural convection heating within a can of liquid food during sterilization is simulated by solving the governing equations for continuity, momentum and energy conservation for an axisymmetric case using a commercial Computational Fluid Dynamics (CFD) package (PHOENICS). Transient flow patterns and temperature profiles within model liquids (sodium carboxy-methyl cellulose (CMC) and water) have been predicted. The model liquids, CMC and water, were assumed to have constant properties except for the viscosity (temperature dependent) and density (Boussinesq approximation). It has been shown that the action of natural convection forces the slowest heating zone (SHZ) to migrate towards the bottom of the can as expected. The shape and the size of the SHZ area are different for CMC and water. The magnitude of the axial velocity was found to be in the range of $10^{-5}$–$10^{-4}$ m/s for CMS and of $10^{-2}$–$10^{-1}$ m/s for water, these magnitudes of course vary with time and position in the can. The time required for the SHZ to reach the sterilization temperature of 100°C was 1800 s for CMC and only, 150 s for water. 

**Notation**

| | |
|---|---|
| $C_p$ | specific heat of liquid food (J kg$^{-1}$ K$^{-1}$) |
| $E$ | activation energy (kJ kg mol$^{-1}$) |
| Gr | Garshof number, $\mathrm{Gr} = g\beta\Delta T x^3 \rho^2/\mu^2$ |
| $g$ | acceleration due to gravity (ms$^{-2}$) |
| $H$ | height of the can (m) |
| $k$ | thermal conductivity of liquid being heated (W m$^{-1}$ K$^{-1}$) |
| $n$ | flow behavior index |
| $p$ | pressure (Pa) |
| $r$ | radial position from center line (m) |
| $r_o$ | radius of the can (m) |
| $R$ | gas constant (kJ (kg mol)$^{-1}$ K$^{-1}$) |
| $t$ | heating time (s) |
| $T$ | temperature (°C) |
| $T_w$ | wall temperature (°C) |
| $T_i$ | initial temperature (°C) |
| $T_{ref}$ | reference temperature (°C) |
| $u$ | velocity in vertical direction (ms$^{-1}$) |
| $v$ | velocity in radial direction (ms$^{-1}$) |
| $z$ | distance in vertical direction from the bottom (m) |

*Greek letters*

| | |
|---|---|
| $\alpha$ | thermal diffusivity (m$^2$ s$^{-1}$) |
| $\beta$ | thermal expansion coefficient (K$^{-1}$) |
| $\gamma$ | shear rate (s$^{-1}$) |
| $\mu$ | apparent viscosity (Pa s) |
| $\eta_0$ | consistency index (Pa s) |
| $\rho$ | density (kg m$^{-3}$) |
| $\rho_{ref}$ | reference density (kg m$^{-3}$) |

## 1. Introduction

Conventional canning processes extend the shelf life of food products and make the food safe for human consumption by destroying the pathogenic microorganisms. Despite the significant advances made in the techniques used for food preservation, canning is still the most effective method. The sterilization of the canned food is usually done by steam heating to a temperature sufficient to kill the microorganisms. The time required for the sterilization process depends on the product specifications, container type and size, and its orientation, as well as the heating medium characteristics. Excessive heating will affect food quality and its nutritive properties.

Most existing mathematical analysis are for conduction heated products only because of the simplicity of the analytical and numerical solutions. However, detailed analysis of the convection heating is of great im-

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portance in the food industry. In natural convection heating, the velocity in the momentum equations is coupled with temperature in the energy equation because the movement of fluid is solely due to the buoyancy force. Because of this coupling, the energy equation needs to be solved simultaneously with the momentum equations. Estimation of the heat transfer rates is essential in order to obtain optimum processing conditions and to improve product quality. Also a better understanding of the mechanism of the heating process will lead to an improved performance in the process and maybe to some energy savings. Basic principles for determining the performance of different, but related processes have been presented by May (1997) and Wilbur (1996).

Conduction, natural convection and forced convection are important means of heat transfer in the thermal processing of food. Foods like canned tuna, thick syrups, purees and concentrates are usually assumed to be heated by pure conduction. For these foods, the required processing time is generally determined by analytical or numerical solution of the heat conduction equation (Datta, Teixeria & Manson, 1986).

Dincer, Varlik and Gun (1993) has also studied transient heat transfer during sterilization of canned foods. Their model was based on solving the conduction equation with constant wall temperature as a boundary condition. Lanoiselle, Candau and Debray (1986) developed a linear recursive model to represent the heat transfer inside a can during sterilization in a retort and predicted the temperature of canned foods during thermal processing.

Akterian (1994) developed a numerical model for the determination of the unsteady-state temperature field in conduction heated canned foods of various shapes under convective boundary conditions. The heat conduction equation is solved by means of a generalized finite difference approach, allowing the reduction of a multidimensional problem to a one-dimensional problem.

