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Enhanced food sterilization through inclination of the container walls and geometry modifications

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Abstract

It is desirable to reduce the time taken for sterilization without compromising on the criterion of the slowest heating zone (SHZ) in the container reaching the minimum prescribed temperature. In this study, the required sterilization times for food cans of equal volumes but different shapes ranging from full cone through truncated cones to full cylinder were investigated. Further, the effect of orientation of the can was also investigated by inclining these geometries from 0–180°. The non-Newtonian fluid (0.85% w/w CMC) was taken as the test food material and its laminar flow behavior analysed using computational fluid dynamics. It was observed that among these geometries the lowest sterilization time was observed for a vertically oriented upright full conical can. The cylinder gave lower sterilization time when oriented horizontally than vertically. The sterilization times of truncated conical cans were intermediate to those determined for full cone and cylinder. Even a small inclination in the orientation of the cans may lead to significant increase in the sterilization times due to decrease in the convective velocities. The slowest heating zone movement in both axial and radial directions was tracked for various geometries and typical results are presented. The convective velocities, volume of region above and the surface area below the slowest heating zone determine the time taken for sterilization. When geometry modifications are made for aesthetic reasons to the food container, the utilization of known sterilization times for the conventional cylindrical can of the same volume may be inappropriate for suitable thermal treatment.

Keywords: Food sterilization; Slowest heating zone; Natural convection; Geometry modifications; Angle of orientation

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1. Introduction

Natural convection induced by thermal buoyancy effects in a gravitational force field has several applications. These include air conditioning of buildings, design of storage of hot fluids in solar power plants, electronic components design and food sterilization [1–3]. Canned liquid foods are sterilized in still retorts with steam flowing around the solid surface. Thermal sensitivity of the food material, fragile/flexible nature of the packing or cost rules out vigorous heat transfers by agitation [4]. Food material that are sterilized in this fashion are heat pasteurized beer, fruit and vegetable juices, thin soups, broth, fruits in syrup or water, evaporated milk, pureed vegetables, mixed fruit salads, and vegetable soups [4,5]. The slowest heating zone (SHZ) refers to a core region in the can that takes the longest time relative to the other regions to reach the final sterilization temperature and hence represents the rate limitation. Pflug [6] defined

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Nomenclature

CMC	carboxy-methyl cellulose
C_p	specific heat of the liquid in the can ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
E_a	activation energy ($\mathrm{kJ\,kg^{-1}\,mol}$)
g	gravitational acceleration constant ($\mathrm{m\,s^{-2}}$)
Gr	Grashoff number ($\frac{g\beta\Delta T H^3\rho^2}{\eta^2}$)
h_total	specific total enthalpy ($\mathrm{J\,kg^{-1}}$)
H	height of the food can (m)
k	thermal conductivity of the liquid in the can ($\mathrm{W\,m^{-1}\,K^{-1}}$)
n	exponent to shear rate in dynamic viscosity expression (–)
R	radius of the food can (m)
S_M	source term for momentum
S_E	source term for energy
SHZ	slowest heating zone
t	time of heating (s)
T	temperature (K)
T_wall	temperature at the wall of the can (K)
Vol_avg	volume average
$\mathbf{V}$	velocity vector
V_r	velocity in the radial direction ($\mathrm{m\,s^{-1}}$)
V_z	velocity in the axial direction ($\mathrm{m\,s^{-1}}$)
β	thermal expansivity ($\mathrm{K^{-1}}$)
δ	Kroneckar delta
γ	rate of shear ($\mathrm{s^{-1}}$)
η	apparent viscosity (Pa s)
η_0	consistency index (Pa s^n)
η_ref	characteristic viscosity (Pa s)
ρ	density ($\mathrm{kg\,m^{-3}}$)

the SHZ as the region in the food product that receives the least sterilization during the heat transfer process.

