Sādhanā Vol. 32, Part 5, October 2007, pp. 535–544. © Printed in India

Heat transfer and heating rate of food stuffs in commercial shop ovens

P NAVANEETHAKRISHNAN*, P S S SRINIVASAN and
S DHANDAPANI

Department of Mechanical Engineering, Kongu Engineering College,
Perundurai 638 052
e-mail: pnkmech@gmail.com, pnkmech@yahoo.co.in

MS received 24 May 2006; revised 2 November 2006

Abstract. The CFD analysis of flow and temperature distribution in heating ovens used in bakery shop, to keep the foodstuffs warm, is attempted using finite element technique. The oven is modelled as a two-dimensional steady state natural convection heat transfer problem. Effects of heater location and total heat input on temperature uniformity of foodstuffs are studied. Placing the heater at the bottom of the oven improves the air circulation rate by 17 times and 10 times than that at the top and side of the oven. But the top location provides better uniformity in foodstuff temperature than the other cases. Side location is not preferable. In the present ovens, the heating elements are located at the top. The analysis shows that if heaters are located at the bottom along with additional flow guidance arrangements, energy efficient oven configuration can be obtained.

Keywords. Heating oven; finite element analysis; energy efficiency; design improvement.

1. Introduction

Technological advancements and improved standards of living have increased the per capita energy use and the associated pollution to an alarming level. A survey carried out on 13 most industrialized nations has shown that about 38 % of the total energy is spent for comfort applications (Liddament & Orme 1998). Chen (2001) strongly points out that similar aspects will be repeated in the developing nations and meeting such exponentially growing energy demand in the developing nations will be a major task among others in this 21st century. In India, the domestic sector energy consumption is 15 % of the total energy consumption during 1993. During the five-year period (1993–98), the average electricity consumption has grown by 48 %, while the domestic sector section consumption raised by 92 %, mainly because of comfort applications. Thus, energy needs to be conserved wherever possible.

Computational fluid dynamics (CFD) is a simulation tool that uses powerful computers and applied mathematics to model fluid flow situations for the prediction of heat, mass and

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*Corresponding author

momentum transfer and design optimization, mainly in industrial processes. It is only in recent years that CFD has been applied in the food processing industry (Da-Wen Sun & Bin Xia 2002). Researchers, equipment designers and process engineers are increasingly using CFD to analyse the flow and performance of process equipment, such as baking ovens, refrigerated display cabinets, stirred tanks, spray dryers, heat exchangers and similar equipment.

Drying is a common manufacturing process and CFD has been applied to drying of fruits (Mathioulakis *et al* 1998), and spray driers (Langrih & Fletcher 2001). CFD has been used to study both temperature distribution and flow pattern of food in the sterilization process so as to optimize the quality of food products. Attempts have been made in thermal sterilization (Datta & Teixeira 1987, Akterian & Fikiin 1994, Abdul Ghania *et al* 2001), canned food sterilization (Abdul Ghania *et al* 1999) using CFD. In food processing, mixing is one of the most common operations. Application of CFD in mixing has been demonstrated (Sahu *et al* 1999, Rousseaux *et al* 2001). Consumption of refrigerated and frozen foods has increased continually over the years because such foodstuffs have demonstrated food quality and safety record. CFD has been considerably used in such applications (Hu and Da Wen Sun 2000, Davey & Pham 2000, Stribling *et al* 1997 and Shyam *et al* 2002).

In India, most of the commercial bakeries use electrical heating oven to keep the foodstuffs warm at a specified temperature. The survey by the authors revealed that in most ovens the heating elements are located at the top of the oven with a fan in few models. The present paper makes an attempt to study the effect of heater location in order to improve the design for possible energy conservation and better quality of foodstuffs.

2. Problem formulation

Electrically heated ovens are mainly used in bakery (retail) shops in order to keep the foodstuffs warm. These ovens are of different sizes with three heating elements located at the top of the oven. Total input power ratings are in the range of 500 to 1000 W. Some of the ovens use an additional fan of 250 W rating for hot air circulation. Most commonly used oven has an outer size of 0·7 m width, 1·2 m depth and 1·2 m hight, with three heating coils at three positions, which is taken for the present analysis. As a preliminary study, the problem is modelled and solved as a two-dimensional one as shown in figure 1. Food items (12 numbers) are arranged

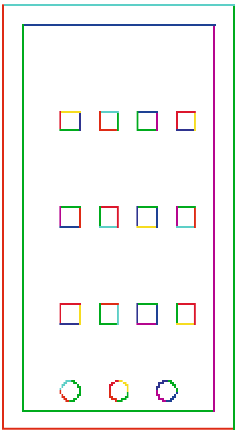


Figure 1. Geometry of oven.

in three rows and four columns, as shown in figure 1. The clearance between the foodstuffs and the walls is 225 mm on top and bottom, 100 mm on the left and 50 mm on the right. The foodstuffs are of 50 mm by 50 mm size. The spacing between the foodstuffs is 200 mm in the vertical direction and 50 mm in the horizontal direction.

