Thermal conductivity and convective heat transfer coefficient for soybean and white bean seeds

R.B. BROWN and L. OTTEN

School of Engineering, University of Guelph, Guelph, ON, Canada N1G 2W1. Received 6 September 1991; accepted 5 October 1992.

Brown, R.B. and Otten, L. 1992. Thermal conductivity and convective heat transfer coefficient for soybean and white bean seeds. Can. Agric. Eng. 34:337-341. A method for determining thermal parameters of seeds from a system thermal response to a pseudo-random temperature disturbance is described. This technique was used to find the particle thermal conductivity and convective heat transfer coefficient for soybean and white bean seeds. Tests were conducted at air temperatures of 40 and 50°C, over a range of seed moisture contents from 4.5 to 13.6%. Particle thermal conductivity values for soybean seeds were 0.211 to 0.221 W·m⁻¹·°C⁻¹ at the stated conditions, and white bean seeds yielded values of 0.206 to 0.225 W·m⁻¹·°C⁻¹. The average fluid-particle convective heat transfer coefficient was 131 W·m⁻²·°C⁻¹ for soybean seeds, and 106 W·m⁻²·°C⁻¹ for white beans.

INTRODUCTION

Heated-air drying and aeration of grain in storage bins are fundamental operations in our food and feed production systems. Both processes involve simultaneous heat and moisture transfer between individual kernels and air moving through the grain bulk. Physical and chemical quality factors of grain are sensitive to its time-temperature history, and all seeds undergo internal chemical changes that affect their nutritive or processing quality if they are overheated. In addition, sudden temperature changes in corn cause kernel stress cracks which result in increased breakage. Soybeans, and the edible bean seeds in particular, also experience seed coat damage and splitting if they are subjected to high drying stresses (Otten et al. 1984; Ting et al. 1980).

The thermophysical properties of grain are usually reported as effective bulk properties in the literature, for example, thermal conductivity. However, those bulk properties are not particularly useful for assessing quality effects, since it is the individual rather than the average kernel treatment that is important. The basic thermal parameters which are essential for analysis of single-seed heat transfer are therefore largely unknown.

Simulation for design of grain dryers or dryer control systems, where quality is of primary importance, is virtually impossible without that information. Single-seed properties that are necessary are the particle thermal conductivity, $k_p$, and the fluid-to-particle surface heat transfer coefficient, $h_c$. In addition, the specific heat, $C_p$, of the kernel is required to model simultaneous heat and mass transfer. Some physical seed properties like size, particle density, moisture content, and bed porosity are required in addition to the thermal parameters.

The specific heat of grain and oilseeds can readily be determined with calorimetry using the method of mixtures (Otten and Samaan 1980). It is not possible to measure the other thermal properties directly with standard methods because the seeds are too small and the integrity of the seedcoat and internal tissues must be maintained.

Indirect methods for determination of particle thermal conductivity have been reported for packed beds of glass beads (Dhingra et al. 1984; Shen et al. 1981; Goss and Turner 1971) and for fertilizer granules, iron ore pellets, and dry soybean seeds (Otten 1974). In each of those studies a thermal system response function was obtained experimentally for a bed of particles, and then a parametric model for the system response was fitted to these experimental data. Values for several unknown thermal parameters in the model can be obtained simultaneously with this approach, if the parameters are independent. A procedure of iterative substitution for parameter values is followed to obtain a best overall fit of observed with calculated responses (i.e. a least-squares estimate).

System response parameter estimation for moist biological material is complicated by the coupling phenomenon which occurs between heat and mass transfer processes. Imposition of a large temperature gradient in such material causes concomitant moisture migration which results in a thermal response that is highly nonlinear.