2. Background and scope

In this work, computational fluid dynamics (CFD) is used to simulate the transient heat transfer in a typical non-Newtonian fluid representing the food medium. Engelman and Sani [7] numerically simulated the pasteurization of beer in glass bottles. Lanoiselle et al. [8] used a linear recursive model to predict the internal temperatures of canned food undergoing thermal sterilization. Datta and Teixeira [4] determined the transient flow and temperature patterns through numerical simulation for a can uniformly heated on all sides. Zechman and Pflug [9] studied the influence of medium properties and size of metal containers on the location of SHZ of the canned media. Kumar et al. [5] numerically simulated the natural convective heating of canned thick viscous liquid food heated from the sidewall. Kumar and Bhattacharya [10] simulated the case involving a pseudoplastic liquid food with heating on all sides. Akterian [11] determined transient conduction temperature profiles in various types of shapes. Brody [12] reviewing food canning in the 21st century observed that a variety of can shapes are offered for low acid foods. He further states that the thermodynamics for post fill processing for this broad matrix are increasingly complex and the engineer must determine the temperature patterns within each under a variety of post-fill protocols to maximize input to achieve sterility. A number of studies have been made on the thermal analysis of different shapes including cones and geometries with elliptic cross-sections [13,14]. However these studies are restricted to conduction heat transfer only. In recent times computational fluid dynamics tools have been applied to numerically simulate the unsteady state natural convective heating of canned food [15]. Ghani et al. [16] studied both experimentally and numerically the thermal deactivation of bacteria in food pouches. These authors [17] also reported simulation and experimental results on the thermal destruction of vitamin C housed within food pouches. Subsequently, Ghani et al. [18] investigated the sterilization of orange soup in a cylindrical container and concluded that the heating rate was faster when the container was vertical. The effect of mechanical rotation of a horizontal container at 10 rpm in the thermal sterilization of viscous orange–carrot soup has also been studied [19]. The combined effect of natural and forced convection was found to split the slow heating zone into two regions.

Modifications to the sterilization process pertaining to the cylindrical container geometry and its orientation, without involving mechanical agitation have received little attention. This study also brings out the effect of specific shape modifications and orientations on the sterilization process. Work carried out prior to this study [20] indicated that between full cones and cylinder of equal volume and heights in the upright position, the cone pointing upwards gave the fastest sterilization followed by the cylinder and the cone pointing downwards (paper under review). Hence there is scope for exploring the possibility of suitably altering the cylinder geometry towards that of a truncated cone of varying angles of inclination of the surface walls with respect to the base to determine a more suitable configuration if any between the full cone and the full cylinder. At a certain critical angle of wall inclination, the truncated cone becomes a full cone. The criterion is to identify the container configuration and its orientation that will reduce the time taken by the slowest heating zone to reach the final sterilization temperature of 100 °C. Equal volumes of the canned material were considered.

In actual sterilization operation, known results for standard configurations such as the cylinder may not suffice to predict the required sterilization times for non conventional designs made for aesthetic reasons. Further the effect of inclination of the can in the sterilization unit, intentional or inadvertent, may also be a factor in influencing the sterilization times. Temperature probes disturb the flow patterns and the measured temperatures measured will be in error [5]. Further the location of the SHZ is also not fixed to a certain location and moves in the domain. Numerical methods involving computational fluid dynamics to determine the temperature-velocity profiles as well as trace the movement of the slowest heating zone were carried out in the present work. The results from this study would then be useful for planning the strategy to be adopted by the food process engineer to design the sterilization process.

3. Details of system and can geometry

The pseudoplastic fluid involving 0.85% w/w CMC solution was taken as the test system. The properties of this system based on Kumar and Bhattacharya [10] are given in Table 1. Steffe et al. [21] suggested that this model to be applicable for tomato puree, carrot puree, green bean puree, applesauce, apricot and banana purees, which are regularly canned and preserved usually by heating. The conventionally used cylindrical can as well as its modifications in forms of truncated/full cones at various orientations was considered for the food sterilization process. Typical configurations are shown in Fig. 1 and details of geometries investigated are presented in Table 2. The volume ($572\ \mathrm{cm}^3$) and height (111.11 mm) are maintained to be the same as that of the cylinder.

Table 1
Properties of the canned food system represented by 0.85% w/w CMC [10]

System properties	Value/expression	Units
Viscosity (η)	$\eta = \eta_0 \exp(\frac{nE_a}{RT})\dot{\gamma}^{n-1}$	Pa s
Consistency index (η_0)	0.002232	Pa s^n
Characteristic viscosity (η_{ref})	13.57	Pa s
Activation energy (E_a)	30.74×10^3	J/g mol
Shear rate ($\dot{\gamma}$)	If below 0.01, assumed as 0.01	s^{-1}
Parameter for shear rate, n	0.57	–
Specific heat (C_p)	4100	J kg^{-1} K^{-1}
Thermal conductivity (k)	0.7	W m^{-1} K^{-1}
Density (ρ)	950	kg m^{-3}
Coefficient of volume expansion (β)	0.0002	K^{-1}

4. Governing transport equations with assumptions

The software CFX v5.6 [22] was used to solve the governing continuity, momentum and energy equations for the defined geometry and associated boundary conditions. The domain was defined in the global co-ordinate frame in which the solver carries out the calculations. The generalized transport equations solved are as follows:

The continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{1}$$

The momentum equation

$$\left(\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot (\rho \mathbf{V} \otimes \mathbf{V})\right) = \nabla \cdot (-p\delta + \eta(\nabla \mathbf{V} + (\nabla \mathbf{V})^t)) + \mathbf{S}_{\mathrm{M}} \tag{2}$$