The numerical predictions of the transient temperature and velocity profiles in a still retort during natural convection heating of canned liquid foods has been carried out by Datta and Teixeira (1988). Water was used to simulate liquid food, which was heated uniformly around the can outside surface in a cylindrical can, and it was found to be stratified inside the container with increasing temperatures towards the top. They predicted significant internal circulation at the bottom of the can and showed that, the slowest heating zone (SHZ) has a doughnut-shape and is close to the bottom of the can at about one tenth of the can height.

Sterilization of a viscous liquid food in a metal can sitting in an upright position and heated from the side wall ($T_w = 121°C$) in a still retort was simulated by Kumar, Bhattacharya and Blaylock (1990). The equations of continuity, momentum and energy conservation for an axisymmetric case were solved to provide plots of temperature, velocity and streamlines for natural convection heating. These were compared with pure conduction contour plots. They also presented a simulation for the same can when its bottom and top surfaces were insulated (Kumar et al., 1990). The model liquid food was assumed to have viscosity varying with temperature but with constant specific heat and thermal conductivity. The results indicated that, natural convection again tends to push the slowest heating region to the bottom of the can.

The sterilization of a can filled with a viscous liquid sodium carboxy-methyl cellulose (CMC), heated by condensing steam on all sides and the case where the top is insulated (i.e. there is an air gap present), were simulated most recently by Ghani, Mohammed and Chen (1998). The temperature difference from top to bottom of the can at the end of 2574 s was 12°C for the can with top insulated and 10°C for the case of can heated from all sides. The results show also that the locations of the SHZ for both cases are similar. This is due to the strong effect of the natural convection current, even when the liquid was highly viscous. In some of the simulations, and for water as a liquid food, the wall was not assumed to be at a constant temperature, but a convective boundary was also used by Ghani (1998). The results of such simulations showed very little difference from those predicted for the constant wall temperatures, this is due to the large heat transfer coefficient of the condensing steam. The change in the temperature distribution was very small in the above two cases, suggesting that the simulation of a can heated from all sides, and assuming constant wall temperature is appropriate for a general purpose.

## 2. Computational fluid dynamics and the food industry

Computational fluid dynamics (CFD) offers a powerful design and investigative tool to process engineers. Its application would assist in a better understanding of the complex physical mechanisms that govern the thermal, physical and rheological properties of food materials. CFD has only recently been applied to food processing applications. It has seen applications in many different processing industries, including airflow in clean rooms, ovens and chillers, flow of foods in continuous-flow systems and convection patterns during thermal processing (Scott & Richardson, 1997).

When considering the flow of food products, it is often necessary to take the rheological nature of a food into account because this will dictate its flow behavior. Most foods exhibit some form of non-Newtonian behavior and many different flow models have been used to describe such behavior. As for turbulence problems, the inclusion of a non-Newtonian flow model requires

the solution of an extra equation. However, It should be noted that the current state of CFD does not permit the prediction of turbulent flow for non-Newtonian fluids because this is at the forefront of numerical non-Newtonian rheology research (Holdsworth, 1993).

In this work, sterilization of canned liquid food in a still-retort was numerically studied and analyzed using CFD and the results were presented in the form of transient temperature, velocity profiles and flow patterns. CMC and water were used as the model liquids. Density variations were governed by the Boussinesq approximation (a commonly used assumption for buoyancy problems whereby the density variations are not explicitly modeled but their effect is represented by a buoyancy force which is proportion to the temperature variation). The viscosity is varying with the temperature. Specific heat, thermal conductivity and volume expansion coefficient were all assumed to be constants.

The PHOENICS code used is based on the finite volume method, as developed by Patankar and Spalding (1972). The key characteristic of this method is the immediate dicretization of the integral equation of flow into the physical three-dimensional space, i.e. the computational domain cover the entire can, which is divided into a number of divisions in the three dimensions (NX, NY, NZ). The details of this code can be found in the PHOENICS manuals, especially the PHOENICS Input Language (PIL) manual.

The observation of the SHZ is a difficult task and requires knowing detailed transient flow patterns and temperature profiles, due to the complex nature of heat transfer in natural convection heating. The partial differential equations, governing such a system, need to be solved in their entirety using numerical techniques. The objective of this work is to study the effect of the natural convection current on the movement of the coldest point or zone in a can of liquid food. The results were compared with those obtained by Kumar and Bhattacharya (1991) for the viscous liquid and with Datta and Teixeria (1988) for water as a liquid food.

## 3. Basic model equations and solution procedure

Most of the previous studies except that of Kumar, Bhattarcharya and Blaylock (1990) and Kumar and Bhattacharya (1991), have been applied to Newtonian foods. In reality foods are generally non-Newtonian. Incorporation of temperature dependence into the viscosity model further complicates the problem for the numerical simulation.

In this study, the computations were performed for a can with the radius of 0.0405 m and height of 0.111 m for the viscous liquid, similar to that used in the study of Kumar and Bhattacharya (1991). For water, a can with radius of 0.0419 m and height of 0.107 m was used, similar to that used in the study of Datta and Teixeira (1988). The choices of the dimensions of the cans were purely for the purpose of comparison. The can outer surface temperature (top, bottom and side) was assumed to rise instantaneously and to be maintained at 121°C throughout the heating period.

