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Effect of heating coil in commercial shop display cabinet

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Abstract

CFD analysis of flow and temperature distribution in display cabinets used in bakery shops, to keep the foodstuff warm, is attempted using finite volume technique. The display cabinet is modelled as a two-dimensional steady-state natural convection heat-transfer problem. The temperature distribution is affected by a number of parameters of which coil location and coil diameter are important. The effect of coil location arrangement and different coil diameters at 1000 W input power is investigated using numerical and experimental methods. The measurements are made over a period of 150 min. About 7–13°C variation is observed in the foodstuff placed at various locations. Numerical and experimental results agree well both in magnitude and trend.

Keywords: Display cabinet, finite volume analysis, heat transfer, foodstuffs, and heating coils.

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 of 13 most industrialized nations has shown that about 38% of the total energy is spent on comfort applications [1]. Chen [2] points out that similar experience will be repeated in the developing countries too and meeting such exponentially growing demand will be a major task in the 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 consumption raised by 92% mainly on comfort applications. Thus, energy needs to be conserved wherever possible.

Computational fluid dynamics (CFD) is a simulation tool, which uses powerful computers and applied mathematics to model fluid flow situations for the prediction of heat, mass and 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 [3]. Researchers, equipment designers and process engineers are increasingly using CFD to analyze the flow and performance of process equipment, such as baking ovens, refrigerated display cabinets, stirred tanks, spray dryers, heat exchangers and similar equipment.

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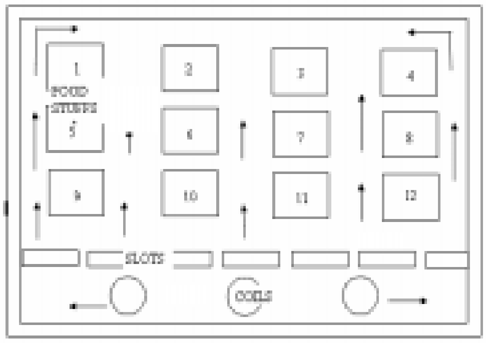

FIG. 1. Schematic representation of natural convection display cabinet heated electrically.

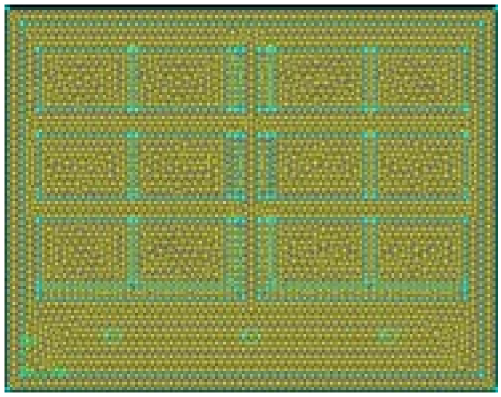

FIG. 2. Meshed model of display cabinet.

Drying is a common manufacturing process and CFD has been applied to drying of fruits [4], and spray driers [5]. 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 [6–8], and canned food sterilization [9]. In food processing, mixing is one of the most common operations. Application of CFD in mixing has been demonstrated [10, 11]. Consumption of refrigerated and frozen foods has increased continually over the years as they have not deteriorated in quality and have a good safety record. CFD has been used considerably in such applications [12–14].

In India, most commercial bakeries use electrical heating display cabinets to keep the foodstuff warm at a specified temperature. A survey by the authors revealed that in most of the display cabinets, heating elements are located at the top and in some cases with a fan. The present paper makes an attempt to study the effect of coil location and coil diameter to improve the design for possible energy conservation and better quality of foodstuff.

2. Problem formulation

The display cabinet used in this study is a commercial natural convection device for the heating of foods and contains three heating elements at the bottom.