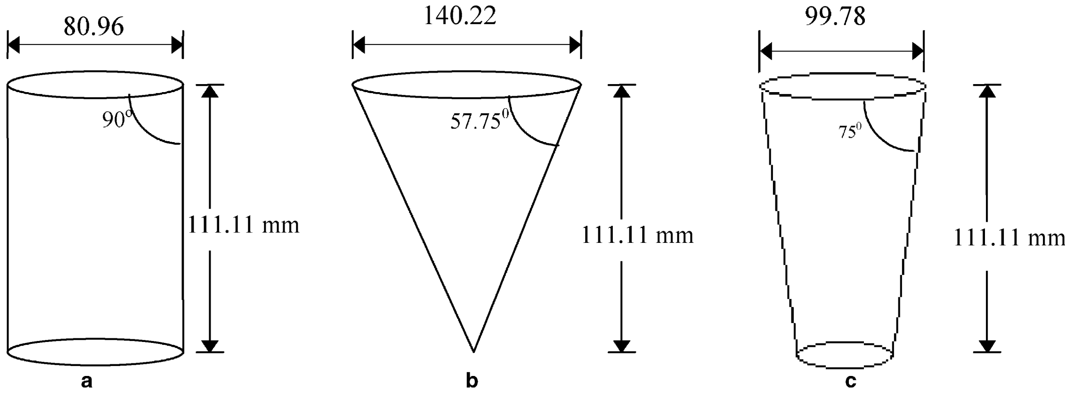

Fig. 1. Representative geometries considered (all dimensions in mm): (a) full cylinder; (b) full cone and (c) a truncated cone.

Table 2
Dimensions of food cans as a function of wall inclination

Wall inclination	Radius 1 (mm)	Radius 2 (mm)	Height (mm)
90° (cylinder)	40.48	40.48	111.11
85°	45.24	35.52	111.11
80°	49.89	30.29	111.11
75°	54.44	24.67	111.11
70°	58.98	18.54	111.11
57.75° (cone)	70.11	0	111.11

The energy equation

$$\left(\frac{\partial \rho h_{\text{total}}}{\partial t} - \frac{\mathrm{D}p}{\mathrm{D}t} + \nabla \cdot (\rho \mathbf{V} h_{\text{total}})\right) = \nabla \cdot (k \nabla T) + \mathbf{S}_{\mathrm{E}} \quad (3)$$

where h_{total} is defined as the specific total enthalpy expressed in terms of temperature and pressure using a constitutive equation for the CMC based system.

Boussinesq approximation is applied for the density in the body force term (S_{M}) as follows:

$$S_{\mathrm{M}} = -\rho_{\text{ref}} \beta (T - T_{\text{ref}}) g \quad (4)$$

For the energy equation S_{E} is taken to be zero as there are no internal sources of energy. A material termed CMC was created in the pre-processor library defining properties in accordance with Table 1. It is assumed that the flow involves an incompressible high viscous liquid with negligible viscous dissipation effects.

4.1. Boundary and initial conditions

Ghani et al. [15] suggest that simulations based on uniform heating on all sides of the can with constant wall temperature are appropriate for a general purpose. All walls of the enclosure are maintained at 121 °C. At the walls of the container, no slip conditions apply with the specified temperatures

$$T = T_{\text{wall}} = 121\ ^\circ\mathrm{C}, \quad \mathbf{v} = 0 \ \text{ for } \ 0 \leqslant z \leqslant H \ \text{ at } r = R$$

At the top and bottom walls of the container, again no slip conditions apply with specified temperatures.

$$T = T_{\text{wall}} = 121\ ^\circ\mathrm{C}, \quad \mathbf{v} = 0 \ \text{ for } \ 0 \leqslant r \leqslant R$$
$$\text{at } z = 0 \ \text{ and } \ z = H$$

Initially the fluid is at rest and at an uniform initial temperature

$$T = 40\ ^\circ\mathrm{C}, \quad \mathbf{v} = 0 \ \ 0 \leqslant r \leqslant R \ \text{ and } \ 0 \leqslant z \leqslant H$$

The condensing steam is assumed to maintain a commonly applied constant temperature of 121 °C at all the boundaries and the temperature is the same at the liquid boundaries owing to the very small thermal resistance of the can material. Further the temperature at the liquid boundaries is assumed to reach this temperature from the initial conditions without any lag.

