LITERATURE CITED

(1) Brant, R., U. S. Geol. Survey, Circ. **226** (1953).
(2) Gauger, A. W., *Am. Inst. Mining Met. Engrs. Trans.* **101**, 148 (1932).
(3) Gordon, M., Lavine, I., Harrington, L., *Ind. Eng. Chem.* **24**, 928 (1932).
(4) Hoeppner, J., Fowkes, W., McMurtrie, R., Bur. Mines, Rept. Invest. **5215** (1956).
(5) "International Critical Tables," Vols. 1 and 2, McGraw-Hill, New York, 1933.
(6) Klein, H., *Braunkohle* **29**, 1 (1930).
(7) Kreulen, D., *Brennstoff-Chem.* **36** (17/18), 266 (1955).
(8) Kube, W., *Proc. N. Dakota Acad. Sci.* **6**, 83 (1952).
(9) Larian, M., Lavine, I., Mann, C., Gauger, A., *Ind. Eng. Chem.* **22**, 1231 (1930).
(10) Lavine, I., Gauger, W., *Ibid.*, **22**, 1226 (1930).
(11) Oppelt, W., *Proc. N. Dakota Acad. Sci.*, **6**, 36 (1952).
(12) Oppelt, W., Golob, E., Cooney, J., Kube, W., Bur. Mines, Mineral Research Invest., Prelim. Rept. **99** (1954).
(13) Oppelt, W. H., Kube, W. R., Chetvick, M. H., Kamps, T. W., Golob, E. F., Bur. Mines, Rept. Invest. **5164** (1955).
(14) Pearson, R., master's thesis (unpublished), University of North Dakota, 1950.
(15) Tasker, C., Ontario Research Foundation, Div. of Chem. Research Lignite, No. **23** (1933).
(16) Terres, E., *Brennstoff-Chem.* **33**, 1 (1952).

Received for review August 29, 1956. Accepted February 7, 1957. Investigation supported by a grant from the National Science Foundation, Washington, D.C. (G. N. Hickox, program director for engineering sciences).

Thermal Properties of Soybean Oil Meal

JOEL O. HOUGEN[1]
Rensselaer Polytechnic Institute, Troy, N.Y.

Annual production of soybeans in the United States exceeds 350,000,000 bushels a year (*7*), probably about one half (*6*) the world total. Within the United States soybeans are grown widely in the Middle West. Cultivation of soybeans is a major effort in the corn belt states; over 20,000,000 acres (*5*) are devoted to this crop in that region, almost all harvested for the beans.

Two major raw materials arise from the soybean: oil and meal. Food products, principally margarine and shortening, utilize about 80% of the oil; the remainder is used in soap, paint and varnish, and miscellaneous nonfood products. Soybean meal is consumed for the most part as feed for livestock (about 90%), smaller amounts being used for soybean flour, plywood glue, and paper coatings, and in various industrial protein-containing materials.

Soybean oil meal is defined as the ground residue which remains after the oil is removed from the soybean, regardless of the process of extraction. Livestock feed is the primary market, except for a small outlet for industrial uses. Accepted specifications for soybean oil meal obtained by the two standard methods of processing, expelling and solvent extraction, are (*1*): for meal from either source, carbohydrates and fiber 7% (maximum), nitrogen-free extract 27% (minimum), and moisture 12.5% (maximum).

Minimum percentages of protein and fat differ, depending on the source of the meal. For hydraulic and expeller meals these are 41.0 and 3.5 and for extracted meals 44.0 and 0.5, respectively.

Following oil extraction the soybean meal is processed for solvent removal and to improve its nutritional properties. This usually involves raising the temperature of the meal by adding thermal energy through the walls of a container, by direct steam injection, or both.

Data useful in the design of apparatus used to process particulate materials are not overabundant. This is particularly true for materials which are biological in origin and hence susceptible to alteration upon exposure to air, moderate temperatures, or both. Typical of such material is soybean oil meal.