2.1 *Computational domain*

The computational domain includes the insulated wall (Glass wool, $k = 0{\cdot}075$ W/m K, three heating elements (Nickel Steel, 5 mm diameter, $k = 380$ W/mK), foodstuffs ($k = 0{\cdot}2$ W/mK, for most of the food items, the thermal conductivity range over 0·09–0·5 W/mK) and the enclosed air region. The walls are normally made of sheet metal containing glass insulation (10 mm thick on each side). As the sheet metal thickness is about 0·5 mm and is of high thermal conductivity ($k =$ 50–150 W/mK), it will offer negligible resistance to the heat flow. Hence, the sheet metal portion is neglected while modelling.

2.2 *Governing equations*

Steady state, natural convection heat transfer environment is assumed. All the fluid (air) properties are assumed to be constant except density, which is assumed to vary as $\rho = \rho_{\text{ref}} + C_1(T - T_{\text{ref}}) + C_2(T - T_{\text{ref}})^2$. T_{ref} is kept as 0°C, the constants C_1 and C_2 are evaluated by curve fitting the data over the range 0–300°C. As the flow is due to natural convection heat transfer, the flow will be laminar. No heat generation is assumed within the computational domain except at the heating coils. Cartesian coordinate system is employed. Gravity (g) is assumed to act vertically downwards. The governing differential equations, viz. the continuity, x-momentum, y-momentum, and the energy equation are coupled and are solved simultaneously in the fluid region. Steady state heat conduction equation without heat generation is solved for the insulated wall and foodstuff regions and with heat generation in the heating coil regions.

2.3 *Boundary conditions*

No slip boundary condition ($Vx = 0$, $Vy = 0$) is assumed on all the solid surfaces that are in contact with the air. Convection is assumed on all the outside surfaces of the insulated wall. The heat transfer coefficient values are 3·0 W/m^{2}K for the vertical surfaces and 3·5 W/m^{2}K for the top surface and 1·5 W/m^{2}K for the bottom surface; these values are calculated using empirical equations available in standard heat transfer text books, assuming natural convection heat transfer between the insulated walls and the surrounding atmosphere. The surrounding atmospheric temperature of 30°C is used in all the analysis. Uniform volumetric heat generation is assumed within the heating element. Total input power of 500, 600, 800 and 1000 W are used for the analysis. Volumetric heat generation rate is applied over the heating coil region, which is estimated by dividing the total heat generation rate with total volume of three coils.

3. Solution technique

The problem is modelled and solved using ANSYS 9·0 Finite Element Analysis software package. The computational domain is first modelled using the pre-processor module of the ANSYS. Then, it is divided into a convenient number of elements using the meshing option. Finer grids are used near the solid–fluid interface regions as shown in figure 2. Grid

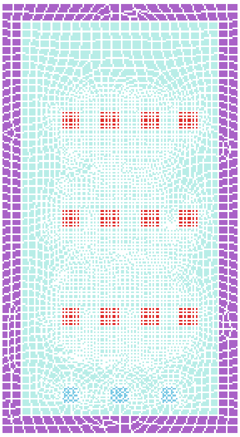


Figure 2. Finite element meshing of the domain.

dependence of the results is verified and grid independence results are reported. The number of elements used is ranged over 35,000 to 50,000. The boundary conditions are then suitably applied. The properties of air at one atmospheric pressure and 60°C are used. The fluid properties (μ, C_p, k) are assumed as constant except the density where quadratic variation is employed. The steady state form of the governing equations (continuity, momentum and the energy equations) are simultaneously solved. The iterative solution is terminated when the maximum residue falls below 10^{-6}. The necessary results from the converged solution are extracted using the post-processing option of the software.

4. Results and discussion

The oven with 12 foodstuffs and three heating elements are modelled and flow pattern and temperature distribution are analysed. Comparison among the three locations of the heating elements, viz. top, side and bottom of the oven are attempted. Total input power (Q) is varied as 500, 600, 800 or 1000 W. In the total 12 cases that are studied, the results of the case with heating elements located at the bottom with $Q = 1000$ W are discussed in detail and then the comparisons are made among the three heater locations.

