Computation of airflow effects on heat and mass transfer in a microwave oven

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Abstract

The magnitude of surface heat and mass transfer coefficients in microwave ovens is important to control food surface temperature and moisture and are a result of the faint airflow present in the oven cavity and of surface radiation. Magnitude and patterns of airflow inside a microwave oven and the resulting surface heat transfer coefficients were studied using a computational fluid dynamics model of the process. The governing Navier–Stokes and energy equations were solved for both natural, forced and combined convection. The magnitude and distribution of surface heat transfer coefficients on the food surface were computed for a 3-D oven cavity with one inlet and one outlet and a cylindrical food placed inside the oven. Calculated convective heat transfer coefficient values were found to be in the same range as has been used in the literature. A combined convection regime proves beneficial for heat transfer uniformity and the reduction of moisture accumulation inside the oven. Radiation heat transfer coefficients for energy exchange between food surface and oven interior were calculated and shown to be of the same order of magnitude as the convection heat transfer coefficients.

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1. Introduction

When a food is heated in a microwave oven, it absorbs the microwaves and thus is directly heated by the microwaves, while the air does not absorb microwaves and therefore stays cold. As the colder air exchanges heat with the food surface, it tends to cool the surface while the air warms up in the process. The eventual increase of food surface temperature from absorbed microwave energy also increases evaporation of water from it into the air. The evaporated water is convected away by the air. These convective heat and moisture exchanges between the food and the air, quantified by the spatial variations in surface heat and mass transfer coefficients, are greatly affected by the airflow pattern inside the microwave oven. These coefficients, in turn, determine the rates of heating and moisture loss and the distributions of temperature and moisture in the food, thus determining its final quality from the heating process. For example, surface moisture accumulation in microwave heating, that often leads to an undesirable soggy food product, can be significantly reduced by increasing the airflow rate over the food (Datta & Ni, 2002).

For a typical microwave oven, the magnetron that generates the microwaves, and stays outside the microwave cavity, is cooled using external forced air. In microwave ovens without a hot air provision, a portion of this external forced air flowing over the magnetron is drawn from the inside of the microwave oven through small holes in the oven walls, resulting in low-velocity airflow inside the oven. This airflow is primarily to reduce the condensation of water inside the oven. However, since this airflow does affect the heat and moisture transfer from the food surface, the objective here is to obtain a quantitative understanding of its effect.
There have been numerous studies of heat and mass transfer in foods heated in a microwave oven (summarized in Datta, 2000). However, these studies have assumed a heat transfer coefficient over the food surface, without profound fundamental considerations of flow regime and air velocity magnitudes. A surface heat transfer coefficient of 2.6 W/m²°C was used in Lobo (1996). Even in a microwave tunnel pasteurizer, where food slowly moves in a tunnel, air is considered relatively still, a surface heat transfer coefficient of 5–10 W/m²°C is quite different inside a microwave oven due to much lower velocity, rendering a regime where forced convection and natural convection currents from the hot food surface are both important.

Thus, detailed measurement or computation of the surface heat transfer coefficient inside a microwave oven has not been available, which was the goal for this study. Such knowledge should make it possible to improve the oven design for better quality of microwaved foods. The quality of the food is affected by the airflow in two ways:

- if surface heat and mass transfer coefficients are too low, a soggy food may result;
- if the magnitude of these coefficients varies considerably from one position on the surface to another, non-uniform heating will lead to non-uniform quality.

CFD can contribute to the understanding of flow patterns and thermal exchanges in a microwave oven cavity, as models for combined flow regimes have been applied successfully in other applications (see, e.g., Chen, 1995; Murakami, Ohira, & Kato, 1999). On the other hand, measurements are expected to be tedious and prone to error, because

- measurements of airflow in an operational microwave oven are difficult if not impossible;
- the magnitude of airflow is expected to be low (in the order of 0.1 m/s), which is always difficult to measure;
- introduction of sensors in the cavity may disturb the airflow;
- inside the microwave cavity it is difficult to measure the distribution of surface heat transfer coefficients on the food surface.

