Penetration of Infrared Radiation within a Vegetable Model

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A vegetable model was constructed in order to evaluate its apparent absorption coefficient and penetration of infrared radiation within it. Carrot, daikon (Japanese radish), eggplant, potato, pumpkin and sweet potato were prepared as the test vegetables. This vegetable model was composed of the dry vegetable material, liquid and gas, and its apparent absorption coefficient was calculated with their absorption coefficients and volumetric fractions. The volumetric fraction of the voids (void fraction) was obtained experimentally by a method provided in this study. Thus the damping of infrared rays within the vegetable model irradiated by near-infrared (NIR) or far-infrared (FIR) radiation was estimated in consideration of the spectral distribution of the radiation. The infrared radiation absorbed by the vegetable model was indicated to be damped to 1/100 of the initial value at a depth of 0.21 to 2.54 mm, and the penetration depth in the case of NIR irradiation was deeper than that of FIR irradiation. Moreover, the calculation results suggested that the penetration depth of infrared radiation became deeper with a decrease in the water content.

Keywords: infrared radiation, penetration, vegetable, absorption coefficient, void fraction

Applications of infrared irradiation to thermal operations in food processing are of considerable interest (Sakai & Hanzawa, 1994) because of the lack of need for a heat medium, simplification of the apparatus and clean working environment. Organic materials and water which are the major components of foodstuffs absorb considerable infrared radiation, especially in the far-infrared (FIR) region. Moreover, infrared heaters made of fine ceramics with high emissivity in the FIR region are commercially available. Thus, the subjects such as drying and pasteurization have been actively examined, and many reports on the utilization of infrared irradiation are easily available. However, it is very difficult to analyze quantitatively the drying and pasteurization of food because of poor understanding of the radiative heat transfer mechanisms within it. This is due to limited understanding of its optical characteristics in the infrared region considering the changes in the components and the geometrical structure during such thermal operations.

Our attention was focused on an apparent absorption coefficient related to penetration of infrared radiation within a food model, since the previous studies (Hashimoto et al., 1992a, 1992b, 1993, 1994; Hirota et al., 1991) suggested that the drying and pasteurization characteristics of the other food models were greatly influenced by penetration of infrared radiation within them. Solids such as metals and many kinds of liquids almost perfectly absorb infrared radiation in the domain of several angstroms or micrometers thickness from the irradiated surface and may be treated as opaque to infrared radiation. On the other hand, gases such as nitrogen are transparent to infrared radiation. In addition, what behaves in-between transparent and opaque is called a semi-transparent medium. Food which is thicker than several millimeters and opaque to infrared radiation may be treated as semi-transparent on paying attention to the domain close to its surface.

Most of the previous studies reported on the penetration of infrared power mainly in the near-infrared (NIR) region within pure homogeneous materials (Arai et al., 1979, 1980; Sado, 1987) and raw foodstuffs (Dagerskog, 1979; Dagerskog & Östeström, 1979; Wade, 1987). Most foodstuffs are complicated in structure and contain many kinds of components; therefore, it is very difficult to apply the knowledge on penetration within pure homogeneous materials to real foodstuffs. Further, penetration of infrared radiation within raw foodstuffs may vary during thermal operations because of a decrease in the water content, even if the other components do not change. Hence, it is necessary to treat the water content as an important factor influencing penetration and to consider the spectral distribution of the radiation.

The apparent absorption coefficient of a foodstuff has a great effect on penetration of infrared radiation within it and is influenced by its water content and void fraction. The present purpose is to study the penetration of radiative power within the foodstuffs in relation to the variables of their water contents and void fractions. In this study, vegetables were prepared as wet porous foodstuffs, and a vegetable model composed of dry solid (dry vegetable material), liquid and gas in the voids was constructed in order to evaluate its apparent absorption coefficient and penetration of infrared radiation. Moreover, we provided a method of estimating the volumetric fractions of the three construction factors in the vegetable model.