4.1 *Flow and temperature distribution*

The variation of x-component velocity (Vx), y-component velocity (Vy), vector plot of total velocity (Vsum), and stream function within the oven for $Q = 1000$ W, heating elements located at the bottom are shown in figures 3 to 6. Variation of temperature (T) is shown in figure 7f. Due to heating, air density decreases. The air with lower density tends to move due to buoyancy and flows through the foodstuffs in the central region of the oven, thus heats the foodstuffs. Once the air reaches the top of the oven, which is relatively at lower temperature, and has higher density, it tends to move down. Thus, at the top region of the oven, air flows towards the side ways and moves down along the gap between the sidewalls (on both sides) and the foodstuffs. Once the air reaches the bottom, which is heated again and the circulation pattern is repeated again and again as shown in figure 5. Thus, the two counter-rotating natural circulation loops are formed which can be clearly observed from the stream function plot shown in figure 6. Certain local circulation is also observed near the right side wall.

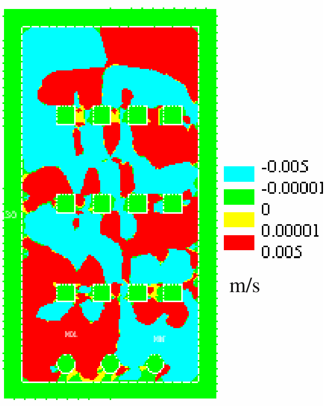


Figure 3. X-component velocity distribution (Bottom, $Q = 1000\,\mathrm{W}$).

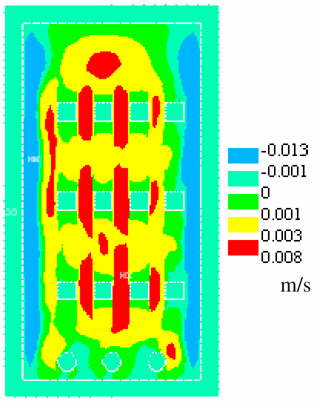


Figure 4. Y-component velocity distribution (Bottom, $Q = 1000\,\mathrm{W}$).

Horizontal component of air velocity varies from $-0{\cdot}005$ to $+0{\cdot}005$ m/s as shown in figure 3. The air movement is left to right at the top-right and bottom-left corners and in the opposite way in the other two corners. As the air has to move up in the gap between the foodstuffs in the central region, higher upward velocities, up to 0·008 m/s, are observed (figure 4).

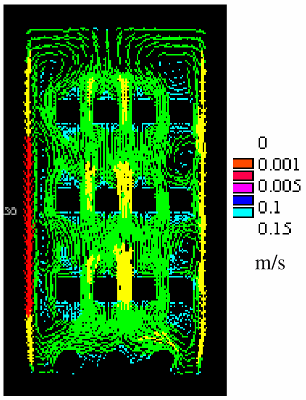


Figure 5. Total velocity distribution (Bottom, $Q = 1000\,\mathrm{W}$).