[1]Present address, Research and Engineering Division, Monsanto Chemical Co., St. Louis, Mo.

The objective of this work was to determine experimentally the thermal properties of a typical soybean oil meal, including thermal conductivity, thermal diffusivity, and heat capacity.

PROPERTIES OF MEAL, EXPERIMENTAL APPARATUS, AND PROCEDURE

Table I lists some of the physical and chemical properties of the soybean oil meal used in these studies. The meal was extracted in conventional Hansa-Meuhle type extractors using Skellysolve B as the solvent. Following the oil extraction the solvent was removed by heat and by direct steam injection at about 200°F. Solvent removal was considered complete. Residual oil content was found to be 0.7 to 0.8%, as shown in Table I.

Table I. Properties of Soybean Oil Meal after Solvent Removal

Size	Will pass 48 mesh
Oil content, %	0.7–0.8
Moisture content, %	13.2
Total protein, %	51.55 (dry stock basis)
Water-soluble protein, %	39.57 of total protein[a] (dry stock basis)
Variety of bean	Lincoln (probably)

[a]Determined by tentative procedure recommended by Soy Flour Association, revision of Dec. 10, 1946.

This meal may be further processed before being sold. It is frequently packaged in metal cans prior to final treatment. Meal which was canned but had not received its final (heat) treatment was supplied by the A. E. Staley Manufacturing Co., Decatur, Ill.

Thermal conductivity was obtained by using the concentric cylinder technique with a material of known conductivity as the reference. (Figure 1). Concentric copper tubes were arranged as indicated, with provisions for producing an atmosphere of saturated steam within the innermost tube. Two small iron-constantan thermocouples were located at points about diametrically opposite each other on each tube at the mid-point of the vertical sections.

The reference material used was Grade 6 Spheron carbon black furnished by Godfrey L. Cabot, Inc., Boston, Mass. At a mean temperature of 118°F. and a bulk density of 20.2

pounds per cubic foot, the thermal conductivity of this material has been reported as 0.182 B.t.u., hr.$^{-1}$, ft.$^{-2}$, inch, °F.$^{-1}$ (3).

With carbon black in one annular space and soybean oil meal in the other, the system was allowed to come to thermal equilibrium and the various surface temperatures were determined. The position of the two materials was then reversed, using fresh material, and the process was repeated. In each case the soybean oil meal was obtained from a freshly opened can in which it had been preserved. Data are shown in Table II.

As the soybean oil meal was available in sealed cans, the transient method appeared to be most suitable for obtaining thermal diffusivity data. Iron and constantan thermocouple wires of small diameter were butt-welded and passed through the can of meal on its longitudinal axis. The junction was located at the geometric center of the can, the holes were sealed, and the can was properly supported inside an autoclave. The thermocouple leads were extended to a Brown Electronik self-balancing potentiometric pyrometer by which changes in temperature could be followed.

The heating medium was steam admitted through a control valve positioned by a Model 40 Foxboro pressure controller.