Model Calculation

Damping of infrared rays within a vegetable Consider a vegetable irradiated with infrared radiation. Because the temperature of a vegetable heated by infrared radiation is usually much lower than the surface temperature of the
infrared heater, the emission within it can be negligible. Thus penetration of infrared radiation within the vegetable may be evaluated by modifying the damping function (Hashimoto et al., 1990).

\[
\phi(x) = \left(1 - r_d \right) q_r, i \exp(-\alpha_d, i x) dx
\]

The transmitted power at the depth of \(x\) is given by the power absorbed by the vegetable.

\[
\phi(x) = \left(1 - r_d \right) q_r, i \exp(-\alpha_d, i x) dx
\]

Here, \(q_r, i\) [W m\(^{-2}\) m\(^{-1}\)] and \(\alpha_{d, i}\) [-] are the irradiation power, the apparent reflectance at the vegetable surface and its apparent absorption coefficient, respectively. Further, \(\lambda_1\) and \(\lambda_2\) are the shortest and the longest wavelength of the infrared radiation, respectively.

Most kinds of vegetables are porous, and their water contents are very high. The surface of such a vegetable is considered to be covered with water, and it was reported that the diffuse reflectance spectra of the wet porous materials whose voids were filled with water were qualitatively approximated to the reflectance spectrum of water (Hashimoto et al., 1997). Further, \(r_d\) is influenced by the geometrical structure close to the surface and it is very difficult to analyze this influence. Thus it is assumed that \(r_d\) may be calculated by the following equation.

\[
r_d = \frac{(n_2 - 1)^2 + k_2^2}{(n_2 + 1)^2 + k_2^2}
\]

\(n_2\) [-] and \(k_2\) [-] are the refraction and extinction coefficients of water, respectively (Hale & Querry, 1973). Hence, \(\alpha_{d, i}\) is needed in order to calculate \(\phi(x)\) by using Eq. (1), because \(q_r, i\) is experimentally obtained (Hashimoto et al., 1994).

**Apparent absorption coefficient of a vegetable model**

We considered a vegetable model in order to estimate \(\alpha_{d, i}\).

The vegetable is composed of dry vegetable material, liquid and gas in the voids. Figure 1 indicates the vegetable model simplified on the basis of this concept. In the model, the liquid and gas are assumed to be water and air, respectively. Moreover, on the assumption of the additivity of the apparent absorption coefficient, \(\alpha_{d, i}\) is approximately expressed by the following equation.

\[
\alpha_{d, i} = f_d \alpha_{d, i} + f_w \alpha_{w, i} + f_+ \alpha_+, i
\]

Here, \(\alpha\) and \(f\) are the absorption coefficient and the volumetric fraction, respectively. The subscripts \(d\), \(w\) and \(v\) mean the dry vegetable material, water and the void, respectively. Because the path length in the void is usually very short and infrared radiation is scarcely absorbed by air, the third term of Eq. (3) may be negligible. So, \(\alpha_{d, i}\) is calculated by Eq. (4).

\[
\alpha_{d, i} = f_d \alpha_{d, i} + f_w \alpha_{w, i}
\]

By the way, \(f_d\) and \(f_w\) are evaluated by the following equations.

\[
f_d = \frac{\omega_h \rho_d}{\rho_w}
\]

\[
f_w = \frac{\omega_h \rho_d}{\rho_w}
\]

Here, \(\omega_h\) and \(\omega_w\) are the water contents on wet and dry bases, respectively. \(\rho_h\) and \(\rho_w\) are the densities of the water and dry vegetable material, and \(\rho_d\) is the bulk density of the vegetable. For these properties except \(\rho_d\), the literature values can be easily cited. Moreover, Eq. (7) is formed based on the vegetable model.

\[
f_d + f_w + f_+ = 1
\]

Hence, when \(\rho_d\) is experimentally obtained, all volumetric fractions are calculated.

For the absorption coefficients, \(\alpha_{w, i}\) is available and can be cited (Hale & Querry, 1973), but \(\alpha_{d, i}\) must be examined. By measuring the infrared spectrum of the dry vegetable material, \(\alpha_{d, i}\) is obtained from the following equation.

\[
\ln\left(\frac{I_0}{I_{d, i}}\right) = -\alpha_{d, i} d
\]

Here, \(I_0/I_{d, i}\) is the monochromatic transmittance through a layer of the dry vegetable material with a thickness of \(d\).

From the above, it is necessary to obtain experimentally the density and the infrared transmittance spectrum of the dry vegetable material in order to perform the model calculation of Eq. (1).