<table>
<thead>
<tr>
<th>Nomenclature</th>
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<tr>
<td>$\beta$ air volumetric expansion coefficient (1/K)</td>
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<td>$\lambda$ air thermal conductivity (W/m°C)</td>
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<tr>
<td>$\mu$ air dynamic viscosity ($\nu = \mu/\rho$) (kg/m s)</td>
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<tr>
<td>$\rho$ air density (kg/m³)</td>
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<td>$Re$ Reynolds number $\rho U_i D_h/\mu$</td>
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<tr>
<td>$Ra$ Rayleigh number $(\text{Gr} = Ra \times \alpha/\nu) (\beta(T_s - T_i)) \times L^3/\nu$</td>
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<tr>
<td>$Ar$ Archimedes number $\text{Gr}/Re^2$</td>
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<table>
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<tr>
<th>Subscripts</th>
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<tr>
<td>i inlet</td>
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<tr>
<td>s food surface</td>
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<td>w cavity wall</td>
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- measurements of airflow in an operational microwave oven are difficult if not impossible;
- the magnitude of airflow is expected to be low (in the order of 0.1 m/s), which is always difficult to measure;
- introduction of sensors in the cavity may disturb the airflow;
- inside the microwave cavity it is difficult to measure the distribution of surface heat transfer coefficients on the food surface.
The specific objectives of the study are

- to determine the patterns and magnitude of airflow inside a microwave oven under forced and natural convection;
- to calculate the magnitude and distribution of the surface heat transfer coefficient on the food surface under various conditions;
- to calculate the contribution of radiation heat transfer to the total surface heat transfer coefficient.

2. Methodology

The airspace in the oven having a cylindrical food placed in the center of the oven is modelled in 3-D. The governing Navier–Stokes and energy equations are solved numerically using a commercial CFD code for laminar flow with typical positions of one inlet and one outlet. Natural, forced and combined convection modes are studied, which are now described.

2.1. Assumptions

The inlet and outlet vary in ovens depending on the model, manufacturer, etc. Our research goal was to understand overall trends of various parameters. Thus, we assumed a standard configuration, as shown in Fig. 1a. The heat and mass transfer in the air and in the food are coupled. The microwaves heat the food, which in turn heats the air. However, our primary interest is in the airflow surrounding the food. To concentrate our discussion on the airflow, the flow field will be solved for a constant temperature food surface boundary conditions. The hypothesis of a constant surface temperature condition is valid in case evaporation takes place from the food surface (Kondjoyan & Daudin, 1994). To reduce computation time, steady-state conditions are assumed that should provide the relevant details of the flow. A laminar flow model is used, as turbulence is assumed to play a minor role due to the low Reynolds numbers ($Re_{inlet} < 10^3$) and Rayleigh numbers ($Ra_{plume} < 3 \times 10^7$) involved.

2.2. Geometry and control volume mesh

A standard household microwave oven cavity is considered (Fig. 1a). The cavity measures 280 mm wide by 280 mm deep by 200 mm high. Looking in from the door side there is a screen of 150 mm wide and 40 mm high on the left hand side wall (“the inlet”), through which fresh air enters the cavity. Air is removed from a 950 mm by 850 mm screen (“the outlet”) on the opposite wall through suction. On the turntable, a disk-shaped food product of 100 mm diameter and 25 mm thickness is positioned. The geometry of the oven cavity is modeled by means of hexahedral blocks on which the numerical mesh is defined (Fig. 1b). A total of 13 blocks is required in this approach. The inlet and outlet are defined as constraining patches on the appropriate walls. The structured mesh of control volumes is refined near the surfaces of the food and the cavity walls in order to accurately resolve the velocity and thermal boundary layers. A typical mesh, consisting of 236,000 control volumes is shown in Fig. 1b. A mesh refinement study is carried out with successively denser meshes near the surfaces. The coarsest and finest meshes contain nodes up to 0.33 and 0.04 mm from the food surface, respectively.