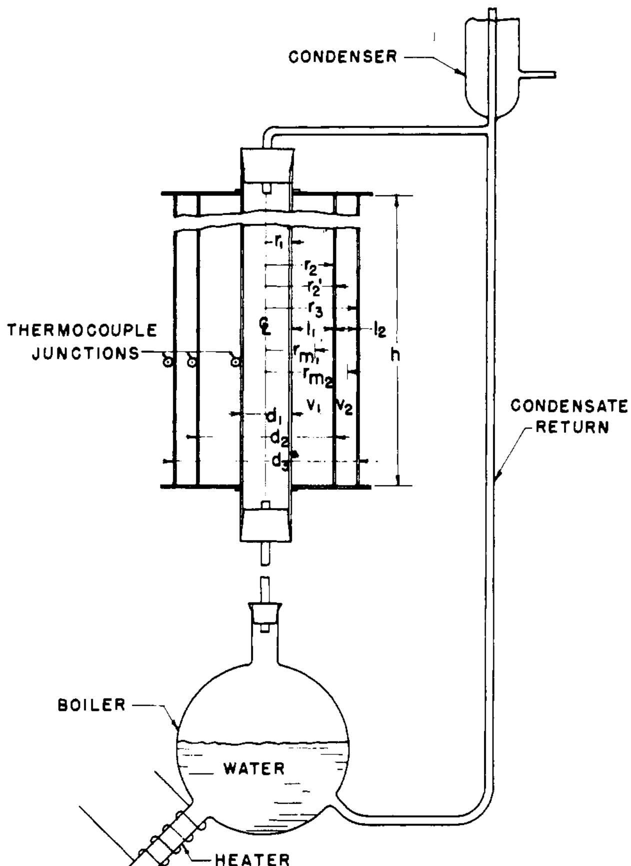

Figure 1. Concentric tube apparatus for determination of thermal conductivity

Linear Dimensions in Inches

d_1 = 0.62	l_1 = 0.43
d_2 = 1.62	l_2 = 0.185
d_3 = 2.15	r_{m_1} = 0.496 (log mean radius)
r_1 = 0.31	r_{m_2} = 0.895 (log mean radius)
r_2 = 0.74	$A_1 = 2\pi r_{m_1} h$ = 0.260 h sq. foot
r_2' = 0.810	$A_2 = 2\pi r_{m_2} h$ = 0.470 h sq. foot
r_3 = 0.995	V_1 = 17.16 cu. inches (inner annulus)
h = 12.07	V_2 = 12.68 cu. inches (outer annulus)

Table II. Measurements for Determination of Thermal Conductivity

	Test 1	Test 2
Inner annulus	109.6 grams of carbon black	171.1 grams of soybean meal
Outer annulus	129.1 grams of soybean meal	81.4 grams of carbon black
T_1, °C.	98.56	100.05
T_2, °C.	50.16	62.35
T_3, °C.	44.78	48.95
$\Delta T_1 = T_1 - T_2$	48.40	37.70
$\Delta T_2 = T_2 - T_3$	5.38	13.40
Bulk density carbon black, lb./cu. foot	24.4	24.5
Bulk density meal, lb./cu. foot	38.9	38.1

The position of the can of meal within the autoclave is indicated in Figure 2.

After initial thermal equilibrium had been attained, steam was quickly admitted to the autoclave, using a manual bypass valve. When the desired pressure had been achieved, the bypass was closed and the controller assumed operation. The time required to attain the desired pressure level was never longer than 1 minute. A duplicate set of data was obtained on a single sample and the results were averaged. Data taken from a smoothed curve are shown in Table III.

THEORETICAL

The thermal properties of interest in predicting heat transfer by conduction are contained in the thermal diffusivity term, $\alpha = k/c_p\rho$.

From the transient studies α may be obtained, while from the steady-state performance k can be found. The bulk density, ρ, may be obtained in any convenient manner, but for the sake of greater consistency was measured in connection with the conductivity tests. Heat capacity may be computed as $c_p = k/\alpha\rho$.

Calculation of conductivity from the steady-state data using the concentric tube technique is straightforward, except that where the space is filled with finely divided solids, such as carbon black, the conduction equation should be $\frac{kA\Delta T}{L - 2d}$ rather than $\frac{kA\Delta T}{L}$ (4).

Thus two sets of data are required to find the unknown conductivity and simultaneously the "surface resistance" factor, d, or d may be found first by using Equation 1 below and conductivity, subsequently, by using Equation 2:

$$d = \frac{\frac{A_1}{A_2}\left(\frac{\Delta T_1}{\Delta T_2}\right)_1 L_2^2 - \frac{A_2}{A_1}\left(\frac{\Delta T_2}{\Delta T_1}\right)_2 L_1^2}{2\left[\frac{A_1}{A_2}\left(\frac{\Delta T_1}{\Delta T_2}\right)_1 L_2 - \frac{A_2}{A_1}\left(\frac{\Delta T_2}{\Delta T_1}\right)_2 L_1\right]} \qquad (1)$$