**Materials and Methods**

**Vegetables** Carrot, daikon (Japanese radish), eggplant, potato, pumpkin and sweet potato were used as the test vegetables. They were cultivated in 1993 at the Experimental Farm, Faculty of Bioresources, Mie University, Tsu, Mie, Japan. The test vegetable was cut into about 5 mm cubes with a knife and dried in an oven at 358 K for 48 h. The dry vegetable material was prepared for the density and infrared spectrum measurements.

**Measurement of density of dry vegetable material** A fully automatic gas displacement pycnometer (Micrometrics Instrument, AccPyc 1330) was used for the volume measurement of the dry vegetable material. About 50 g of the dry vegetable was placed in a sample cup. After the sample cup was inserted into the cell chamber of the pycnometer, the cell chamber cap was replaced. Helium gas (purity: higher than 99.995%) was used for the purge and the displacement. After sixty purges of the cell chamber, the volume measurement was repeated sixty times. The experimental values from the fortieth to the sixtieth measurement were averaged. These conditions were determined by measuring the volume of a spherical
standard sample made of stainless steel for this pycnometer (Nitta, 1997).

Before and after the volume measurement, the weight of the sample was measured with an electric balance (A&D, ER-182A) and the average was obtained. From the averages of the volume and weight of the dry vegetable material, its density, $\rho_d$, was evaluated.

**Infrared spectral measurement of dry vegetable material.** The dry vegetable was crushed with a mortar and a pestle made of agate, and a powder of 200 to 300 mesh was prepared. Potassium bromide (KBr) powder (Merck, for spectroscopy) had been dried in the oven at 378 K for 48 h and powdered by the same method described above. Three, five and ten milligrams of the dry vegetable powders were mixed with 120 mg of the KBr powder, respectively. The mixture was pressed at 8 t cm$^{-2}$ for 10 min in a KBr tablet die (Shimadzu, Model SSP-10A). During the pressing, the pressure in the die was kept at several mmHg under vacuum using a pump.

Fourier transform infrared (FT-IR) spectra was collected on a Fourier transform spectrometer (PERKIN ELMER, Model 1600). The data were recorded from 500 to 7000 cm$^{-1}$ (from about 1.4 to 20 $\mu$m wavelength) in 4-cm$^{-1}$ increments at $T$, in which $T$ is the ratio of the transmitted intensity for the background to that of the sample. The combination of the KBr tablet from that composed of the dry vegetable material and KBr, the path length was obtained.

**Results and Discussion**

**Volume fractions of water, dry material and voids of vegetable model.** The density of the dry vegetable materials obtained by the experiments with the fully automatic gas displacement pycnometer is listed in Table 1, which also indicates the water content and the bulk density of the vegetable (Sado, 1987). These properties are needed in order to calculate its volumetric fractions. Each $\rho_d$ was greater than $\rho_s$ (= 1000 kg m$^{-3}$), and the standard error in the measurement was less than 1%. Moreover, the values of $\rho_d$ were almost the same in each case except for that of the pumpkin.

Table 2 shows the volumetric fractions obtained by substituting the properties in Table 1 into Eqs. (5), (6) and (7). Figure 2, (a) and (b) display the relationship between the water content and the volumetric fraction of the voids (void fraction, $f_v$). We focused our attention not on the weight basis water content ($\omega_w$ or $\omega_d$) but on the volumetric water content ($f_w$), because $\alpha_{\text{conv}}$ is influenced by the volumetric fractions as expressed in Eqs. (3) and (4). For the water content of the eggplant, its volumetric fraction was the least among the six kinds of vegetables, though its weight fraction was greater than the others. This was the effect of a very large void fraction. Moreover, the influence of the void fraction on $\alpha_{\text{conv}}$ may be understood by noticing those of the eggplant and sweet potato, because their volumetric water contents were almost the same.

**Transmittance of dry vegetable material** Figure 3 shows the transmittance spectra of the carrot. The strong peak at about 3400 cm$^{-1}$ (about 3 $\mu$m wavelength) was assigned to the O-H stretching mode. For the spectra of all six kinds of vegetables, the transmittance decreased with an increase in the amount of the dry vegetable material in the tablet while retaining the same spectral patterns.

All sample vegetables contain a large amount of cellulose

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**Table 1.** Characteristics of vegetables.