### 3.1. Computational grid

The boundary layer occurring at the heated walls and its thickness is one of the very important parameters to the numerical convergence of the solution. Temperature and velocities have their largest variations in this region. To adequately resolve this boundary layer flow i.e. to keep discretization error small, the mesh should be optimized and a large concentration of grid points are needed in this region. If the boundary layer is not resolved adequately, the underlying physics of the flow is lost and the simulation will be erroneous. On the other hand, in the rest of the domain where the variations in the temperature and velocity are small, the use of a fine mesh will lead to increases in the computation time without any significant increase in accuracy. Thus a non-uniform grid system is needed, to resolve the physics of the flow properly.

A non-uniform grid system was used in the simulations with 3519 nodal points: 69 in the axial direction and 51 in the radial direction, graded in both directions with a finer grid near the wall. The natural convection heating of CMC was simulated for 2574 s. It took 100 steps to achieve the first 180 s of heating, another 100 steps to reach 1000 s and 300 steps for the total of 2574 s of heating. In the simulation of water as a model liquid food, the total time of heating was also divided into 300 time steps. The time interval was increased progressively with heating, It took 100 steps to achieve the first 200 s of heating, another 100 steps to reach 600 s and 300 steps for the total of 1800 s of heating. This required 63 and 18 h respectively of CPU time on the UNIX IBM RS6000 workstations at the University of Auckland.

### 3.2. Physical properties

In the simulation of water and CMC, the viscosity was assumed function of temperature, and a second order polynomial of the form

$$\mu = a + bT + cT^2 \tag{1}$$

was used as in the PHOENICS program.

In the simulation of water, values of $a$, $b$ and $c$ were $1.6\times10^{-3}$, $-2.988\times10^{-5}$ and $7.8\times10^{-8}$. These values were obtained from the curve fitting of viscosity verses temperature (Holman, 1992).

Food materials are in general highly non-Newtonian and hence the viscosity is a function of shear rate and

temperature with a flow behavior index typically less than one. CMC suspended in water was used as the model fluid. Due to the extremely high viscosity of the CMC, which causes liquid velocities to be very low, the shear rate calculated from our previous simulation (Ghani, 1998), was found of the order of 0.01 $s^{-1}$, which is in agreement with values reported by Kumar and Bhattacharya (1991). Because of the low shear rate the viscosity may be assumed independent of shear rate and the fluid will behave as Newtonian fluid. This Newtonian approximation is valid for most liquids food materials such as tomato puree, carrot puree, green bean puree, apple sauce, apricot puree, and banana puree which are regularly canned and usually preserved by heating (Steffe, Mohamed & Ford, 1986).

Kumar and Bhattacharya (1991), used the following viscosity model

$$\mu = \eta_0 \gamma^{n-1} \exp\left(\frac{nE}{RT}\right). \tag{2}$$

At the low shear rate observed in our work, Eq. (2) shows that, the viscosity can be assumed independent of shear rate. Eq. (2), with the parameters given in Table 1. was used to calculate the values of viscosity at different temperatures. This was done to maintain the same values of viscosity that used by Kumar and Bhattacharya (1991) for the purpose of comparison. These values were correlated in a second order polynomial of the form similar to that for water, with $a$, $b$ and $c$ having the values of 4.135, $-6.219\times10^{-2}$ and $2.596\times10^{-4}$.

The variation of the density with temperature is usually expressed (Adrian, 1993) as:

$$\rho = \rho_0[1 - \beta(T - T_0)], \tag{3}$$

where $\beta$ is the thermal expansion coefficient of the liquid, $T_0$ and $\rho_0$ are the temperature and density at the reference condition (Adrian, 1993). The density was assumed constant in the governing equations except in the buoyancy term (Boussinesq approximation), where Eq. (3) was used to describe its variation with temperature.

Table 1
Properties of the 'liquid food' measured at room temperature used in the simulation, same as those used by Kumar et al. (1991)

| Property | Value |
|---|---|
| Density ($\rho$)[a] | 950 kg $m^{-3}$ |
| Specific heat ($C_p$) | 4100 J $kg^{-1}$ $K^{-1}$ |
| Thermal conductivity ($k$) | 0.7 W $m^{-1}K^{-1}$ |
| Volumetric expansion coefficient ($\beta$) | 0.0002 $K^{-1}$ |
| Flow behavior index ($n$) | 0.57 |
| Consistency index ($\mu_0$) | 0.002232 Pa $s^n$ |
| Activation energy ($E$) | $30.74\times10^3$ kJ kg $mol^{-1}$ |

[a] $\rho$ = constant and varies only in the gravitational force term in the momentum Eq. (6) according to Eq. (3).

For viscous liquids, the viscous forces are high and thus Grashof number is low. This can be shown clearly for CMC at which Grashof number is in the range $10^{-2}$–$10^{-1}$ (using maximum temperature difference and maximum viscosity) as compared to the water case, which is in the range of $10^9$–$10^{10}$. The magnitude of the Grashof number gives a good indication whether the natural convection flow is laminar, transitional or turbulent.