and

$$\frac{k_{sb}}{k_{cb}} = \frac{A_1}{A_2}\left(\frac{\Delta T_1}{\Delta T_2}\right)\frac{L_2}{L_1 - 2d} = \frac{A_2}{A_1}\left(\frac{\Delta T_2}{\Delta T_1}\right)\frac{L_1}{L_2 - 2d} \qquad (2)$$

where subscripts 1 and 2 refer to the test data shown in Table II. It is assumed that conductivity is independent of temperature in the range encountered.

To find the thermal diffusivity, the equations describing the unsteady-state heat transfer to a right circular finite cylinder are employed and the value of α is selected such that the theoretical transient heating curve fits the experimental curve reasonably well. The theory has been outlined by Olson and Schultz (2) and convenient numerical tables have been prepared from which rapid solutions for time-temperature relations for a number of geometric shapes may be obtained.

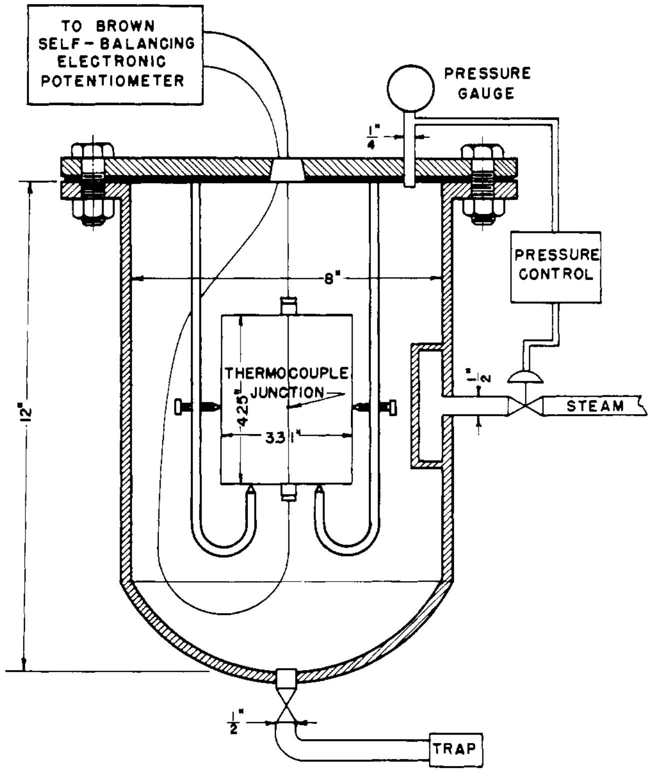

Figure 2. Apparatus for heating canned soybean oil meal at constant surface temperature

The essence of the mathematical treatment may be described as follows. If a "theoretical" temperature be defined as

$$u = (T_1 - T)/(T_1 - T_0)$$

it may be shown that the value of u for an infinite cylinder of radius r with T being the temperature at the axis may be found at any time t by the formula $u = C\,(\alpha t/r_2)$ where function C is the infinite series of the form

$$\sum_{i=1}^{i=\infty} A_i \exp\,(-R_1^2\,\alpha t/r^2)$$

For infinite slabs of thickness a with T taken at the midpoint

$$u = S\,(\alpha t/a^2)$$

where $$S = \frac{4}{\pi}\sum_{i=1}^{i=\infty} B_i \exp\,(-b_n \pi 2 \cdot \alpha t/a^2)$$

Table III. Thermal Response Data for Finite Cylindrical Section of Soybean Oil Meal

t, Sec.	T, °F.	$T_1 - T$	u (Exptl.)	u (Calcd.)
0	65	168	1.000	1.000
500	66	167	0.994	0.998
1000	70	163	0.971	0.944
1500	91	142	0.845	0.818
2000	118	115	0.685	0.672
2500	147	86	0.511	0.538
3000	168	65	0.386	0.425
3500	183	50	0.297	0.333
4000	192	41	0.244	0.259
4500	197	36	0.214	0.202
5000	202	31	0.184	0.156

$T_1 = 233$ °F., $T_0 = 65$ °F., $T_1 - T_0 = 168$
r = 1.65 inches a = 4.25 inches

Each series represents the solution of the appropriate partial differential equation describing the physical situation.