2.3. Governing equations and boundary conditions for convection heat transfer

The governing equations for flow and heat transfer in the air inside the microwave oven at steady state are given by

\[ \nabla \cdot \mathbf{V} = 0 \]  \hspace{1cm} (1)
\[ \rho \mathbf{V} \cdot \nabla \mathbf{V} = -\nabla P + \mu \nabla^2 \mathbf{V} + \rho (1 - \beta (T - T_0)) \mathbf{g} \]  \hspace{1cm} (2)
\[ \mathbf{V} \cdot \nabla T = \kappa \nabla^2 T \]  \hspace{1cm} (3)

The symbols are explained in the nomenclature section above. For forced convection only, the last term on the right hand side of Eq. (2), representing the Boussinesq approximation, is removed.
At the cavity and food surfaces, the no-slip boundary condition is imposed for the flow. When the food rotates on turntable, air velocity on the food surface is set at the corresponding tangential velocity of the food surface. At cavity surfaces two alternative boundary conditions are evaluated—constant temperature and constant heat transfer coefficient. At the food surface a constant temperature boundary condition is implemented (see Section 2.1). Air velocity at the inlet is uniform over the cross-section of the inlet and is at a uniform temperature equal to the ambient temperature. The velocity and temperature at the outlet are determined by the solution.

From the computed temperature data, heat transfer coefficient, \( h \), is calculated over the food surface from its defining equation:

\[
\dot{q}_{\text{rad}} = \frac{h}{T_s - T_i} \frac{S_f}{S_{\text{surface}}} \tag{4}
\]

2.4. Computation of radiation heat transfer

Since radiation heat transfer from the food surface to the oven interior walls is always present, it is useful to estimate this radiation heat transfer coefficient since its effect will be analogous to that of convection heat transfer coefficient. The radiation exchanges in the cavity are calculated by means of a Monte Carlo simulation of photon trajectories (Guilbert, 1989; Lewis & Miller, 1984). This method tracks a large number of photons through the geometry by a collection of events (emission, reflection, absorption) and adds up the incident photon energies on each surface. The simulation procedure consists of the defining a geometrical model and the implementation and solution of the physical photon tracking model (CFX-4.3: Solver user manual, 1999). The basis of the geometrical model is a body-fitted model of the geometry, as it was built for the airflow analysis, explained above. The wall surfaces in this geometry are subdivided into sets of non-overlapping primitive planar wall surfaces, on which the surface temperature and appropriate emissivity are defined. The Monte Carlo simulation with 5,000,000 photon trajectories was required for an accurate calculation of the radiation heat transfer between the surfaces of the oven cavity interior and the food. Computation times were close to 1 h on a HP C160 (128 MB RAM) workstation. The radiation surface heat transfer coefficient is calculated based on the resulting net radiative heat fluxes from the food surface:

\[
h_r = \frac{q_{\text{rad}}}{T_s - T_w} \tag{5}
\]

2.5. Numerical solution

The governing equations are solved by means of the CFD code CFX 4.3 (AEAT, Harwell, UK) that uses a conservative block-structured finite-volume approach with all variables defined at the center of control volumes (CFX-4.3: Solver user manual, 1999). The diffusion terms are discretized in space using second-order central differencing. For the convective terms, the QUICK scheme was chosen. QUICK uses a three-point upstream interpolation and is third-order accurate. It was found that for both the forced convection and natural convection cases the QUICK scheme resulted in good convergence properties. The algebraic multi-grid solver was used to solve the linear discretized equations. Pseudo-time stepping was applied to enhance diagonal dominance of the coefficient matrix and hence improve convergence. Convergence was achieved when the sum of absolute residuals of all equations reduced by four orders of magnitude (to a typical level of 10\(^{-9}\) N for the momentum equations, which is 100,000 times lower than the supplied momentum at the inlet). A total of 1500 pseudo-time steps or 5000 iterations (three iterations per time step) were required on the 236,000 control volumes mesh, using 45 CPU hours on an HP C160 with 128 MB RAM workstation.