### 3.3. Assumptions used in the numerical simulation

To simplify the problem, the following assumptions were made:

1. Axisymmetry which reduces the problem from three-dimensional to two-dimensional;
2. Heat generation due to viscous dissipation is negligible, this is due to the use of high viscous liquid with very low velocities (Mills, 1995);
3. Boussinesq approximation is valid;
4. Specific heat ($C_p$), thermal conductivity ($k$), and volume expansion coefficient ($\beta$) are constants (Table 1);
5. The assumption of no-slip condition at the inside wall of the can is valid;
6. The condensing steam maintains a constant temperature condition at the can outer surface;
7. The thermal boundary conditions are applied to liquid boundaries rather than the outer boundaries of the can, because of the low thermal resistance of the can wall.

### 3.4. 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, Stewart & Lightfoot, 1976) as shown below:

Continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v) + \frac{\partial}{\partial z}(\rho u) = 0. \tag{4}$$

Energy conservation:

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial r} + u\frac{\partial T}{\partial z} = \frac{k}{\rho C_p}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right]. \tag{5}$$

Momentum equation in the vertical direction:

$$\rho\left(\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial r} + u\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) + \frac{\partial^2 u}{\partial z^2}\right] + \rho g. \tag{6}$$

Momentum equation in the radial direction:

$$\rho\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial r}+u\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv)\right)+\frac{\partial^2 v}{\partial z^2}\right]. \tag{7}$$

The boundary conditions used were:At the can boundary, $r = R$,

$$T = T_w, \quad u = 0, \quad v = 0, \quad \text{for } 0 \leqslant z \leqslant H. \tag{8}$$

At the bottom of the can, $z = 0$,

$$T = T_w, \quad u = 0, \quad v = 0 \quad \text{for } 0 \leqslant r \leqslant R. \tag{9}$$

At symmetry, $r = 0$,

$$\frac{\partial T}{\partial r} = 0, \quad \frac{\partial u}{\partial r} = 0, \quad v = 0, \quad \text{for } 0 \leqslant z \leqslant H. \tag{10}$$

At the top of the can, $z = H$

$$\frac{\partial T}{\partial z} = 0, \quad u = 0, \quad v = 0, \quad \text{for } 0 \leqslant r \leqslant R. \tag{11}$$

Initially the fluid is at rest and is at a uniform temperature

$$T = T_i, \quad u = 0, \quad v = 0 \quad \text{at} \quad 0 \leqslant r \leqslant R, \quad 0 \leqslant z \leqslant H. \tag{12}$$

The same set of governing equations describes a wide variety of flow situations in liquids and gases. The boundary and the initial conditions are the most important parameters that specify the desired solution amongst many solutions possible for the set of equations.

To obtain 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. The improper over-relaxation or under-relaxation parameter can easily make the computations impracticably long. Many of these optimum parameters are not known at the initial stage and can only be found through numerical experimentation.

For the simulation of water as a liquid food, and because it has lower viscosity, more iterations were required to improve the accuracy. Different under relaxation was also used, to keep the computation stable.