Pertinent published studies on system response parameter identification fall into two categories, frequency response analysis of packed beds and pulse response methods. Pulse
The modified Dispersion-Concentric (D-C) model, as described by Wakao and Kaguei (1982), is routinely used to describe unsteady state heat transfer in a packed bed of spherical particles. Assumptions for that model are that the fluid phase is in dispersed plug-flow mode and that individual particles exhibit a radially symmetrical temperature gradient. For seeds which are roughly spherical, like soybeans (Glycine max) and white beans (Phaseolus vulgaris), those conditions are met during forced air drying. The system of equations comprising the modified D-C model is:

\[
\frac{\alpha_{ax} \frac{\partial^2 T_f}{\partial x^2} - U \frac{\partial T_f}{\partial x} - \frac{\partial T_f}{\partial t} - 3k_p \left( 1 - \epsilon \right) \frac{\partial T_p}{\partial r} }{R \rho_f C_f \epsilon} \bigg|_{r=R} = 0 \quad (3)
\]

\[
\frac{\partial T_f}{\partial t} = \frac{k_p}{\rho_p C_p} \left[ \frac{\partial^2 T_p}{\partial r^2} + \frac{2}{R} \frac{\partial T_p}{\partial r} \right] \quad (4)
\]

\[
\frac{\partial T_p}{\partial r} = \frac{h_c}{k_p} (T_f - T_p) \quad \text{at } r=R \quad (5)
\]

An analytical solution for the model is possible if an appropriate transformation of Eqs. 3 to 5 is made. In the Laplace domain, the solution takes the form of a transfer function relating the inlet and outlet air temperatures across a bed of particles:

\[
F(s) = \exp \left[ \frac{L U}{2 \alpha_{ax}} \left( 1 - \sqrt{1 + \frac{b}{s}} \right) \right] \quad (6)
\]

where,

\[
b = \frac{4 \alpha_{ax}}{U^2} \left( s + \frac{3k_p \left( 1 - \epsilon \right)}{R^2 \rho_f C_f \epsilon} \left( \frac{k_p}{h_c R} + \frac{1}{\phi \coth \phi - 1} \right) \right)
\]

and,

\[\phi = R \sqrt{s / \alpha_p}\]

and where \(L\) is the length of a finite section of a deep bed, and \(s\) is the complex Laplace variable.

**THEORETICAL DEVELOPMENT OF THE METHOD**

**PRBNS system identification**

The theoretical development of the PRBNS parameter estimation method and verification with a packed bed of small acrylic spheres has been presented earlier (Brown and Otten 1988). PRBNS signals are deterministic approximations of white noise which are used for statistical system testing. One useful property of a PRBNS signal is its autocorrelation function (ACF) which is very close to that of an ideal impulse signal when \(N\), the sequence length, is large. Since the signal is periodic, the cross-correlation function (CCF) between the input signal and the output signal can be identified after a minimum of two sequence runs. Using convolution integral theory, the CCF for a discretely sampled system with a PRBNS technique uses a derived impulse response for the fluid (air) phase of a packed bed of seeds to obtain estimates for the thermal parameters of the individual particles (seeds).

**EXPERIMENTAL EQUIPMENT AND PROCEDURE**

**Apparatus and methods**

A section through the apparatus built to determine the experimental response data is shown in Fig. 1. The acrylic section holding the bed of seeds was 305 mm long and 146 mm in diameter. It was mounted in a 3500-mm length of PVC pipe machined to the same inside diameter to ensure flush mounting and fully developed flow at the bed inlet. The bed-to-particle diameter ratio was greater than 10:1 for any of the particles studied.

Ambient air supplied by a blower was humidified by forcing it through a column packed with wetted ceramic saddles. Both the inlet air and the water sprayed over the column packing were heated to achieve outlet air saturation at a particular temperature. The saturated air was then heated with an electric heater to a particular range for the conditions of the test. This airstream was split between the inner duct containing the particle bed and an outer concentric duct enclosing the bed section. The outer wall of the column was heated in order to eliminate any radial heat transfer. The balance of airflow between the inner and outer ducts was adjusted to establish a superficial air velocity of 0.5 m s\(^{-1}\) through the bed (i.e., 0.5 m s\(^{-1}\) per m\(^2\) of cross-sectional area), a value typical of the airflow rate in many commercial grain dryers (Meiering et al. 1977).

A personal computer was used as a data logger to monitor air temperatures at the inlet and outlet planes of the bed with a pair of resistance wire temperature detectors. These data were written to a RAM disk during experimental runs, and
calculate the thermal impulse response of the bed from the temperature data using the correlation procedure described earlier. A BASIC program was written to calculate the identification signal pulse train as a maximum-length sequence. The shift register output logic level was written to the parallel port, where it appeared as either a 0 or +5 VDC signal. That output signal, connected to an opto-isolated solid state relay, would open either of a pair of solenoid valves. The valves in turn diverted a stream of compressed air to either a hot or a cold heat exchanger, resulting in an intermittent flow of hot or cold air. The compressed air stream was then introduced into the main airstream through a diffuser at the bed inlet, producing the series of small temperature perturbations. The PRBNS amplitude was 2.0°C and the sequence length was 127 bits with a base pulse width of 15.0 s.