The internal dimensions of the display cabinet are 1 m width and 0.5 m height. The hot air from the heaters flows into the foodstuff region through the distribution plate containing slots. The problem is modelled and solved as a two-dimensional one as shown in Fig. 1. The length of the foodstuff is 0.2 m and the width is 0.08 m. The horizontal and vertical spacing between the foodstuff is 0.04 m. Three heating coils of five different diameters 0.01, 0.02, 0.03, 0.04 and 0.05 m and at three different locations, namely, bottom, side and middle are considered for analysis.

2.1. *Computational domain*

The computational domain includes the insulated wall (glass wool, k = 0.75 W/mK), three heating elements (nickel steel, 20-mm diameter, k = 46 W/mK), foodstuff (k = 0.2 W/mK, as the thermal conductivity range for most of the food items is between 0.09 and 0.5 W/mK) and the enclosed air region. The walls are normally made of sheet metal containing glass insulation (50-mm thickness on each side). As the sheet metal thickness is about 1 mm and is of high thermal conductivity material (k = 50–150 W/mK), it will offer negligible resistance to heat flow. Hence, the sheet metal portion is neglected while modelling.

3. Numerical simulation

Transient laminar flow form of natural convection heat-transfer environment is assumed. All the fluid (air) properties, except density, are assumed to be constant. The flow is due to natural convection only. The calculated Grashof number is below 10^6, so laminar flow is considered for analysis. 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. continuity, x-momentum, y-momentum, and the energy equation are coupled and are solved simultaneously in the fluid region. Conduction equation without heat generation is solved for the insulated wall and foodstuff regions and with uniform heat generation in the heating coil regions.

3.1. *Boundary conditions*

No slip boundary condition ($V_x = 0$, $V_y = 0$) is assumed on all the solid surfaces, which is in contact with the air. Convection is assumed on all the outside surfaces of the insulated wall. The heat-transfer coefficient values used 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 textbooks, 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 heat generation rates of 1000 W were 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.

3.2. *Solution technique*

Computational domain is created and meshed using Gambit software and triangular-type control volume is used. Boundary layer-type mesh [15] is employed on all solid surfaces and expanding grid is used with finer grids near the solid surfaces (Fig. 2). The solution is obtained using FLUENT 6.1 Finite volume software. Each analysis is carried out for a period of 150 min with internal time step of one minute. At each time step the residue converges to a level of 10^{-6} before proceeding to the next time step.

4. Experimental set-up

A display cabinet of 1-m width, 0.5-m height and 0.5-m depth with three heating coils at the bottom with three racks is fabricated. In each rack, four items are kept. For each item of foodstuff, one resistance temperature detector (RTD) is fixed for measuring its temperature. The RTDs are PT100, which measure the temperature in the range –50°C to 200°C. The EMF produced by the RTDs is given as input to data logger DAS 8000.

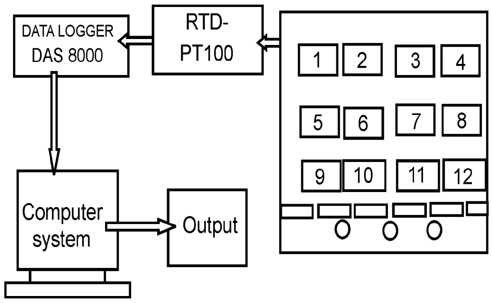

FIG. 3. Schematic arrangement of the experimental set-up.

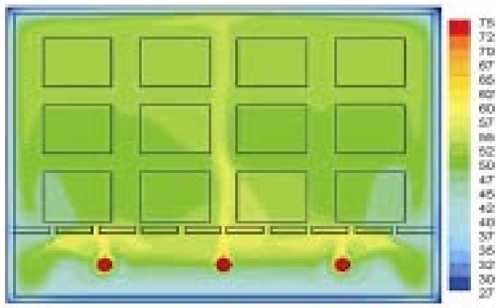

FIG. 4. Temperature distribution inside the display cabinet–bottom coil location.

DAS 8000 is an 8-channel data logger, which is connected to computer through COM port. The schematic arrangement of the experimental set-up is shown in Fig. 3. The temperature of the foodstuff is recorded in the computer system and can be viewed in MS Excel format. The time interval for data logger is kept as 60s to compare with CFD results. An uncertainty analysis is carried out to find out error in experimental analysis. The error is around 6%.