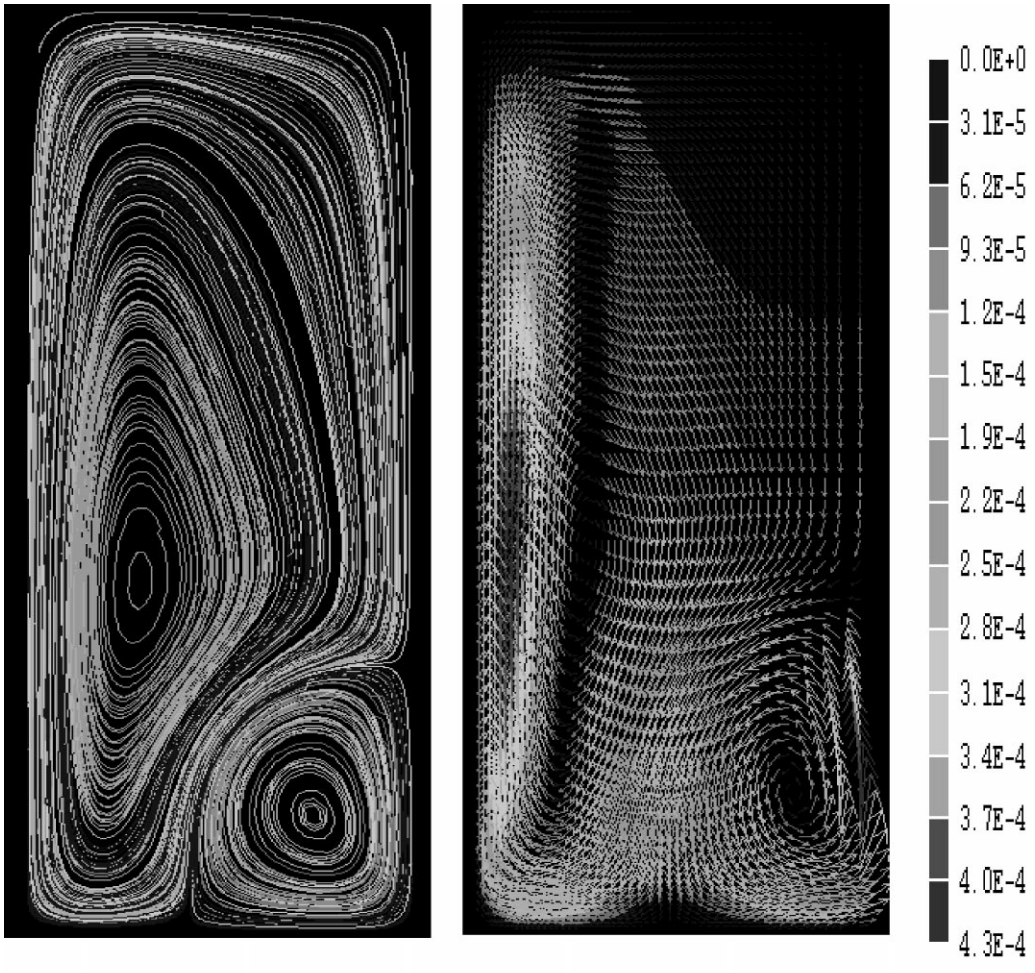


Fig. 1. Velocity vector and flow pattern of CMC in a cylindrical can heated by condensing steam (constant wall temperature, variable viscosity) after 1157 s.

## 4. Results and discussion

### 4.1. Flow pattern

Figs. 1 and 2 show, the velocity vector and the flow pattern of the CMC and water in a can heated by steam condensing along its outside surface. Both figures show that, the liquid adjacent to the wall, top and bottom surfaces will receive heat from the condensing steam. As the liquid is heated, it expands and thus gets lighter. Liquid away from the side wall stays at a much lower temperature. The buoyancy force created by the change in liquid density due to temperature variation (from the wall to the core) produces an upward flow near the side wall. The hot liquid going up is deflected by the top wall and then travels radially towards the core. Being heavier, the liquid in the core moves downwards and then towards the wall. Thus a recirculating flow is created.

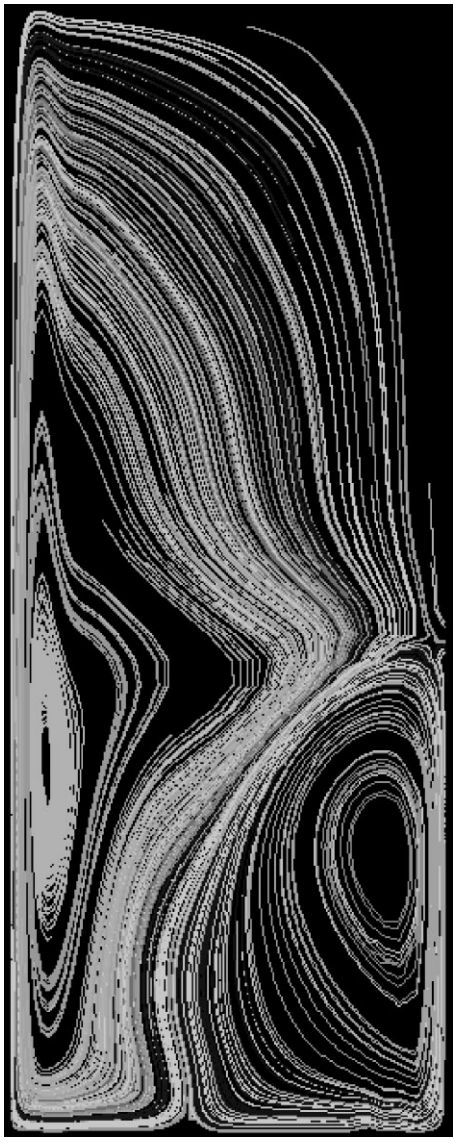

Fig. 2. Flow patterns of water as a liquid food in a cylindrical can heated by condensing steam (constant wall temperature, variable viscosity) after 180 s.

These figures, also, show that the liquid next to the wall is at rest because of the no-slip boundary conditions. For CMC, the magnitude of the maximum axial velocity at the mid-height near the wall were 0.31 mm $s^{-1}$ at $t = 1157$ s, which was in a good agreement with the results of Kumar and Bhattacharya (1991), who used the same viscous liquid (CMC) and the same heating conditions. Much higher velocities for water contained in a can and heated under similar conditions have been obtained. The magnitudes of the velocity were 40 and 19 mm $s^{-1}$ after 30, 240 s of heating. These differences in the magnitudes of the velocity vectors between CMC and water can be explained in terms of the Grashof number, which represents the ratio of the buoyancy force to viscous force. These results are also in reasonable agreement with the results of Datta and Teixeria (1987) for water. Because of these high velocities, the coldest region in the can reached 99°C after only 120 s of heating, compared to 1700 s for the CMC. As heating progressed, a more uniform velocity was obtained, reducing buoyancy force in the liquid that lead to significant reduction in the velocity. The difference in the magnitude of the velocities for water and the more viscous liquid used in our analysis is expected to be due to the large difference in the viscosity of the two liquids.