Soybeans (variety Maple Arrow) and white beans (variety Seafarer) were studied. Wet samples at about 22% moisture content (wet basis) were conditioned to moisture levels of about 10, 12, 14, and 16% prior to tests. The equilibrium relative humidity for the seeds at each temperature and moisture level was calculated from the Chung-Pfost equation with constants from Standard D245.4 (ASAE 1988) for soybeans and edible beans. The tests were run at two air temperatures, either 40 or 50°C.

Parameter estimation
The D-C model describes the response of a finite section of an infinitely long bed (i.e., the ends of the bed are very far from the region of interest). However, an experimental response also contains end effects as well as the effects of any transducers used to introduce test signals and measure variables of interest. A procedure using the responses for two bed lengths was developed to remove those effects. The Laplace transform of a measured impulse response is a transfer function which is the product of individual transfer functions for the transducers, the end effects and bed effects. The quotient of response curves for two bed lengths then, in the Laplace domain, is the corrected transfer function for a finite section from an infinite bed. The length of that section is equivalent to the difference in length between the two beds used. In this study bed lengths of 76 mm and 38 mm were used.

Determination of estimates for $h_c$ and $k_p$ resulted from an iterative comparison of an observed system response to a calculated response using Eq. 6. As the unknown parameter values in the model expression were adjusted, the two responses ultimately converged. A downhill simplex method of multi-dimensional minimization similar to the "amoeba" algorithm of Press et al. (1986) was used to arrive at the best parameter estimates. That scheme did not require derivatives of the objective function to be minimized. First, a discrete Laplace transform of experimental response data over many values of the complex Laplace variable, $s$, was performed. The optimization routine then sought a minimum of the root mean square error between the transformed observed data and the calculated response.

RESULTS AND DISCUSSION
The Chung-Pfost equilibrium moisture content relationship used to calculate the air state points for maintaining a particular moisture content was very inaccurate. This was particularly evident at low moisture levels. With the air humidity determined for a nominal 10% moisture content, after equilibration the actual moisture content was 8.7% for soybeans and 8.0% for the white beans. Similarly, the other treatments were all 1.5-2% lower than expected.

Preliminary tests were conducted to demonstrate the validity of the method and to confirm the proper operation of the apparatus. These tests were run with 6.35-mm diameter acrylic beads. The thermal conductivity of the acrylic beads was known to be in the range of 0.188 to 0.201 W m$^{-1}$°C$^{-1}$, and the value from the experiments was 0.193 W m$^{-1}$°C$^{-1}$ (Brown and Otten 1988). The convective heat transfer coefficient for the acrylic beads, 92.0 W m$^{-2}$°C$^{-1}$, was the same as the value calculated from a formula published by Wakao et al. (1979) for smooth spheres (92.3 W m$^{-2}$°C$^{-1}$). From the close match between the observed and expected parameter values for the test particles, it was concluded that the method was valid and the apparatus was satisfactory.

An important limitation of the test method was discovered when tests were conducted with moist seeds. Parameters for seeds above 13-14% moisture content at 40°C could not be determined. Apparently the humidity of air in equilibrium with seeds at that temperature and moisture level was so high that even a small temperature depression of 2°C caused some condensation, with the release of latent heat of vaporization. It was impossible to maintain a stable operating air temperature for those conditions. At 50°C the highest moisture level which could be accommodated was only 9-10%. Consequently, only the tests at a nominal moisture content of 10, 12, and 14% were conducted.
Table I. Summary of parameters for experimental determination of thermal properties.