5. Results and discussion

CFD simulation of display cabinet is carried out for five different coil diameters (0.01, 0.02, 0.03, 0.04 and 0.05 m) and three different coil positions (side, bottom and middle). Experimental investigation was also carried out for the bottom coil position with 0.03-m coil. The results of the simulation and investigations are discussed here.

5.1. *CFD simulation*

CFD simulation of display cabinet with loaded condition is carried out in transient state. Figure 4 shows the temperature distribution inside the display cabinet. The bottom portion gets more heat (55°C) compared to the top portion (45°C).

5.1.1. *Effect of coil diameter*

Heating coils are the source of heat for display cabinets. The present display cabinets come with 0.03-m-diameter heating coils and are fitted at the bottom. Figure 5 shows the temperature variation of foodstuff with time for different coils. All the analysis is carried out for 1000-W input power. The figure shows that the temperature increases for 30 min and remains nearly constant for the rest of the analysis with minor variations. All the coils take 75–80 min to reach the steady state.

The 0.01- and 0.04-m-diameter coils give heat output of around 45°C only, and the 0.02-m coil around 50°C. But the 0.03- and 0.05-m coils give around 70°C. The 0.05-m coil gives some variations. The 0.03-m coil gives less variation compared to 0.05-m coil. As 0.03-m coil gives high temperature output without much variation, it is best suited for the display cabinets.

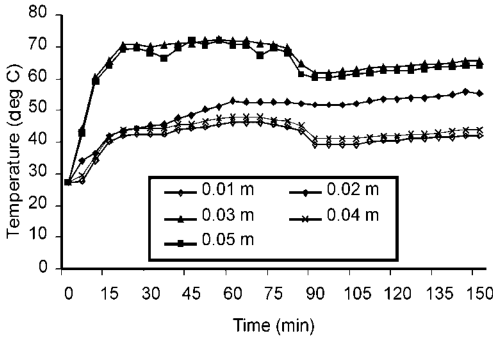

FIG. 5. Temperature variation of foodstuff with time for different coil diameters.

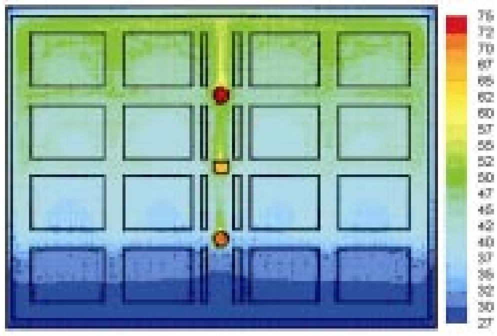

FIG. 6. Temperature distribution inside the display cabinet–middle coil location.

5.1.2. *Effect of coil location*

Figure 6 shows the CFD simulation of heating coil of 0.03 m placed at the middle of the oven. From the figure, we can observe that if the heating coils are located at the middle, the top portion gets heated up in lesser time compared to the bottom row. Figure 7 shows the comparison of temperature for three different position heating coils for the food particle (10).

Figure 7 shows that the side location is not preferred as it gives around 35°C only and is not sufficient to keep the foodstuff warm for a long period. The middle location gives around 50°C. The bottom location gives around 60°C with minor variation. As the flow is in natural circulation mode, the bottom location is preferred.

5.2. *Experimental investigation*

The experimental variation of the foodstuff temperature with time is plotted in Figs 8 and 9. It shows the temperature of four foodstuff in the top row (1–4) and the four at the bottom row (9–12). The temperature of all the foodstuff rises from the initial temperature to a peak value in about 15–40 min and then drops a little and stays almost constant over time. The

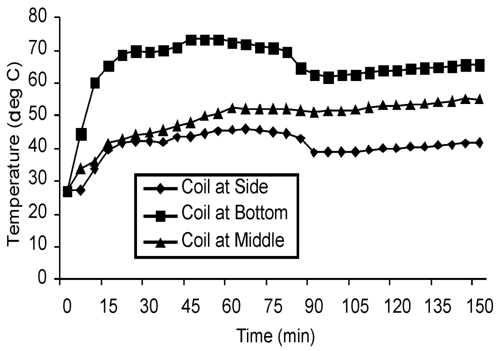

FIG. 7. Temperature variation of foodstuff(10) with time for different positions.