<table>
<thead>
<tr>
<th>Vegetables</th>
<th>$\omega_v$ $&lt; 100$ [% w.b.]</th>
<th>$\omega_d$ $&lt; 100$ [% d.b.]</th>
<th>$\rho_v$ [kg m$^{-3}$]</th>
<th>$\rho_d$ [kg m$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td>90.0</td>
<td>900</td>
<td>190 (1.45 ± 0.01 $\times$ 10$^9$)</td>
<td>1.45 ± 0.01 $\times$ 10$^9$</td>
</tr>
<tr>
<td>Daikon</td>
<td>93.0</td>
<td>1329</td>
<td>1010 (1.47 ± 0.01 $\times$ 10$^9$)</td>
<td></td>
</tr>
<tr>
<td>Eggplant</td>
<td>92.8</td>
<td>1289</td>
<td>1060 (1.55 ± 0.01 $\times$ 10$^9$)</td>
<td></td>
</tr>
<tr>
<td>Potato</td>
<td>80.4</td>
<td>410</td>
<td>990 (1.16 ± 0.01 $\times$ 10$^9$)</td>
<td></td>
</tr>
<tr>
<td>Pumpkin</td>
<td>78.0</td>
<td>355</td>
<td>1040 (1.45 ± 0.01 $\times$ 10$^9$)</td>
<td></td>
</tr>
</tbody>
</table>

$a$) literature values (Sado, 1987).

$b$) calculated from $\omega_v$.

**Table 2.** Volumetric fractions of vegetables.

<table>
<thead>
<tr>
<th>Vegetables</th>
<th>$f_w$ [-]</th>
<th>$f_v$ [-]</th>
<th>$f_d$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td>0.064</td>
<td>0.006</td>
<td>0.070</td>
</tr>
<tr>
<td>Daikon</td>
<td>0.039</td>
<td>0.048</td>
<td>0.013</td>
</tr>
<tr>
<td>Eggplant</td>
<td>0.065</td>
<td>0.032</td>
<td>0.323</td>
</tr>
<tr>
<td>Potato</td>
<td>0.052</td>
<td>0.145</td>
<td>0.002</td>
</tr>
<tr>
<td>Pumpkin</td>
<td>0.772</td>
<td>0.188</td>
<td>0.004</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>0.645</td>
<td>0.272</td>
<td>0.083</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Relationship between water content and void fraction; (a) volumetric water content, (b) water content on wet basis.
and starch. Cellulose is one of the most prevalent organic materials in the nature and one of the major components of vegetables. On the other hand, starch is one of the most important nutrients in vegetables and is largely contained in the potato genus. All of the spectra for the six kinds of vegetables had the characteristics of both cellulose and starch spectra (Keller, 1986a, b). Thus, all of the spectra were analogous. In addition, the influences of the differences between the cellulose and starch contents on the spectral patterns were slightly observed.

**Apparent absorption coefficient of dry vegetable material** We examined applying Eq. (8) approximately to the measured infrared spectra of the dry vegetable material (Fig. 3). Figure 4 shows the results. The ordinate is the logarithmic value of the transmittance of the dry carrot material, and the abscissa is the path length through the material. Based on Fig. 4, because the good linearity was observed at each wavenumber (wavelength) and all correlation coefficients were greater than 0.92, we considered that Eq. (8) could be applicable.

Figure 5 shows the apparent absorption coefficients of the dry vegetable materials obtained by the procedure described above and the absorption coefficient of water (Hale & Querry, 1973). The apparent absorption coefficients slightly varied from $1 \times 10^4$ to $2 \times 10^5$ m$^{-1}$, though the absorption coefficient of water changes dynamically from $7 \times 10^2$ to $2 \times 10^6$ m$^{-1}$. Moreover, the difference in the apparent absorption coefficients is fractional.

**Penetration of infrared radiation within vegetable model** We evaluated the damping of infrared radiation within the vegetable model irradiated by Heaters A and B, which are respectively typical NIR and FIR heaters. Figure 7 (Hashimoto et al., 1994) shows the spectral distribution of the radiation ($q_{tr}$), and Fig. 8, (a) and (b) display the model calculation results of $\phi(x)$ respectively for NIR and FIR irradiation. In the model calculation, $\lambda_1$ and $\lambda_2$ described in Eq. (1) were respectively treated as 1.4 and 20.0 $\mu$m with NIR.
and FIR irradiation. The value of $\phi(x)$ for the eggplant model was the greatest among the six kinds of vegetable models. This meant that infrared radiation was the most penetrative within the eggplant model whose void fraction was the highest. On the contrary, infrared radiation was the least penetrative within the sweet potato model whose volumetric fraction of water was the lowest. Hence, this suggested that a large amount of infrared radiation was absorbed within a very thin domain near the surface. Moreover, for the carrot and daikon models whose volumetric fractions of water were higher than the others, the penetration of infrared radiation was more significant than the others except for the eggplant.