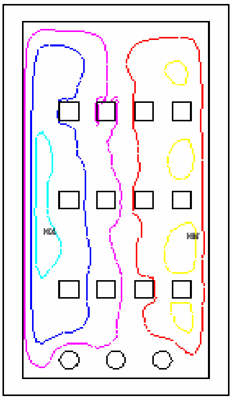


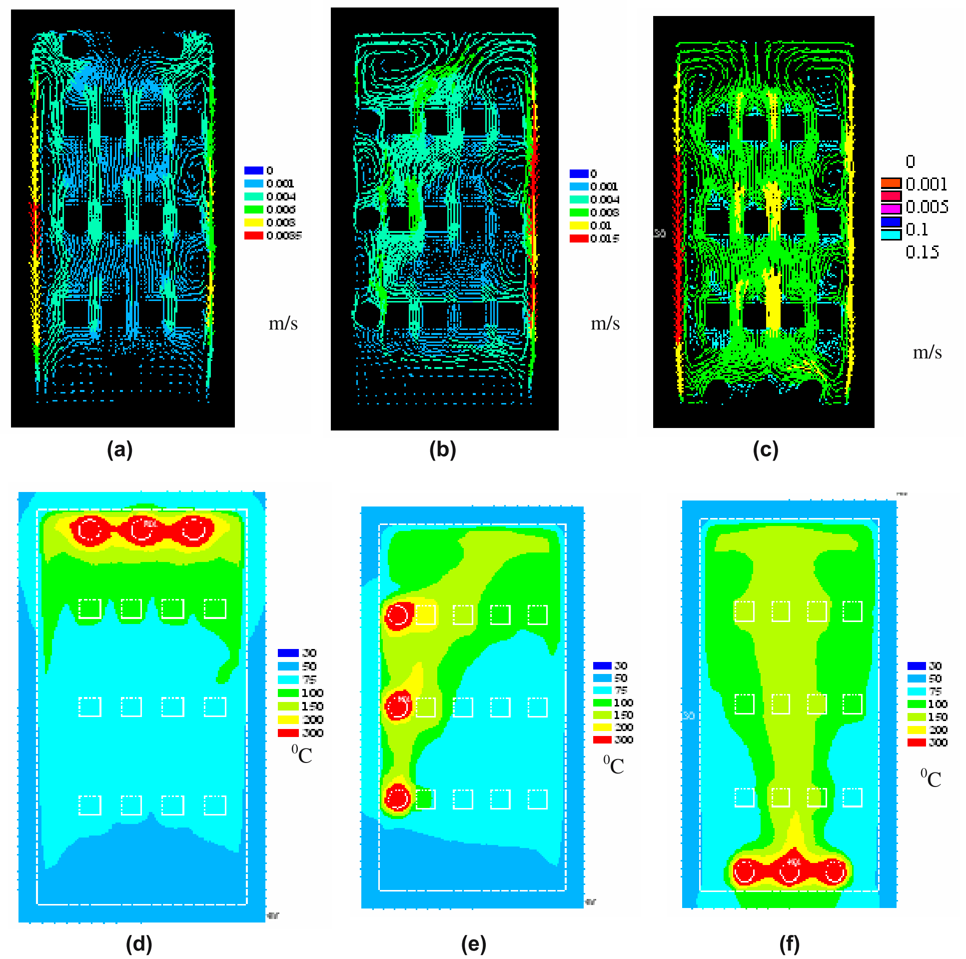
Figure 6. Stream function distribution (Bottom, $Q = 1000\,\text{W}$).

As all the air went up in the central region returns downwards along both the sidewalls, downward velocities of about 0·013 m/s are observed. The temperature plot shown in figure 7f indicates that nearer to the heating elements, sharp variation in temperature, ranging from 300 to 150°C is observed. Along the central region, the temperature ranges over 100–150°C. In the adjoining regions, the variation is in the range of 75–100°C in the top half and 50–75°C in the bottom half of the oven.

4.2 *Effect of location of heaters and power input*

For the same heat total input ($Q = 1000\,\text{W}$), the effect of heater location on the distribution of total velocity and temperature are shown in figure 7. The heaters are located at the top (commercial case), at the bottom and at one side (left) of the oven are studied. Figures 7a to c show the vector plot of the total velocity for the three heater locations. The maximum velocities observed are lower (0·0085 m/s) in case of heater location at top, moderate (0·015 m/s), and relatively larger (0·15 m/s). Thus, the heater location at top provides about 17 times and 10 times better circulation than the top and side heater locations. In case of top location, the temperatures, in the zones where the foodstuffs are kept, varies in the range of 50–100°C. The side location of the heater results in larger temperature non-uniformity (50–175°C) in the foodstuff region. The heater location at the bottom provides moderate non-uniformity (75–150°C) in the foodstuff region.

Temperature at the middle of foodstuffs obtained for the various heater locations, for the total input power of 1000 W, are plotted in figures 8 to 10. For almost all the cases analysed, the variation of temperature between the middle and the surfaces of foodstuffs are within 2°C. In case of bottom location, the bottom row experiences the higher temperature and the temperature drops from bottom row to top row. As the natural circulation is more effective, the foodstuffs at the central region have higher temperature than that at the sides. In case of side location of the heater, temperatures of foodstuffs near the heater are significantly larger than the other regions which are not desirable. For top location, the temperatures of foodstuffs at the top row are larger and decrease from the top to the bottom. For the given heat input, the temperatures of foodstuffs are about 2 times higher in the case of bottom heater location than the top location. Hence, with the lower heat inputs, the desired temperature of foodstuffs can be achieved in the case of bottom location of heaters, thus, resulting in energy savings. But, from temperature uniformity point of view, top location is better than the bottom location for



(a) (b) (c)

(d) (e) (f)

Figure 7. Velocity distribution Vsum (Top, $Q = 1000$ W) **(a)**, (Side, $Q = 1000$ W) **(b)**, (Bottom, $Q = 1000$ W) **(c)**; Temperature distribution (Top, $Q = 1000$ W) **(d)**, (Top, $Q = 1000$ W) **(e)**, (Top, $Q = 1000$ W) **(f)**.

the arrangements investigated. Thus, it appears that by incorporating additional flow guiding arrangements, it may be possible to obtain better temperature uniformity in the case of bottom location of heaters, but with a lower heat input than the top location of heaters, which is under further investigation.