4.2. Mesh details

To keep the discretisation error small, finer mesh was used closer to the wall where steep gradients in temperatures and velocities were encountered. On the other hand, a uniform fine mesh will increase the computational time unnecessarily without any significance improvement in accuracy. Hence an inflation parameter of 10 layers are used, which will arrange the prismatic element with its rectangular edge perpendicular to the surface in 10 layers with a length equal to the specified maximum edge length (3.5 mm) from the wall. This will give the adequate number of elements near the wall, while the sudden jump in mesh size is avoided by using a geometric expansion factor of 1.3, which will increase the size of mesh slowly from the inflation boundary to the core region. The unstructured mesh led to nearly 53,000 nodes, 1.05×10^5 tetrahedral elements and more than 65,000 wedges for each geometry analysed. There was a slight variation in the number of nodes between the cone and cylinder but as the total numbers of nodes were very high, the effect of this variation on the overall results could be neglected. The results are found to be nearly mesh independent below this size. Results were tried by reducing mesh size up to a minimum possible size viz. 1% of the maximum size dimension. Convergence criteria were set when the residuals root mean square (RMS) value attained below 10^{-5}. To solve the coupled system of partial differential equations, the high-resolution scheme with first order backward Euler method was adopted. The unstructured mesh option, rather than the structured mesh option had to be adopted since the meshes were far simpler to develop especially in the case of truncated cones. The transient runs were set-up following the step size-time relationship provided by Kumar and Bhattacharya [10]. The published results of these authors for the vertical cylinder were used to validate the computation procedures adopted in the present simulation study and were found to be in good agreement.

5. Analysis of the results

The Grashoff number (*Gr*) based on the height of the three geometries, maximum temperature difference and the minimum viscosity in the domain was typically estimated at 1200 at the beginning of the sterilization process and reduced to 3 at the end. The low Grashoff numbers during the entire thermal treatment justify the laminar flow assumption.

5.1. Effect of orientation and geometry on the sterilization times

For the food processing engineer the objective is to provide adequate thermal treatment, which will ensure that the slowest heating zone (SHZ) within a container receives the necessary heat for sufficient period of time to inactivate the most damaging microorganisms, while maintaining sensory and nutritive properties. The slowest heating zone doesn't have a constant location in the enclosure. It changes with time as well as the geometry of the enclosure. In this study the point in the domain with lowest temperature is taken as the representative of slowest heating zone. The temperature and movement of this point were traced for all geometries at different angles of orientation. The variation of sterilization time (i.e. the time taken for the SHZ to reach a value of 373.15 K) with angle of orientation for various geometries is compared in Fig. 2.

For a vertically positioned enclosure (i.e. orientation angle 0°), among all geometries the full cone (wall inclination 57.7°) showed the best performance in terms of lowest sterilization time while the cylinder produced the highest sterilization time. For the SHZ to reach 373.15 K the cone took 1098 s while the cylinder took 1288 s and the times for truncated cones lie in between these two limits. These results indicate that the full cone is quite advantageous to use when oriented in the vertical upright position. Fig. 2 also indicates that even when there is a small inclination with respect to the vertical, the sterilization times begin to increase.

At 90° the maximum time difference between the various geometries considered for the SHZ to reach the final sterilization temperature is about 58 s. With further increase in the orientation angle, there is a cross over between the various cones and the cylinder at different orientation angles. Closer to 180° (fully inverted position) the cylinder begins to demonstrate better performance than the cone and truncated cones. At an exact inverted position the cylinder is the best geometry to use. The cone took 1424.5 s at an inverted position (for SHZ to reach 373.15 K) and this is 136 s more than that of the cylinder. The truncated cone's performances were intermediate to that of the cone and cylinder. The cylinder sterilization time is symmetric about 90° inclination.

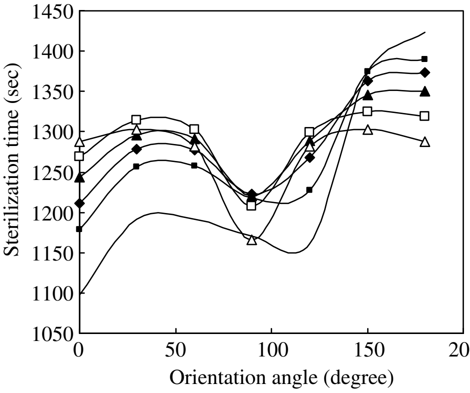

Fig. 2. Comparison of sterilization times for various geometries as a function of angle of orientation. Full cone (—) and truncated cones and their wall inclinations: (■) 70°; (♦) 75°; (▲) 80°; (□) 85° and (△) 90°.

The sterilization time increases with orientation angle and passes through a maximum around an orientation angle 40°, then reduces to a minimum value between orientation angles of 90°–120° and then begins to increase again. For the cylinder and truncated cone with wall inclination 85° there is slight decrease in sterilization time after this increase. However, the remaining geometries show only increasing trends, but the rate of increase is different for different geometries. The results indicate that there is a cross over of curves in the orientation angle 120–150°. This completely reverses the performance of geometries between 0° and 180° inclinations. The cone gives the best performance for 0° inclination with the cylinder at the worst performance, and at 180° inclination the cylinder is found to perform the best, relegating the cone to the worst performance. The performances of the truncated cones lie in between.