We defined $x_{\text{pen}}$ as the penetration depth where the infrared radiation absorbed by the vegetable model was damped to 1/100 of the initial value at its surface. The estimated penetration depth is listed in Table 3 in which $\omega_0$ is the water content on wet basis at the initial stage and was from 0.38 to 2.54 mm in the case of NIR irradiation and from 0.21 to 0.64 mm in the case of FIR irradiation. Hence, Fig. 8 and Table 3 suggest that NIR radiation was more penetrative within the vegetable model than FIR radiation. Further, these results indicated that the penetration depth depended especially on the water content and the void fraction. The water content and the void fraction of the vegetable irradiated by infrared radiation decrease and increase during irradiation, respectively. Therefore, we evaluated the damping behavior of infrared radiation in consideration of infrared drying process. In the calculation, we assumed that the water reduced by evaporation in the vegetable model created the voids, and that the

Table 3. Damping of infrared power within vegetable model.

<table>
<thead>
<tr>
<th>Vegetables</th>
<th>Heater A (NIR irradiation)</th>
<th>Heater B (FIR irradiation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x_{\text{pen}}$ [mm]</td>
<td>$x_{\text{pen}}$ [mm]</td>
</tr>
<tr>
<td></td>
<td>$\omega_0$</td>
<td>$\omega_0/2$</td>
</tr>
<tr>
<td>Carrot</td>
<td>1.30</td>
<td>1.46</td>
</tr>
<tr>
<td>Daikon</td>
<td>1.40</td>
<td>1.60</td>
</tr>
<tr>
<td>Eggplant</td>
<td>2.54</td>
<td>3.00</td>
</tr>
<tr>
<td>Potato</td>
<td>0.57</td>
<td>0.61</td>
</tr>
<tr>
<td>Pumpkin</td>
<td>0.49</td>
<td>0.52</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>0.38</td>
<td>0.40</td>
</tr>
</tbody>
</table>
shrinkage during drying could be negligible. Figure 9 and Table 3 display the effect of the water content on the damping of infrared radiation within the vegetable model. With the decrease in the water content, the penetration depth of infrared radiation became deeper for all vegetable models. This tendency was more significant for FIR irradiation than for NIR irradiation. Hence, it was considered that \( \sigma_{\text{app}} \) in the FIR region was affected by the water content more than that in the NIR region, because the absorption coefficient of water in the FIR region is higher than that in the NIR region (Fig. 5).

Though Fig. 8 and Table 3 indicated the short penetration depth of infrared radiation within vegetable model, its depth may be very important for thin-layered foods such as sheet foods. Moreover, it was reported that the pasteurization effect and the drying characteristics were greatly influenced by the absorption of infrared radiation at the very thin domain close to the surface of the food models (Hashimoto et al., 1992a, b, 1994). Consequently, the penetration depth evaluated in the present study was suggested to have an important effect on the thermal operation by infrared irradiation in food processing. Therefore, after this, it is necessary to develop a good understanding of the apparent reflectance and of the influence of the structure on the optical characteristics.

Conclusions

The vegetable model was constructed in order to evaluate its apparent absorption coefficient in consideration of its water content and void fraction which was obtained by the method provided in this study. Using the coefficient, we studied the penetration of infrared radiation within the vegetable model. The following results were obtained.

1) We provided a method of estimating the volumetric fractions of water, the dry vegetable material and the voids within the vegetable by experimentally obtaining the density of the dry vegetable material.
2) The differences in the apparent absorption coefficients of the vegetable models were marginal, and the spectral patterns of those coefficients were analogous to that of water.
3) It was suggested that infrared radiation absorbed by the vegetable model was damped to 1/100 of the initial value at a depth of 0.38 to 2.54 mm in the case of NIR irradiation and of 0.21 to 0.64 mm in the case of FIR irradiation. Moreover, the calculation results suggested that the penetration depth of infrared radiation became deeper with a decrease in the water content.

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References