Hiddink (1975) reported that for viscous fluids, the thickness of the ascending liquid region near the wall was greater than that for water which was attributed to the large difference in the values of viscosity of the two fluids. The reported thickness was about 12–14 mm for the viscous liquid as compared to 6–7 mm for water. Kumar and Bhattacharya (1991) illustrated that the thickness of ascending liquid for a more viscous liquid was in the range of 15–16 mm. Fig. 1 shows that the thickness of ascending viscous liquid (CMC) is in the range of 16–20 mm, which is the distance between the location of the stagnent region and the wall (measured based upon the actual can dimension). This results is in agreement with the results of Kumar and Bhattacharya (1991) and Hiddink (1975). Datta and Teixeira (1987) have reported the formation of secondary flow (or eddies formation) at the bottom of the can near the center line. The simulation, which has been done by Kumar and Bhattacharya (1991) for thick liquid (CMC) did not show any formation of secondary flow or eddies, however in our simulation, the secondary flow was evident in all the cases studied which is expected whenever there is heating from the buttom. Figs. 1 and 2for both CMC and water show clear secondary flow formation at the bottom of the can.

### 4.2. Slowest heating zone and temperature profile

The temperature distribution during heating is presented in the form of isotherms in Figs. 3 and 4, for CMC and water respectively, and for different periods of heating. For CMC, the isotherms at $t = 54$ s are almost identical to pure conduction heating but over time, the isotherms are seen to be strongly influenced by convection. However for water, Fig. 4 shows a strong influence of natural convection, even at the early stages of heating.

After short period of heating, the fluid near the bottom is heated by conduction. However, instability results from the large difference in the temperature between the heated bottom and the colder liquid coming in contact with the bottom. This instability in the bottom layer gives rise to bursts of convective cells (i.e. the Benard convection cells). Fig. 4 for water shows the irregular shape of the isotherms near the bottom, which is caused by the random nature of Benard convective cell formations.