Location of foodstuffs

9–12	Top row (Row 3)
5–8	Middle row (Row 2)
1–4	Bottom row (Row 1)

(1–4; Left to right)

The total input power (Q) to the heaters in all the three cases is varied as 500, 600, 800 and 1000 W. The temperature plots (not shown) revealed that the corresponding foodstuff

Figure 8. Temperature of foodstuffs with coil at bottom position for $Q = 1000\,\text{W}$.

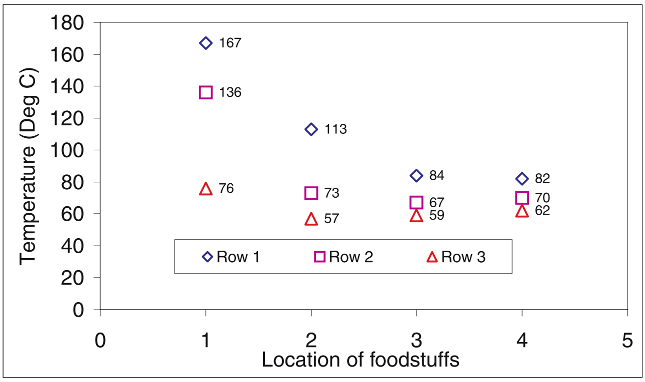


Figure 9. Temperature of foodstuffs with coil at side position for $Q = 1000\,\text{W}$.

temperatures varied within 2°C, when the total input power is increased from 500 to 1000 W. Thus, the steady-state analysis does not show the effect of the heat input. However, lower total heat input may take larger time for the foodstuffs to attain the steady-state. Hence, transient analysis would reveal more while studying the effect of the heat input.

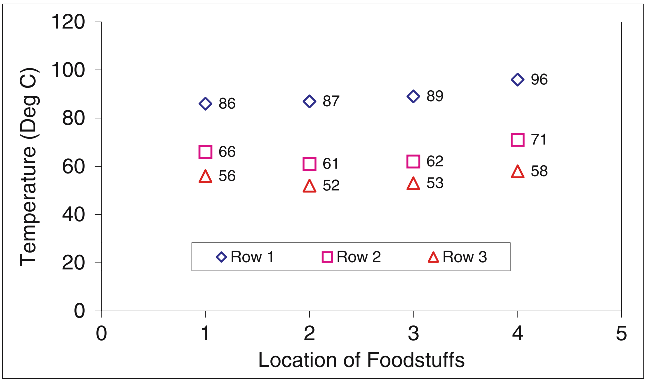


Figure 10. Temperature of foodstuffs with coil at top position for $Q = 1000\,\text{W}$.

5. Conclusion

Design improvement for energy conservation is the field of intense research. In this direction, temperature and flow distribution in a commercial foodstuff heating oven is investigated using finite element analysis. The system is modelled as a two-dimensional steady state natural convection heat transfer one. Commercial ovens have the heating elements at the top region inside the oven. In addition to the existing location, bottom and side location of the heaters are also investigated. The following conclusions are arrived at:

(i) Placing the heater at the bottom of the oven improves the air circulation rate by 17 times and 10 times than that at the top and side location.
(ii) Top location provides better uniformity in foodstuff temperature than the other cases.
(iii) Side location is not preferable.
(iv) For the given total heat input, the bottom location results in almost two time's higher temperature of foodstuffs than that of top location.
(v) Bottom heater location with additional flow guides may result in energy efficient oven configuration.
(vi) Transient studies are necessary to understand the effect of heat input.

Nomenclature

ρ	Density of the fluid (kg/m^3)
μ	Dynamic viscosity (Pa-S)
Cp	Specific heat (kJ/kg K)
g	Acceleration due to gravity (m$^2/s$)
h	Convective film co-efficient (W/m^{2}K)
k	Thermal conductivity (W/m K)
Q	Total input power to heaters (W)
V_x	Velocity in the x-direction (m/s)
V_y	Velocity in the y-direction (m/s)
V_{sum}	Total Velocity (m/s)
T	Temperature (K)

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