Research Note

Thermal Conductivity of Potato as a Function of Moisture Content

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ABSTRACT

To measure the thermal conductivity of potato, a line-source probe system was developed. The thermal conductivity of potato was determined at various moisture contents in the temperature range of 40–70°C, using the heated probe method. The thermal conductivity of potato decreased with the decrease in moisture content. Temperature had little effect on the thermal conductivity. Thermal conductivity data were correlated with moisture content by a semi-logarithmic equation.

INTRODUCTION

The heat and mass transport properties of foods have received more attention recently because of their fundamental importance in modelling, optimizing and designing food processes and processing equipment (Singh, 1982; McPrond & Lund, 1983; Szczesniak, 1983). The thermal transport properties are needed in the quantitative analysis of important thermal processes, i.e. drying, sterilization, extrusion cooking, etc. Although several techniques have been developed for measuring the thermal properties, only a few data are available in the literature (Sweat, 1986).

Thermal conductivity of foodstuffs and its relationship to moisture content is one of the most important transport properties required to model processes in which mass and energy are exchanged. Typical...
examples are drying processes, rehydration processes and moisture pick-up by packaged dried foods during storage. Existing values have been reviewed by Qashou et al. (1972) and Rha (1975). Neither of these reviews shows data for the change in thermal conductivity as a function of moisture content. Sweat (1974) reported thermal conductivities of selected fruits and vegetables, exploring a range of moisture contents between 60 and 100% on a wet basis. The changing moisture content refers, in this case, to different moisture contents of different foodstuffs, not to the change in thermal conductivity of one foodstuff as its moisture content changes.

Two methods have been applied to the measurement of thermal conductivity of food materials, the steady-state and the unsteady-state methods (Mohsenin, 1980). The steady-state technique (guarded hot-plate) has been used to obtain accurate thermal conductivity values of freeze-dried gels (Saravacos & Pilsworth, 1965) and high-moisture starch gels (Drusas et al., 1986). The unsteady-state methods are faster and more versatile than the steady-state technique. Among the unsteady-state methods the heated probe technique has been the most widely used (Reidy & Rippen, 1971; Sweat, 1974, 1986; Mohsenin, 1980). The theoretical and experimental bases of this technique were discussed by Vos (1955) and Nix et al. (1967). The method is based on the application of electrical heating to a food sample and the measurement of the resulting temperature rise of the sample.

The purposes of this investigation are to determine the thermal conductivity of potato as a function of moisture content and the influence of temperature on thermal conductivity.

MATERIALS AND METHODS

Materials

To calibrate the measurement system, both glycerine and a gel of 0.5% agar and water were used.

Fresh Desiree potatoes were purchased from a local market. The water content of the potato was 82.1% (wet basis), measured by drying the sample in a vacuum oven at 70°C for 24 h, with six replicates. To obtain samples with a range of moisture contents, cylindrical samples of potato were dried for various times in an experimental hot-air drier at air temperatures of 40, 50, 60 and 70°C. The partly dried samples were sealed in polyethylene film and stored at constant temperature for 24 h to ensure a uniform moisture content throughout the sample.
Thermal conductivity apparatus

The experimental apparatus for measuring the thermal conductivity by the heated probe method is shown in Fig. 1. The thermal conductivity probe used in this research was constructed according to Sweat (1986).

A 21-gauge hypodermic needle of 0.80-mm o.d. and 38-mm length was used. A constantan wire, 0.076 mm in diameter, was used as the heated line source. The temperature was measured with a T-type thermocouple of 0.076-mm diameter (Omega Engineering Co.). The heater wire and the thermocouple were inserted in the needle and an epoxy glue was used for sealing. Constantan was used for the heated wire because its electrical resistance does not change with temperature (Sweat, 1986).

The probe's length/diameter ratio was higher than 25, as recommended in the literature (Sweat, 1986), and the ratio of the probe diameter to sample diameter was 0.036, in the range of 0.43–0.033 recommended by Sweat et al. (1973) and Drouzas and Saravacos (1988).