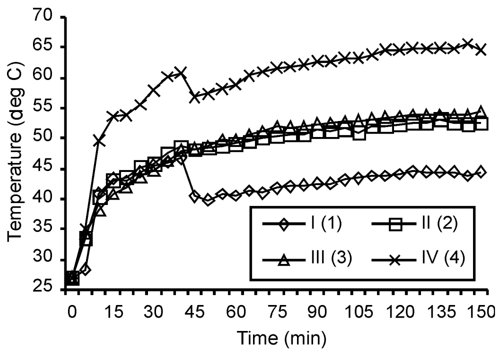

FIG. 8. Temperature variation of foodstuff with time for the top row–experimental.

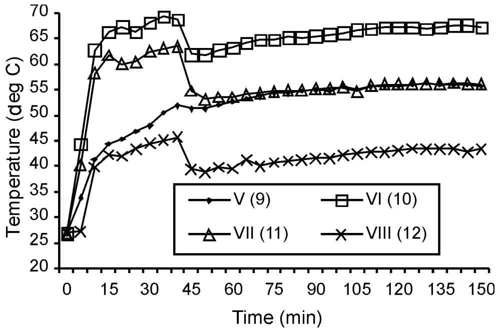

FIG. 9. Temperature variation of foodstuff with time for the bottom row–experimental.

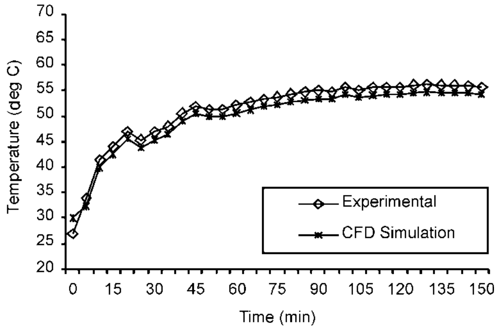

FIG. 10. Comparison of experimental and CFD simulation results for foodstuff (9).

temperature of foodstuff(10) is the highest (at any instance of time) as it is located near the heating coil. On the other hand, foodstuff(1) registered the lowest temperature as it is located at the farthest point from the heating coils and at the corner of the oven. The temperature of the other foodstuff varies in between.

5.3. *Comparison of CFD simulation and experimental*

The comparison between the CFD and experimental results is shown in Fig. 10 for foodstuff location(9). Both the results follow the same trend. Experimental results are slightly (about 5–10°C) higher than the CFD results. However, they are within the experimental error and numerical accuracy values. Similar aspects are observed in all the other foodstuff locations. With this validation, CFD can be safely used for further parametric analysis and optimization of oven configuration.

6. Conclusions

CFD simulation and experimental investigation of display cabinet are carried out for different coil diameters and coil locations. The following are the major conclusions from the present investigation.

(1) The results of CFD simulation and experimental investigation are in good agreement both in trend and magnitude.
(2) The coil with 0.03-m diameter and bottom location is the most preferable compared to other locations.
(3) About 7–13°C variations are obtained among the various locations of foodstuff. They have to be reduced by suitable methods.
(4) Experimentation may be extended to measure the energy consumption to find out the energy efficiency.

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Nomenclature

ρ = Density of the fluid (kg/m^3)
μ = Dynamic viscosity (kg/ms)
C_p = Specific heat (kJ/kg K)
g = Acceleration due to gravity (m^2/s)
h = Convective film coefficient (W/m^{2}K)
k = Thermal conductivity (W/m K)
Q = Total heat input 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)