<table>
<thead>
<tr>
<th></th>
<th>Soybean seeds</th>
<th>White bean seeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void fraction</td>
<td>0.400</td>
<td>0.382</td>
</tr>
<tr>
<td>Interstitial air velocity (m/s)</td>
<td>1.23</td>
<td>1.29</td>
</tr>
<tr>
<td>Seed radius (mm)</td>
<td>3.33</td>
<td>3.35</td>
</tr>
<tr>
<td>Seed density (kg/m³)</td>
<td>1190-1200</td>
<td>1270-1400</td>
</tr>
<tr>
<td>αₚ (m²/s)</td>
<td>4.42×10⁻³</td>
<td>4.66×10⁻³</td>
</tr>
<tr>
<td>Bed depths (mm)</td>
<td>38,76</td>
<td>38,76</td>
</tr>
</tbody>
</table>

Table II. Results of thermal parameter determination

<table>
<thead>
<tr>
<th>Moisture Content (% wet basis)</th>
<th>Convective heat transfer coefficient (W/m²·°C⁻¹)</th>
<th>Thermal conductivity (W/m·°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean seeds (40°C)</td>
<td>4.5</td>
<td>129</td>
</tr>
<tr>
<td>White bean seeds (40°C)</td>
<td>4.0</td>
<td>102</td>
</tr>
<tr>
<td>Soybean seeds (50°C)</td>
<td>8.7</td>
<td>132</td>
</tr>
<tr>
<td>White bean seeds (50°C)</td>
<td>10.0</td>
<td>114</td>
</tr>
</tbody>
</table>

Experimental parameters for the soybean and white bean tests are listed in Table I. Three thermal response curves were determined for each combination of seed type, moisture and temperature. These were averaged, and the convective heat transfer coefficient and the particle thermal conductivity for each combination were determined and are listed in Table II.

The particle thermal conductivity determined for both types of seeds was about the same. The values increased from 0.211 to 0.221 W/m²·°C⁻¹ for soybeans over the moisture range from 4.5 to 13.6% wet basis. For white beans, the conductivity values were 0.206 to 0.225 W/m²·°C⁻¹ over the range of 8.0-12.5% moisture.

CONCLUSIONS

The implementation of a PRBNS system identification technique for determining thermal parameters of moist seeds in a packed bed was investigated. Pertinent conclusions drawn from this study are:

1. Application of the method was limited to seeds with a moisture content of 14% (wet basis) or less.
2. The average fluid-particle convective heat transfer coefficients, at the superficial velocity of 0.5 m/s, were 131 W/m²·°C⁻¹ for soybean seeds and 106 W/m²·°C⁻¹ for white beans.
3. Particle thermal conductivity values were 0.211 to 0.221 W/m²·°C⁻¹ for soybean seeds over the moisture content range of 4.5 to 13.6% (wet basis). White beans yielded values of 0.206 to 0.225 W/m²·°C⁻¹ over the range of 8.0-12.5% moisture.

REFERENCES

Otten, L., R. Brown and W.S. Reid. 1984. Drying of white beans - effect of temperature and relative humidity on
seed coat damage. *Canadian Agricultural Engineering* 26(2):101-104.


**SYMBOLS USED**

- $a$ = amplitude of PRBNS ($^\circ$C)
- $C_f$ = heat capacity of fluid phase (kJ•kg$^{-1}$•$^\circ$C$^{-1}$)
- $C_p$ = heat capacity of the particle (kJ•kg$^{-1}$•$^\circ$C$^{-1}$)
- $h_c$ = convective heat transfer coefficient (W•m$^{-2}$•$^\circ$C$^{-1}$)
- $i, j$ = index variables
- $k_p$ = particle thermal conductivity (W•m$^{-1}$•$^\circ$C$^{-1}$)
- $L$ = length of bed section (m)
- $N$ = length of PRBNS sequence
- $r$ = particle radial displacement (m)
- $R$ = particle radius (m)
- $s$ = complex Laplace variable
- $\tau$ = time interval (s)
- $T_f$ = temperature of fluid ($^\circ$C)
- $T_p$ = temperature of solid particles ($^\circ$C)
- $u$ = input signal level ($^\circ$C)
- $U$ = interstitial fluid velocity (m•s$^{-1}$)
- $W_i$ = impulse response weighting factor
- $x$ = bed axial displacement (m)
- $z$ = output signal level ($^\circ$C)
- $\alpha$ = thermal diffusivity of fluid, (ax), or particle, (p) (m$^2$•s$^{-1}$)
- $\varepsilon$ = bed porosity factor
- $\rho_f$ = fluid density (kg•m$^{-3}$)
- $\rho_p$ = particle density (kg•m$^{-3}$)