Experimental procedure

The potato sample was placed in a bottle of 22-mm i.d. and 60-mm length. The probe was inserted into the centre of the sample until its length was covered by the sample. The filled sample bottle with the probe was first equilibrated to the desired temperature (40, 50, 60 and 70°C) in a temperature-controlled water-bath (±0.1°C) (Mgw Lauda). When the probe reached constant temperature, a constant DC voltage was applied to the heater wire from the power supply unit (Electroplan). The probe temperature was recorded at various time intervals. A typical experimental run was for about 30 s. A straight line was obtained by
plotting temperature vs ln(time). The samples were weighed before and after the experiment to ensure that the water content had not changed. The water content was measured on the same sample by drying it in a vacuum oven at 70°C for 24 h. Each data point was replicated three times and averaged.

The thermal conductivity of the sample is calculated using eqn (1) (Sweat, 1974):

\[ K = \frac{Q}{4\pi M} \]  

where \( Q \) is the heat supplied by the probe (in W/m) and \( M \) is the slope of the temperature vs ln(time). An example of such plots is shown in Fig. 2.

RESULTS AND DISCUSSION

The system was satisfactory for quick thermal conductivity \((K)\) measurements with reasonable accuracy and reproducibility. During the experiments, calibration was checked against a 0.5% agar and water gel at 30°C with six replicates. The mean \( K \) value was 0.617 W/m°C, with standard deviation of ±0.014 W/m°C. Sweat and Haugh (1974) reported a value of 0.628 W/m°C. The system was also calibrated against glycerine at 25°C with six replicates. The mean \( K \) value was 0.282 W/m°C with standard deviation of ±0.0079 W/m°C. Perry and Green (1984) reported a value of 0.284 W/m°C.

Figure 3 shows the thermal conductivity of potato as a function of moisture content at various temperatures. The points shown in this

Fig. 2. An example of plots of temperature vs ln(time).
Thermal conductivity of potato

Fig. 3. Thermal conductivity of potato as a function of moisture content at various temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>0.259</td>
<td>0.271</td>
<td>0.272</td>
<td>0.301</td>
</tr>
<tr>
<td>$h$</td>
<td>0.328</td>
<td>0.308</td>
<td>0.309</td>
<td>0.227</td>
</tr>
<tr>
<td>$r'$</td>
<td>0.99</td>
<td>0.99</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>$E$ (%)</td>
<td>7.85</td>
<td>6.67</td>
<td>8.34</td>
<td>7.45</td>
</tr>
</tbody>
</table>

$K = a + b \log(M)$ (2)

The values of the thermal conductivity of undried potato were compared with those of raw vegetables and fruits reported in the range from 0.605 W/m°C for carrot to 0.422 W/m°C for apple in the literature (Sweat, 1974; Lozano et al. 1979). A good agreement was found.

The experimental data were correlated using a semi-logarithmic equation of the form

It can be seen from Fig. 3 that thermal conductivity decreases with decreasing moisture content. This pattern is expected.

It can also be seen from Fig. 3 that the thermal conductivity values are independent of temperature within the range studied (40–70°C). This was analysed using ANOVA analysis (SAS, 1985) with 95% confidence. Triebes and King (1966) obtained a similar result for freeze-dried turkey. Lozano et al. (1979) also found a similar relationship for apples.
Fig. 4. Comparison between experimental and predicted values of thermal conductivity of potato at 50°C.

where $K$ is the thermal conductivity (W/m°C), $M$ is the moisture content (dry basis), and $a$ and $b$ are the constants. A nonlinear regression procedure (SAS, 1985) was used to estimate the constants in the eqn (2). The constants estimated are shown in Table 1.

$E$ is the mean relative percentage deviation. It is generally considered that $E$ values below 10% indicate a reasonably good fit for practical purposes (Boquet et al., 1978; Lomauro et al., 1985).

Figure 4 shows one example of the comparison between experimental and predicted values using eqn (2).

The experimental data failed to fit the Sweat’s straight line correlation (Sweat, 1974). However, Sweat’s correlation referred to different moisture contents of different foodstuffs, not to the change in thermal conductivity of one foodstuff as its moisture content changed.

CONCLUSIONS

From this study of the thermal conductivity of potato, it may be concluded that moisture content has a great effect on the thermal conductivity of potato, that is, the thermal conductivity decreases with decreasing moisture content. Thermal conductivity of potato is independent of the temperature within the range studied. The thermal conductivity values of potato at different moisture content could be predicted by a semi-logarithmic equation.
Thermal conductivity of potato

REFERENCES