Finally, for a finite cylinder with T measured at the geometric center it can be shown that

$$u = C\,\frac{(\alpha t)}{r^2} \times S\,\frac{(\alpha t)}{a^2}$$

Olson and Schultz present tables where, for various values of $\alpha t/r^2$ or $\alpha t/a^2$, the corresponding values of C and S may be found.

EXPERIMENTAL RESULTS

In this case, from experimental observations, values of u as a function of time, t, have been found. r and a were obtained from the dimensions of the cylindrical container. The problem is to select, by trial and error, the appropriate value of α so that the product, C × S, gives a value of u in agreement with the observed values over a reasonable portion of the experimental region.

In Table III experimental values of T are given along with the calculated values of u with a value of thermal diffusivity taken as 0.0048 square foot per hour and in Figure 3 results are compared graphically. A reasonable fit is obtained.

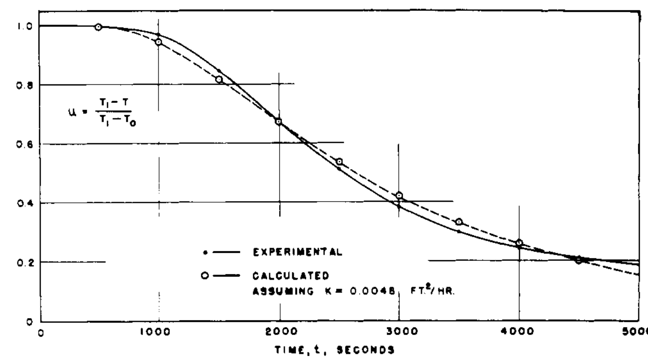

Figure 3. Experimental and theoretical values of temperatures

Using the data given in Table II, the thermal conductivity of soybean oil meal was found to be about 2.6 times that of carbon black. Consequently, the experimentally obtained values for the thermal properties of the meal are as shown in Table IV. The calculated value of heat capacity appears to compare well with that of similar materials. However, these results apply only to the particular samples tested. These values will change with moisture and oil content, bulk density, and particle size and will also depend on the past history of the material as well.

Table IV. Thermal Properties of Soybean Oil Meal Tested

Thermal diffusivity, α, sq. ft./hr.	0.0048
Thermal conductivity, k, B.t.u./hr.-sq. ft. (°F./ft.)	0.040
Heat capacity, c_p, B.t.u./hr.-°F.	0.215

ACKNOWLEDGMENT

Thanks are extended to Frank Bunk, James Codding, and Raymond Gerow, former students at Rensselaer Polytechnic Institute, for their assistance in obtaining some of the experimental data.

NOMENCLATURE

a = height of cylinder
A, A_1, A_2 = area for heat flow
A_i = coefficients in Bessel-Fourier expansion
b_n = exponents in series for $S\,(\alpha t/a^2)$
B_i = coefficients in series for $S\,(\alpha t/a^2)$
c_p = heat capacity
d = "surface resistance"

k, k_{sb}, k_{cb} = thermal conductivity
k_{sb} for soybean oil meal
k_{cb} for carbon black
α = thermal diffusivity
L, L_1, L_2 = length of path for heat transfer
r = radius of cylinder
t = time
T = temperature at geometric center of finite cylinder except as noted
T_0 = initial temperature of cylinder
T_1 = surface temperature of cylinder at time θ (forcing temperature)
u = "theoretical" temperature, $T_1 - T/T_1 - T_0$
ρ = density