The performances of the truncated cones also get interchanged when going from 0° to 180° inclinations. The wall inclination of the geometries shows considerable effect on the time required for sterilization. They also affect the orientation angle at which the minimum in sterilization time occurs after the first maximal value. This minimum is found to occur when the geometry is oriented close to the horizontal. For truncated cone with wall inclination ⩾80° and the cylinder this position (sidewalls close to horizontal) of geometry is the most preferred for sterilization, as it gives the least sterilization time in the entire range of orientation angles. For the truncated cone with wall inclination 70° and the full cone (wall inclination 57.5°) the minimum shifts further to the right i.e. towards increasing angles of inclination. For these solids the minimum occurs at around 110°.

If the conventional cylindrical can is to be used, the horizontal geometry is the best orientation in terms of minimum time for sterilization. These results are in variance with those presented by Ghani et al. [18] for orange soup where the vertical can was observed to give faster heating rates than the horizontal one. While the physical properties of orange soup and CMC solution were similar, they had adopted a Newtonian model approach for the fluid viscosity. A polynomial approximation for viscosity variation with temperature was adopted. In the present case, a rigorous pseudo plastic model with temperature dependence (Table 1) was directly incorporated in the CFD simulations. The

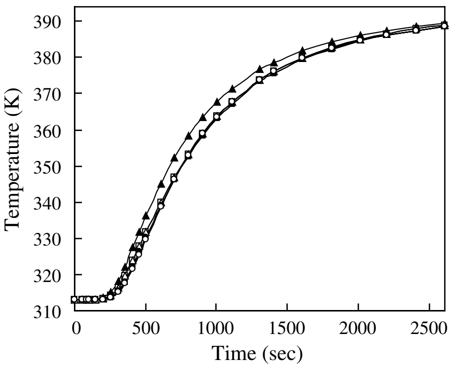

Fig. 3. Effect of orientation on slowest heating zone temperature in the case of a cylinder. Orientation angles: (—) 0° vertical; (■) 30°; (□) 60°; (▲) 90° horizontal; (△) 120°; (●) 150°; (○) 180° inverted.

transients involving the SHZ temperature for the cylinder as a function of the angle of orientation is presented in Fig. 3. When the wall inclination angles are less than 80° and for the cone, the horizontal (side wall) position leads to more sterilization times relative to the case where these geometries were at zero inclination i.e. in the vertical position.

5.2. Movement of the SHZ

Initially, for all geometries with different orientations the position of the slowest heating zone was found to be near the geometric centre. Initially the convective currents induced by buoyancy are yet to influence the thermal patterns. Subsequently the SHZ tracks the path of a moving fluid until certain duration. For all geometries, the slowest heating zone starts from the geometric centre, moves in the direction of the flow until the hot region in its path curtails its onward movement. Hence the SHZ has to change its direction near the wall. After a certain period of time, the SHZ settles at a fixed position for a relatively long period of time surrounded by the hot regions. This steady position of the SHZ is found to be in range of 10% of the maximum height, near the bottom region. SHZ holds this steady position for more than 500 s in the time interval of 500–1200 s. Subsequently, the SHZ reverses its movement towards the geometric centre of the enclosure. For time intervals after 1200 s, the natural convective flow in the enclosure has diminished to a large extent. By this time the conduction is the dominating mode of heat transfer. Even though conduction is responsible for movement of SHZ the temperature profile established earlier by the convective currents decides the path for SHZ to reach the geometric centre along the temperature gradients.

A certain temperature profile is already set in enclosure due to convective flow, which is different for different geometries and orientations and these in turn lead to differences in the quantitative movement of the slowest heating zone. Typical plots tracking the SHZ movement axially and radially are presented in Fig. 3 for the truncated cone of wall inclination 85° at orientation angles of 30° and 150°. Values of position coordinates are constant in the time interval of around 500–1000 s, which represents the steady position of SHZ in this time interval. After nearly 1000 s, the SHZ starts moving in the reverse direction. The movement of the SHZ in the reverse direction is an indication of the taking over of conduction mode of heat transfer from convective mode. Since the simulation time was restricted to 2611 s, the SHZ could not reach its original position i.e. geometric centre of the can in this timeframe. In both these cases the SHZ moved radially away from the centre axis during initial times and then towards the centre at later times. The extent of the radial movement is more in the case of the truncated cone at 30° inclination. However, the axial movement in the two orientations are initially in the opposite directions. This may be explained by the fact that the truncated cone is nearly inverted at 150°.

A typical plot of the fully inverted truncated cone (wall inclination 75°) is shown in Fig. 4. It maybe noted that in this case the radial movement is non existent after some time which implies that the SHZ has returned to the centre after some time and subsequently moves only in the axial direction. This is in contrast to the truncated cone (85° wall inclination) of 150° (Fig. 3) which showed some radial movement during the entire period of analysis. However, the axial profile movements are similar in both cases. The axial movement is upwards initially, almost nil for a significant period of time and then downwards subsequently.