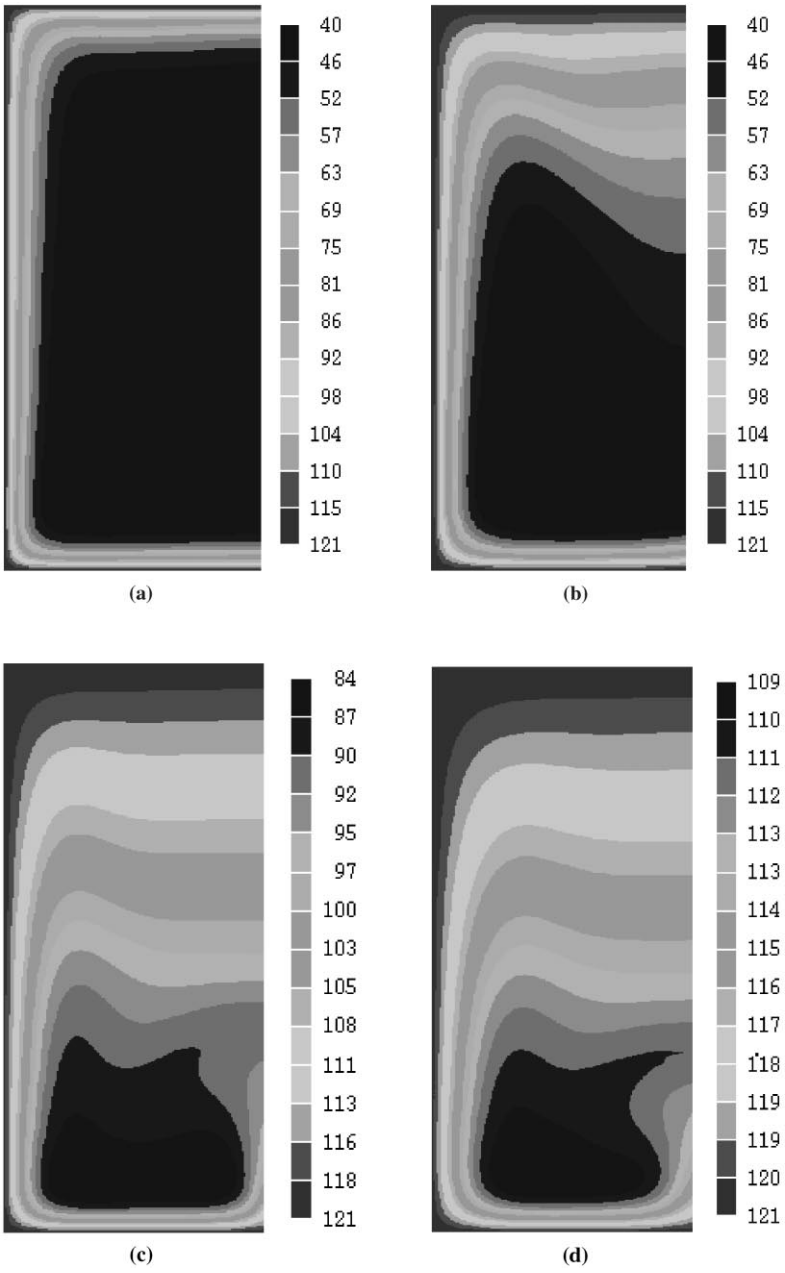


Fig. 3. Temperature contours in a can filled with CMC and heated by condensing steam after periods of (a) 54 s; (b) 180 s; (c) 1157 s; (d) 2574 s. The right-hand side of each figure is centre line.

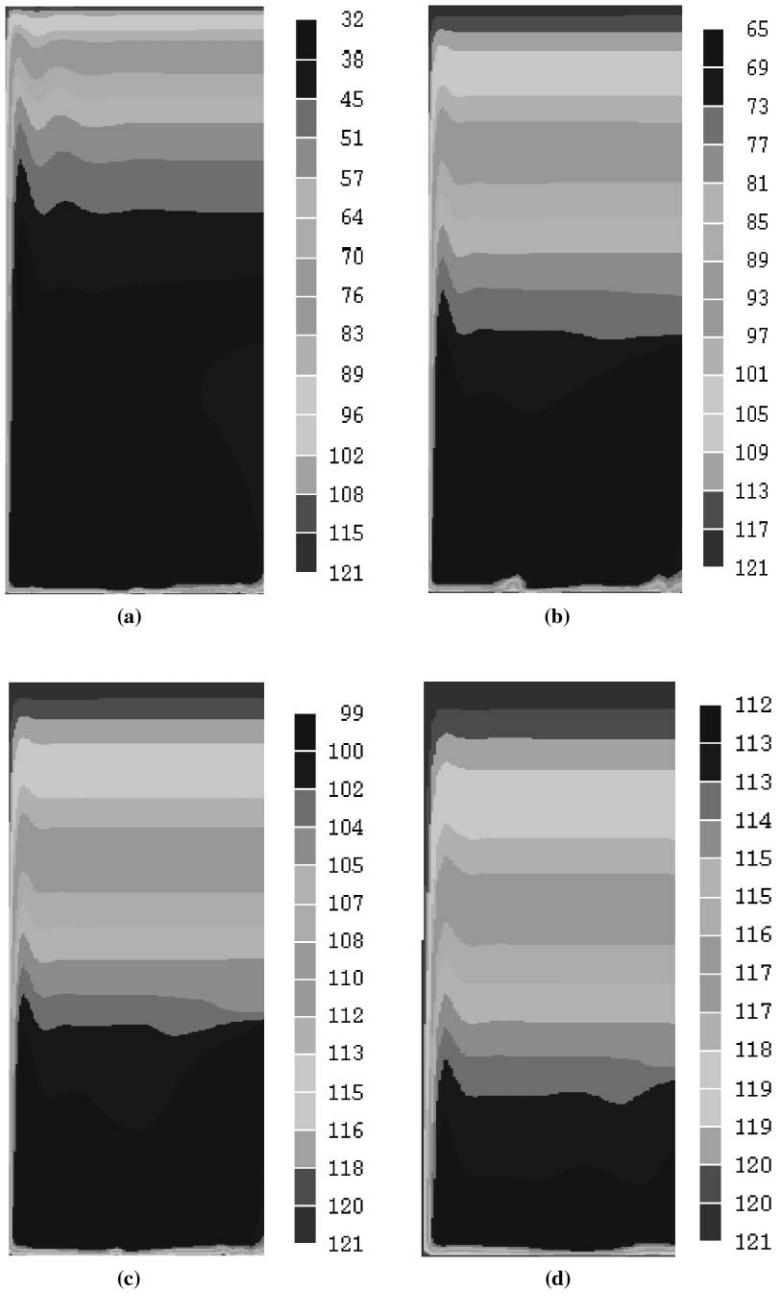


Fig. 4. Temperature contours in a can filled with water heated by steam (constant wall temperature, variable viscosity), for the periods of (a) 20 s; (b) 60 s; (c) 120 s; (d) 180 s. The right-hand side of each figure is center line.

The SHZ in the can (i.e. the location of the lowest temperature at a given time) is not a stationary region in the liquid undergoing convection heating. Its location is not at the geometric center of the can as it is in the case of conduction heating. Initially the content of the can is at uniform temperature. As heating begin, the mode of heat transfer changes from conduction to convection, and the SHZ moves from the geometric center to the heel of the can as shown in Fig. 3 for CMC. Fig. 4 for water, shows that the SHZ is not at the center of the can even during the initial period of heating. As heating progresses, the SHZ is pushed more towards the bottom of the can as with the CMC. It appears that the SHZ keep moving during heating and eventually stays in a region that is about 10–12% of the can height from the bottom in both cases.