2.6. Input data

The input parameters used in the model are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Input parameters used in the calculations</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td>Inlet air temperature, ( T_i )</td>
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<tr>
<td>Inlet air velocity, ( U_i )</td>
</tr>
<tr>
<td>Food surface temperature, ( T_s )</td>
</tr>
<tr>
<td>Food surface heat flux, ( q_{\text{s}} )</td>
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<tr>
<td>Air reference temperature, ( T_0 )</td>
</tr>
<tr>
<td>Emissivity of cavity walls</td>
</tr>
<tr>
<td>Emissivity of food</td>
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<tr>
<td>Density of food</td>
</tr>
<tr>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>Specific heat</td>
</tr>
<tr>
<td>Emissivity of turntable rotation speed</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
</tr>
<tr>
<td>Turntable rotation speed</td>
</tr>
</tbody>
</table>

3. Results and discussion

3.1. Validation of the computations

Measurements in a microwave oven cavity are difficult, since metallic components are not allowed in the oven. The computations are validated by addressing several other issues. First, the grid independence of the simulated results is verified. Second, the model outcome is compared with cases for which valid experimental results exist, namely, natural convection on a vertical
wall, flow over a cylinder and, finally, flow over wall-mounted objects.

3.1.1. Grid independence of the solution

The average surface heat transfer coefficient is chosen as the variable to follow convergence. Fig. 2 shows how convergence is achieved as the grid is refined. Solutions on three successively refined grids show convergence for both natural and forced convection. The use of the higher order discretization schemes mentioned earlier results in an excellent grid dependence reduction. Using the Richardson extrapolation method (Richardson, 1910), we find a convergence error of 0.005 W/m²°C (<0.1%) on the finest grid for natural convection and 0.04 W/m²°C (<1%) for forced convection. Computation error for forced convection heating is higher because the grid could not be refined to the same level as the natural convection case, where symmetry was used to mesh only a quarter of the oven.

3.1.2. Comparison with related published literature

As a first case for comparison, natural convection along a vertical plate is considered. Fig. 3 displays the comparison of model prediction and values obtained by the LeFevre correlation of numerical results (1956) for a typical Grashof number of $Gr_L = 3 \times 10^8$. Only towards the top of the plate ($L = 0.5$ m), some deviation between model and reference is recognised. However, such lengths will not be present in the microwave oven, restricting Grashof numbers to $2 \times 10^7$. Therefore, natural convection can be accurately predicted by means of the model.

Forced flow over a single infinitely long cylinder is the second important case for comparison. This case involves complex phenomena such as flow separation and vortex shedding. A transient procedure is required to capture these effects. Fig. 4 shows the computed time-averaged local Nusselt number distribution along the surface of the cylinder, compared to experimental data of Krall and Eckert (1973), which were interpolated for a Reynolds number of 500. At a Reynolds number of 500, the flow over the cylinder is transient and the wake region is turbulent. Therefore the accuracy of the prediction in the relatively small separated region (angles larger than 120°) is somewhat less, as the model uses laminar assumptions. However, due to the relatively low Reynolds numbers, the errors remain small. In the attached region (angles smaller than 120°), the comparison is excellent.

Finally, the case of forced flow over an obstacle on a surface can be used to interpret the validity of the results over a food surface obtained in this study. For flow over a wall-mounted cube at a Reynolds number of 795, Meinders, van der Meer, and Hanjalic (1998) measured the distribution along the flow center line shown in Fig. 5a. For the cylindrical food in the microwave oven we...
find the center line distribution according to Fig. 5b for forced flow with an inlet velocity of 0.1 m/s ($Re = 150$). Although the actual values cannot be compared due to differences in configuration and Reynolds number, the overall pattern of both cases is very similar (looking in the streamwise direction). The surface heat transfer coefficients increase on the upstream face (DC), decrease on the parallel top face (CB) and increase towards A on the line BA. Due to the lower Reynolds number, the pattern would be less pronounced in the microwave oven.

From the grid independence of the computed data and its good comparison with published experimental data, the computations are considered to be sufficiently accurate.