It was generally observed that for wall inclination angles less than 70° and orientation inclination angle 180°, there will be axial but no radial movement of the SHZ. Since the truncated cones have a sharp taper, these cases have very small cross-sectional area available at the bottom. Hence the liquid coming down near the bottom cannot travel radially and it directly reverses its direction upon reaching the bottom. SHZ follows the fluid till it reaches bottom. Due to lack of radial movement and the presence of hot fluid up above prevents it from moving upwards. Hence the SHZ stays there until the convective currents have died out and then it moves upwards owing to conduction.

5.3. Factors influencing the SHZ

Fig. 5 gives the relation between the sterilization time and the velocity in the domain as a function of inclination angles and time for two different geometries (70° and 75° truncated cones). The magnitudes of the prevailing velocity in an equal extent of the domain in the dif-

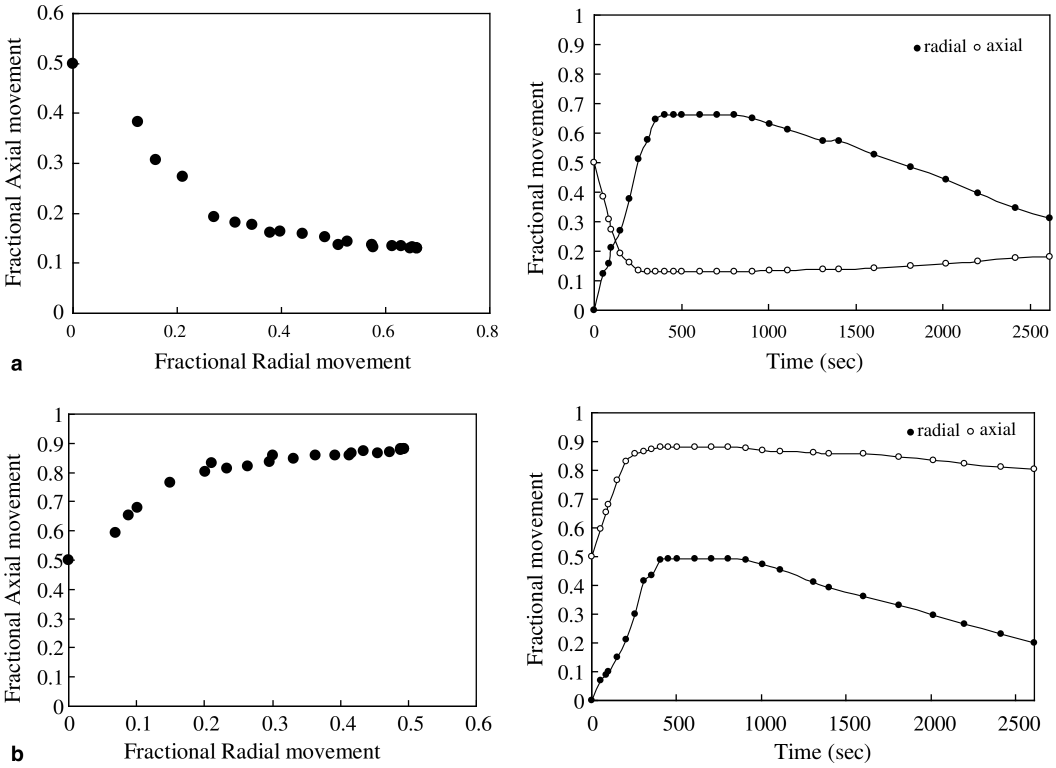

Fig. 4. Movement of SHZ for a truncated cone with wall inclination of 85° and angle of inclination: (a) 30° and (b) 150°.

ferent geometries, is considered for comparison. The isosurface option available in CFX was used to locate the values of velocity.

The magnitude of the convective velocity corresponding to a surface area of 100 cm^2 is considered here for comparison. The value of the velocity in each domain was slowly increased from a very low value and the areas corresponding to the region where this velocity value was prevalent was estimated. The velocity value prevalent in significant portion (100 cm^2) of the container domain was estimated on a common basis. From Fig. 5 the trends of the curves shows that the velocities have considerable influence on the sterilization times. At inclination angles until 120° the increase/decrease of the sterilization times roughly coincides with the corresponding decrease/increase of the convective velocities in the chosen domain. However for 120° orientation and above, despite the increase in the convective velocities there is not much change in the sterilization times. Hence, it maybe concluded that the convective velocity