Traditionally, the movement of the coldest point is a critical parameter in identifying the SHZ for food products in thermal process designs. Zechman and Pflug (1989) reported a location of the SHZ at about 10% height from the bottom whereas Datta and Teixeira (1987) found it to migrate to slightly higher locations

(15% from the bottom). These observations are in agreement with those found in this work and also with those reported by Kumar and Bhattacharya (1991).

Fig. 3 shows that, for CMC, the SHZ develops peculiar shape after only short period of heating. The SHZ does not cover the whole bottom section of the can. However, for water, the SHZ fills the whole bottom section of the can as shown clearly in Fig. 4. The simulation shows, for the first time, the effect of secondary flow on the shape of the SHZ. The effect is to push the SHZ towards the wall as may be clearly seen in Fig. 3 for the CMC. According to this finding, careful consideration must be made in representing the coldest point by the measured temperature at the axis of the can, particularly at extreme locations close to the top and bottom, as may be seen in both Figs. 3 and 4. The temperature of the SHZ reached about 100°C in 1800 s, in comparison to 150 s for water.

Fig. 5 for water, shows that, the change of the temperature of the SHZ with heating time as predicted by our simulation based on constant viscosity (measured at the film temperature) and the viscosity as function of temperature. This figure includes also, the data reported by Datta and Teixeira (1987), which based on constant viscosity. The result of the simulation done in this work, based on constant viscosity, is in a good agreement with that of Datta and Teixeira (1987). When the viscosity is assumed a function of temperature, a much faster heating rate is observed. This shows the importance of taking into account, the variation of viscosity with temperature, which has not been considered in the simulation of water as a liquid food, in most of the previous work. Similar observation may be found in Fig. 6 for the temperature at the mid point location of the can.

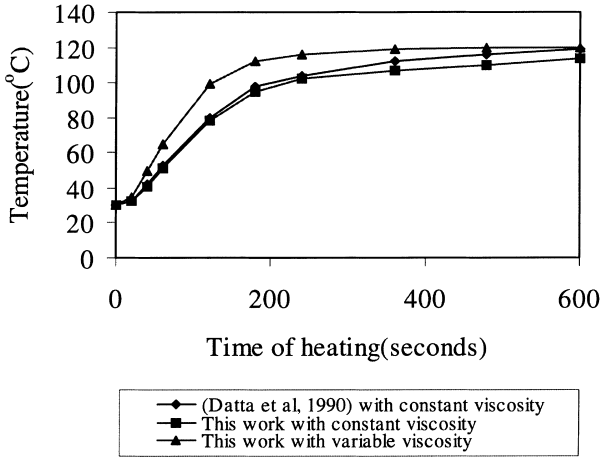


Fig. 5. Transient temperature of water at a slowest heat location in a cylindrical can during 600 s of heating.

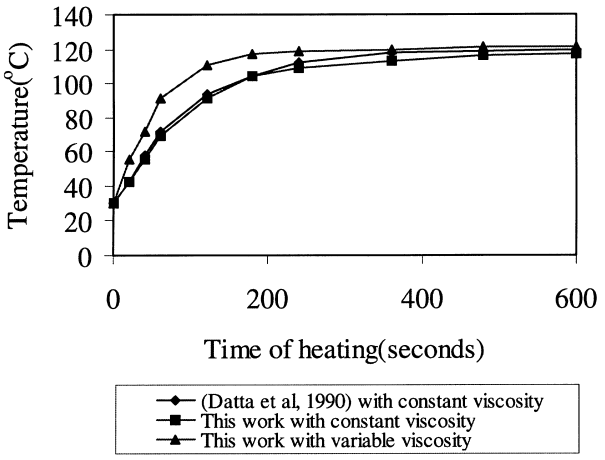


Fig. 6. Transient temperature of water at a mid point location on axis in a cylindrical can during 600 s of heating.

## 5. Conclusions

Transient temperature and velocity distribution evolving during natural convection heating of thick liquid (CMC) and water in a cylindrical can have been simulated by solving the governing equations for continuity, momentum and energy conservation using finite volume method of solution. A CFD software package (PHOENICS) was used to carry out the computations.

The results of the simulation show a recirculating flow inside the can consisting of liquid rising near the wall, radial flow, and uniform core flow downwards near the axis. Also, a secondary flow occurs at the bottom of the can due to reverse flow. The liquid inside the container shows an increase in temperature towards the top. For CMC the coldest region ( i.e. the location of the SHZ) covers the whole cross sectional area of the can at the early stages of heating while it migrates towards the bottom of the can. The secondary flow at the bottom of the can pushes the SHZ closer to the wall.

The SHZ in the simulation of water fills the whole bottom section of the can. While for CMC, the region develops peculiar shape after only short period of heating. Also, it appears that the SHZ kept moving during heating and eventually stayed in a region that is about 10–15% of the can height from the bottom in both cases. It was found also, that, the heating rate is much faster, when the viscosity assumed to be function of temperature, than for constant viscosity.

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