3.2. Airflow patterns

Although in reality the convection inside the oven is a combined one (natural as well as forced), it is interesting to first look at the separate cases of solely natural and solely forced convection to better understand the flow pattern in the microwave cavity. Note that because of symmetry, the natural convection case can be performed on a single quarter of the geometry. The air velocity vectors for natural convection are shown in Fig. 6a. A rising plume of warm air is established from the hot food surface near the bottom of the cavity and returns along the colder walls of the cavity. The maximum velocity in the plume is as high as 0.3 m/s. The flow generated by the hot food surface can therefore be significant.

The flow pattern in the forced convection case is completely different (Fig. 6b). In this case, fresh cool air moves primarily from the inlet to the outlet at a speed almost equal to the inlet speed (0.1 m/s). Part of the incoming air deviates from the cavity walls and impinges the food surface on the right hand side with considerably lower velocity than at the inlet. Comparing Fig. 6a and b one can see that (1) opposite flows are established by natural (upward) and forced (downward) convection modes; (2) natural convection leads to rising hot air, while the forced flow is mainly cool air, entering the cavity; (3) flow due to the buoyancy effect is comparable to the forced flow, which is indicated by the magnitude of the maximum velocities (0.3 m/s for natural and 0.1 m/s for forced convection).

Eventually, a combined regime of natural and forced convection will be established. During combined convection, a third dimensionless number, the Archimedes number ($Ar$, ratio of the Grashof to the squared Reynolds number), determines the flow behavior. At
high Archimedes number (strong buoyancy to inertia forces), the inlet forced flow may be deviated by the buoyant plume. The Archimedes number in the present case equals 128, which is much larger than the threshold of 1 below which natural convection is of minor importance. The combined convection flow pattern for the set of conditions in Table 1 is given in Fig. 7. One can recognise the strong interaction of the buoyant plume and the forced incoming flow. The air at the inlet bends downwards and impinges on the food surface. A complex upward movement is established towards the outlet of the cavity. The combination of natural and forced convection improves the mixing inside the cavity, allowing fresh air to penetrate the zone around the food surface. In a pure forced convection regime (e.g., if the inlet velocity were increased) a flow pattern very similar to Fig. 6b would be established, and most of the fresh air moves directly from inlet to outlet. This can be achieved if the inlet velocity is increased to approximately 1 m/s ($Ar \sim 1$). It is likely that such practice is not recommendable with the current configuration when moisture accumulation around the food should be avoided. Even so, if the inlet velocity is dropped to lower values, natural convection will start to dominate the flow as in Fig. 6a. In that case, excessive moisture accumulation may as well occur because air is trapped within the cavity. In terms of air mixing therefore, an optimal refreshment rate exists for this arrangement of inlet and outlet. It should be noted that in the case of combination ovens, the flow pattern is different and better mixing is achieved by means of centrifugal fans. For these devices, the above discussion does not hold.

### 3.3. Magnitude and distribution of surface heat transfer coefficients

The average surface heat transfer coefficients over the top surface, the side, and top and side combined are shown in Table 2.

#### 3.3.1. Variation between natural and forced convection

The surface heat transfer coefficient due to natural convection depends on the temperature or heat flux set at the food surface, while for forced convection it depends to a large extent on the velocity magnitude specified at the inlet. In the cases presented in Table 2 we find larger coefficients for the natural convection thus, pure forced convection will not occur with inlet velocities around 0.1 m/s, and natural convection is likely to dominate the flow and heat transfer, as was shown in Fig. 7.

#### 3.3.2. The real case: combined convection

For combined convection, an average surface heat transfer coefficient of 7.3 W/m² °C was found, which resembles the natural convection value. The average values at the top and side surfaces for combined convection are 4.4 and 10.3 W/m² °C, respectively, for