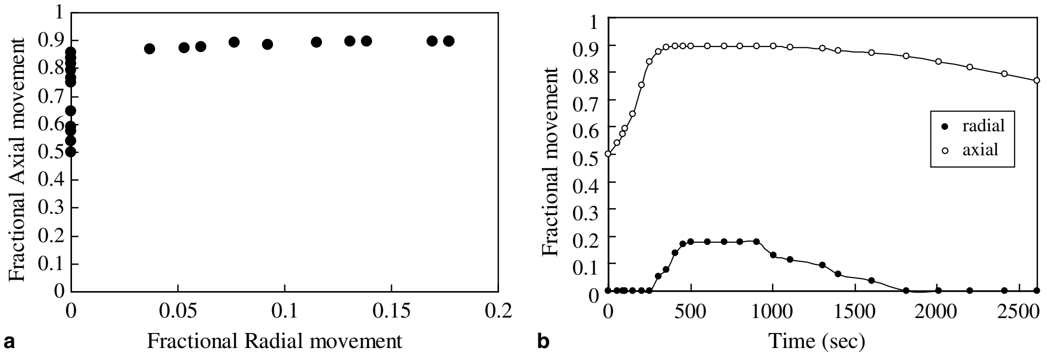

Fig. 5. Movement of SHZ for the inverted truncated cone (orientation angle 180°), with wall inclination of 75°.

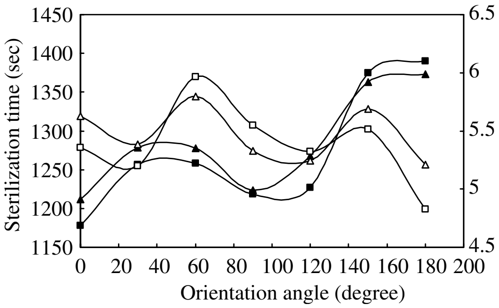

Fig. 6. Relation between the sterilization time and velocity in the domain as a function of orientation angle for two different typical wall inclination angles of 70° and 75°. Sterilization time: (■) wall inclination 70° and (▲) wall inclination 75°. Velocity × 10^5 (m/s): (□) wall inclination 70° and (△) wall inclination 75°.

in the domain is not likely to be the sole factor influencing the sterilization times (see Fig. 6).

The convective flow induced by buoyancy play an important role in the sterilization process, and this flow is upward near the heated wall, and directed downward in the core. The SHZ spends most of the time in the bottom region. Hence if the heat transfer to the slowest heating zone through convective mode is considered, this energy has to travel the same path as that of flow in the domain. This means that energy has to travel all the way through the volume of the fluid above the SHZ; hence this volume certainly must have an effect on the performance of the system. Again considering later time intervals in which the convective flow have become insignificant, the SHZ is still located in the bottom region, heat transfer is now mainly due to conduction. Here the surface area near the SHZ will have an effect on the performance of the system. To demonstrate this effect of volume and surface area, a horizontal plane passing through the SHZ at the required final sterilization temperature (373.15 K) is considered. The surface area below the plane was considered since the wall regions close to the SHZ would be a major source of heat conduction due to sharper temperature gradients and smaller conduction paths. A typical temperature contour plot for an upright cone at 1099 s is shown in Fig. 7. For other geometries the temperature gradients

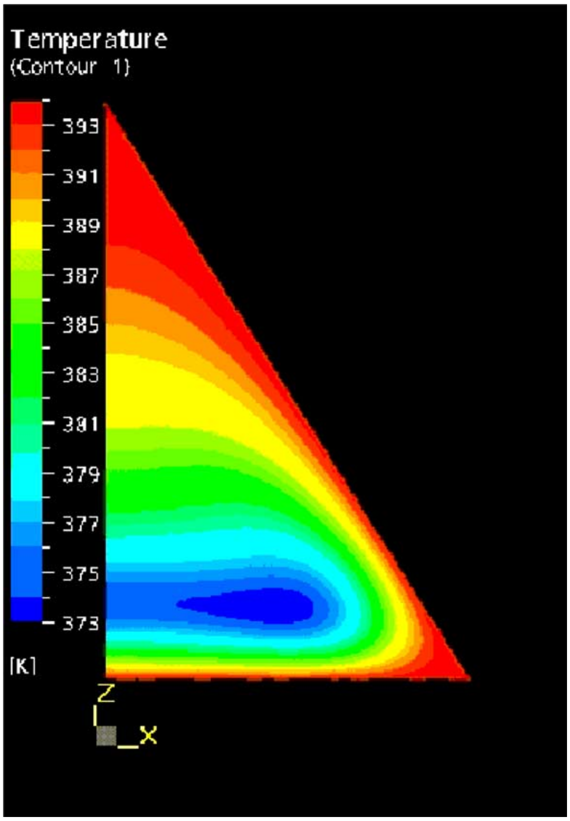

Fig. 7. Temperature regions in an upright cone at 1099 s of heating.