LITERATURE CITED

(1) Markley, K. S., "Soybeans and Soybean Products," p. 436, Interscience Publishers, New York, 1950.
(2) Olson, F. C. W., Schultz, O. T., *Ind. Eng. Chem.* **34**, 874 (1944).
(3) Smith, W. R., Wilkes, G. B., *Ibid.*, **36**, 1111 (1944).
(4) Smoluchowski, M., *Proc. 2nd Refrig. Congr.* 1910, 187–93.
(5) U. S. Dept. of Agriculture, Agricultural Statistics 1955, Table 181, p. 126.
(6) *Ibid.*, Table 182, p. 127.
(7) *Ibid.*, Table 184, p. 128.

Received for review May 13, 1954. Accepted September 24, 1956.

Thermal Conductivity of Some Organic Liquids High Temperature Measurements

O. B. CECIL, W. E. KOERNER, AND R. H. MUNCH
Organic Chemicals Division, Monsanto Chemical Co., St. Louis 4, Mo.

Although thermal conductivity values are becoming more numerous in the literature, they represent for the most part values determined at relatively low temperatures—i.e., below 100° C. Engineers desiring to use these data for high temperature problems must extrapolate low temperature values to the desired temperature. In many cases, only one value exists and this must be used for all calculations. Such extrapolations are obviously questionable.

This report deals with the extension of a technique for determining absolute values of thermal conductivity (*1*) to temperatures as high as 200° to 250° C. This work does not represent a limit for thermal conductivity measurements but serves to illustrate how values at higher temperatures can be determined.

EXPERIMENTAL

The method used [described in detail elsewhere (*1*)] is a highly refined modification of the hot-wire technique. The thermal conductivity cell proper employs a four-lead arrangement analogous to a four-lead platinum resistance thermometer, thereby eliminating end effects. All constants necessary for thermal conductivity measurements are determined from the dimensions of the cell. The determined thermal conductivity values are thus absolute.

Of prime importance in the success of this method is the constancy of the temperature of the thermostated bath. In the previous low temperature work, simple on-off control of the thermostated bath provided a temperature which was constant to within about ± 0.003° C. Duplicate measurements at 30° C. had shown an average deviation from the mean of ± 0.3%, and this deviation had increased to ± 0.5% at 80° C. These data demonstrate one of the inherent faults of on-off control—namely, that progressively less satisfactory performance is obtained as the desired operating temperature differs more widely from ambient temperature. For this reason other types of controls and thermostating were considered. The final choice for the high

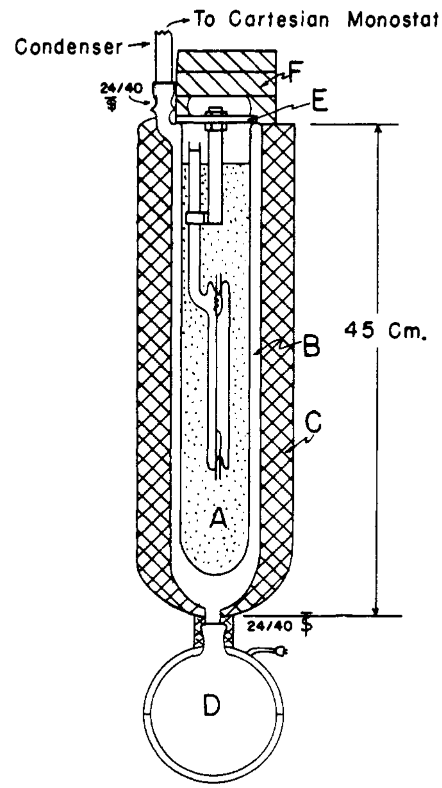

Figure 1. Thermal conductivity cell and condensing vapor thermostat

A. Silicone oil reservoir
B. Condensing vapor jacket
C. 1¼-inch thick magnesia insulation
D. 1-liter pot heated with spherical mantle
E. Transite top and cell holder
F. Glass wool insulation