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**Table 2**

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>Natural convection</th>
<th>Forced convection ($U_i = 0.1$ m/s)</th>
<th>Radiation (3) (emissivity = 0.96)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top and side</td>
<td>Rotation on</td>
<td>Rotation off</td>
<td>Rotation on</td>
</tr>
<tr>
<td>(1)</td>
<td>7.0</td>
<td>7.0</td>
<td>4.1</td>
</tr>
<tr>
<td>(2)</td>
<td>5.5</td>
<td>–</td>
<td>2.9</td>
</tr>
<tr>
<td>Top</td>
<td>Rotation on</td>
<td>Rotation off</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>2.8</td>
<td>2.8</td>
<td>1.6</td>
</tr>
<tr>
<td>(2)</td>
<td>2.7</td>
<td>–</td>
<td>2.4</td>
</tr>
<tr>
<td>Side</td>
<td>Rotation on</td>
<td>Rotation off</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>11.1</td>
<td>11.1</td>
<td>6.4</td>
</tr>
<tr>
<td>(2)</td>
<td>8.2</td>
<td>–</td>
<td>3.4</td>
</tr>
</tbody>
</table>

(1) Constant food surface temperature ($T_s = 50$ °C), constant temperature at cavity walls ($T_w = 20$ °C).
(2) Constant food surface temperature ($T_s = 50$ °C), convection boundary condition at cavity walls ($h_w = 5$ W/m² °C).
(3) Radiative food and oven surface temperatures are 50 and 20 °C, respectively.
conditions of constant temperature at the food surface and cavity walls. The effect of the low forced airflow therefore acts to decrease the differences in the heat transfer coefficient around the surface of the food. The impingement of the incoming fresh air on the food surface is recognised in Fig. 8. Here the radial distribution of \( h \) from left to right on the top surface is shown for natural, forced and combined convection. While a low value of \( h \) exists at the center of the top surface for natural convection, the impingement of fresh air causes a high surface heat transfer coefficient in the combined convection mode. Forced convection leads to relatively uniform heat transfer rates over the top surface, but it does not lead to higher values of the heat transfer coefficient.

3.3.3. Variation between side and top surface

Considerable differences (Table 2) between the heat transfer coefficient at the side and the top surfaces of food can be attributed to the difference in boundary layers on the sides due to natural convection and impingement (forced convection). However, the fixed temperature boundary condition defined on the cavity walls also contributes to the large \( h \) values on the side surface. When a convection boundary condition is specified on the cavity walls, a lower estimate of \( h \) is obtained for side surface of the food (Table 2). The general trend of a lower value of \( h \) on top surface compared to side is retained, however.

3.3.4. Variation along the perimeter for forced convection

There are differences in \( h \) values on the side surface along the perimeter in the forced convection case. Fig. 9 shows the distribution of \( h \) at two locations on the side surface of the food as a function of position from the bottom for the forced convection case. On the air outlet side of the food (Fig. 9b), the airflow impinges the surfaces, resulting in a higher \( h \) than on the air inlet side of the food (Fig. 9a). Considerable variation of the surface heat transfer is found on the different surfaces, especially near the edges of the food, which could help explain excessive drying of sharp edges of the foods (see also Section 3.5).

![Fig. 8. Surface heat transfer coefficient along the top surface of the food in the microwave oven, from inlet to the outlet side, along the direction perpendicular to the inlet (conditions of constant food surface and cavity wall temperature).](image1)

Fig. 8. Surface heat transfer coefficient along the top surface of the food in the microwave oven, from inlet to the outlet side, along the direction perpendicular to the inlet (conditions of constant food surface and cavity wall temperature).

![Fig. 9. Variation along the height of the food surface (on a surface location perpendicularly across from the middle of the inlet) of heat transfer coefficient in the microwave oven for forced convection with constant food surface temperature at the inlet side (a) and outlet side (b) of the food (conditions of constant food surface and cavity wall temperature).](image2)
3.3.5. Effect of rotation

Rotating the food at 6 rpm results in a side surface velocity of the food at 0.03 m/s. The rotation of the food does not affect the magnitude of the average surface heat transfer coefficients (Table 2). During natural convection, the local transfer coefficients are also not affected. This could be expected as the rotation works in the direction where virtually no temperature gradients exist along the surface (as the geometry is nearly axisymmetric). In the forced convection case, rotation does slightly improve the uniformity of the surface heat transfer coefficient on the side surfaces, in a fixed reference frame (Fig. 9). However, as the food rotates, the remaining differences in surface heat transfer coefficient from one side to the other are of minor importance (rotation averages the values anyway).