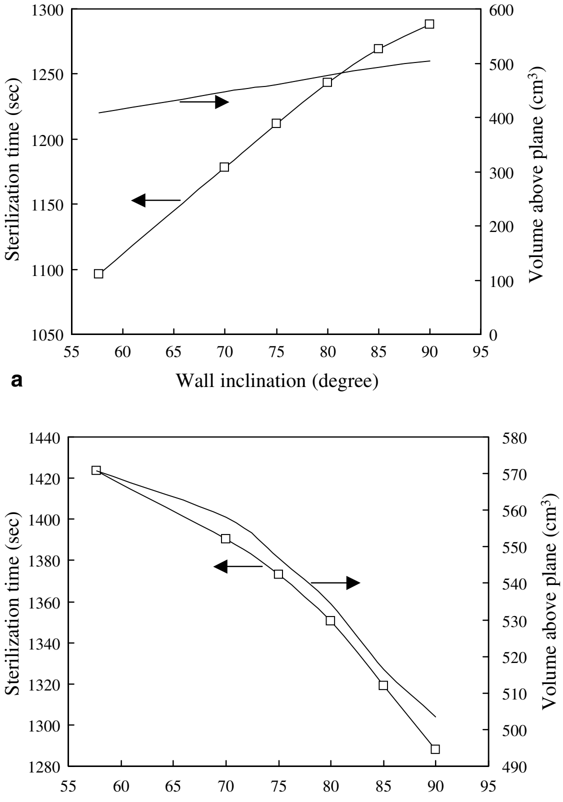

Fig. 8. Effect of volume above the plane for different geometries on sterilization time in: (a) upright position and (b) inverted position.

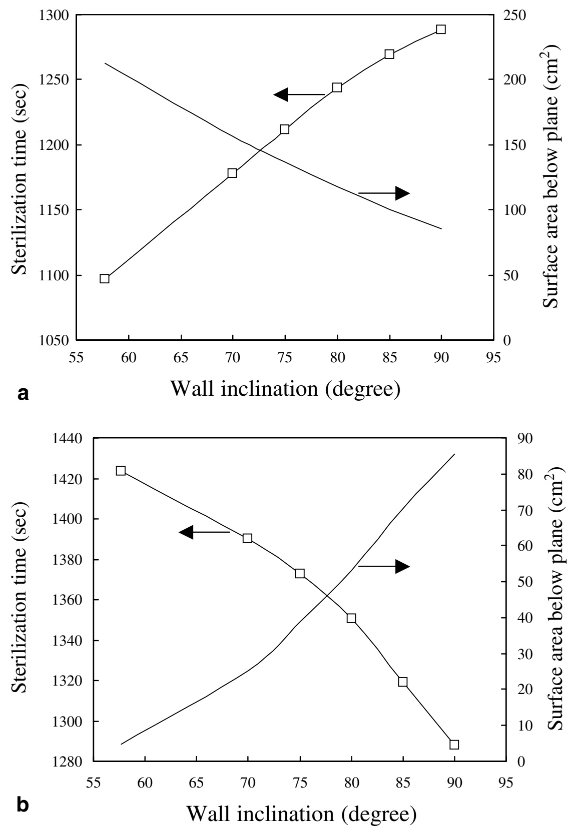

Fig. 9. Effect of surface area below the plane for different geometries on sterilization time in: (a) upright position and (b) inverted position.

close to the SHZ would be even more pronounced. The main objective is to demonstrate qualitatively the effect of surface area in the case of conduction dominated heat transfer and the effect volume above the SHZ in the case of convection dominated heat transfer. Results obtained are shown in Figs. 8 and 9 showing the effect of volume above the plane and the surface area below the plane, respectively. For demonstration purposes, two extreme cases of orientation angles 0° and 180° are considered for calculations for all the geometries. The results from Fig. 8 shows that the sterilization time is proportional to the volume of the fluid above the plane, and from Fig. 9 shows the sterilization time is inversely proportional to the surface area below the plane.

6. Conclusions

The wall inclination of the container geometry and the orientation angle were found to have considerable effect on the performance of the sterilization system. Even a small inclination of the container orientation may adversely affect the sterilization times. A 0° orientation saves more than 17% of total time required and consequently energy, provided a cone is used instead of the cylinder. On the other hand for 180° inclination, the cone tends to give the worst performance and the cylinder the best. The cylindrical can gives better performance when placed horizontally (orientation angle 90°). By keeping the cylinder horizontal instead of vertical, there is a decrease of 10% in time required for the sterilization. The movement of slow heating zone also influences the performance of the system. Due to this movement, the SHZ gets shifted from geometric centre to the near bottom region. As the SHZ remains steady in this region for a long time, the volume above SHZ and surface area below SHZ are found to decide the performance of the system. When geometry modifications are made for aesthetic reasons to the food container, the utilization of known sterilization times for the conventional cylindrical can of the same volume may be inappropriate for suitable thermal treatment.

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