3.4. Effect of radiation on total surface heat transfer

Radiation calculations were done for two emissivities of the food surface in the range likely to be encountered for foods. The radiation surface heat transfer coefficients for side and top surfaces of the food are given in Table 2 with an average value of 5.1 W/m² °C for a food surface emissivity of 0.96 and food and oven surface temperatures of 50 and 20 °C, respectively. For an emissivity of 0.8, a radiation heat transfer coefficient value of 4.6 W/m² °C is obtained, which is of the same order of magnitude as the convective heat transfer coefficient and therefore cannot be neglected. The surface radiation heat transfer coefficients are higher for the top surface than for the sides, i.e., they vary opposite of the convection heat transfer coefficients. The resulting total (convection + radiation) values of the surface heat transfer coefficients in a combined convection regime (see Section 3.3.1) are 12.4 W/m² °C for the entire food surface, and 10.5 and 14.3 W/m² °C on the top and side, respectively. Thus, the magnitude of the total surface heat transfer coefficient, for convection and radiation together, is rather uniform over the entire food surface.

3.5. Effect of convection–radiation on surface moisture and temperature during microwave heating

The surface convection and radiation heat transfer coefficients found in the above analysis equal 7.3 and 5.1 W/m² °C, respectively. Based on the surface convection heat transfer coefficient and the Lewis analogy (Bird, Stewart, & Lightfoot, 2002), the surface convection mass transfer coefficient is 0.0063 m/s. Because the air and cavity walls are colder than the food during microwave heating, the combined convection–radiation will result in faster cooling of the surface as compared to when just radiation heat transfer is present. Lower temperatures resulting from faster cooling lead to slightly reduced evaporation from the food surface. Also, the convection mass transfer coefficient value of 0.0063 m/s is low enough that it will probably not be able to remove moisture at a rapid enough rate (as suggested from the food internal moisture transfer computations of Datta & Ni, 2002). Thus, the airflow is likely to reduce the surface evaporation but is not high enough to remove significant moisture from surface. This points to a high probability of having a soggy food surface in the microwave oven studied.

4. Summary

A combined natural and forced convection regime is likely to be established inside a traditional microwave oven (one without significant forced air), resulting in a complex airflow. In this oven design, the combination of a low-velocity fresh airflow and a hot food surface is beneficial from two viewpoints. First, mixing of fresh air with oven air will result in reduced moisture accumulation inside the cavity with a reduced likelihood of condensation. Second, the incoming fresh air impinges the food surfaces and results in more spatially uniform and higher surface heat and mass transfer coefficients that affect the food heating and drying rate during the microwave process. However, the mass transfer coefficient is not high enough to reduce undesirable moisture accumulation on the food surface in all cases. When the forced airflow is removed altogether, the benefits will also be less pronounced. When the forced airflow is increased beyond a certain value, the air mixing around the food will be less, but higher surface heat and mass transfer coefficients can help reduce undesirable moisture accumulation on the food surface. To improve both mixing and surface transfer coefficients, air inlets and outlets need to be optimally placed and different fans should be used, i.e., the design of the oven should be modified.

Convection heat transfer coefficient values ranged from 2.7 to 7.0 W/m² °C when averaged over the entire surface. These heat transfer coefficient values confirm the values used in earlier studies on microwave heating. Convection heat transfer coefficient values averaged over top and side surfaces, respectively, ranged from 1.5–3.8 W/m² °C and 3.3–11.1 W/m² °C. Within the same top or side surface, there are similar variations of the convection heat transfer coefficient. Radiation heat transfer coefficients are in the same range and tend to decrease differences between top and side. The rotation of the food due to the turntable does not affect the magnitude of the convective transfer coefficients, but provides more uniform heating for the case when the heat transfer is different from one side to another (as in the forced convection case). The insight developed here is useful for comparing oven designs with respect to heating uniformity and moisture distribution inside the
food being heated, and moisture accumulation in the oven.

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