Research Article

Development of a Coaxial Dual Cylinder Apparatus for Measurement of Thermal Conductivity of Food Grains

Ganesh Upadhyay[1]*, Khan Chand[1], Neeraj Kumar[1] and Gulshan Kumar Malik[2]

[1]Department of Post Harvest Process and Food Engineering, College of Technology, G. B. Pant University of Agricultural and Technology, Pantnagar-263145, India
[2]Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur 721302, India

Abstract

Coaxial dual cylinder apparatus based on steady state method was developed and used to determine the thermal conductivity of four different types of food grains. The study was conducted on freshly harvested whole grains of wheat (*Triticum aestivum*), paddy (*Oryza sativa L*), Bengal gram (*Cicer aritinum L*) and black gram (*Vigna mungo L*) obtained from university farm of Pantnagar, India. Moisture content and bulk density of the above cited grains was determined by hot air oven and simple measuring cylinder method, respectively. Its suitability for different food materials was also checked. Time to achieve steady state was found to be around 1.5 hours. Asbestos sheets and glass wool were used to insulate the apparatus and to prevent any heat loss to the surroundings. The average bulk thermal conductivities of wheat, paddy, Bengal gram and black gram at moisture contents (wb) of 9.7±0.30%, 10.5±0.20%, 10.3±0.35% and 11.4±0.20% and bulk densities of 765.4±16, 535.6±20, 721.5±15 and 740.7±25 kg m^{-3}, respectively were found to be 0.2384, 0.1288, 0.2091 and 0.1460 Wm^{-1} $°C^{-1}$, respectively.

The developed apparatus was found to be widely suitable for cereals, pulses and different varieties of oilseeds. However, it was not found suitable for products containing higher moisture content because of moisture migration phenomena. Its simplicity in the mathematical processing of the acquired data, simple construction, low operational cost involved and its applicability to different varieties of cereals, pulses and oilseeds makes it effective method for determination of thermal conductivity of granular food products.

Keywords: Thermal conductivity, Wheat, Paddy, Bengal gram, Black gram

***Correspondence**
Author: Ganesh Upadhyay
Email: ganesh.upadhyay0@iitkgp.ac.in

Introduction

Freshly harvested cereals and pulses should be aerated during storage or dried before storage depending on their moisture content variation from optimum value which is appropriate for storage in the grain bins. Farmers and the food grain industries are largely dependent on the drying, storage and aeration characteristics of grains [1]. Optimization of drying facilities required for bulk storage of grains have necessitates the significance of precise determination of thermal properties of food grains like thermal conductivity, specific heat and thermal diffusivity which enables to predict temperature distribution within the granular material [2]. Thermal conductivity is defined as the quantity of heat that flows per unit time through a food of unit thickness and unit area having unit temperature difference between faces [3]. It represents ability of a material to conduct heat and is an essential thermal property for predicting temperature changes in grains during production, handling, drying and storage.

Knowledge about the thermal conductivity of grains is essential in predicting the temperature and moisture of preserved food grains from available mathematical models of heat and mass transfer during drying and periodic aeration. This prediction is important for proper storage without causing damage to grain structure or loss of nutritional value of grain. Thermal conductivity of grain is affected by its moisture content, porosity, temperature and bulk density that change during drying and aeration [1, 4]. Thermal conductivity data is also useful in determining thermal diffusivity, a ratio of thermal conductivity to specific heat which further helps in computing the processing time required in cooking, drying, heating and cooling [5]. Thermal conductivity of the food materials lies between the limits of air (0.026 W m^{-1} $°C^{-1}$ at 27°C) and that of water (0.614 W m^{-1} $°C^{-1}$ at 27°C) which could be considered as the least and the most conductive components in foods products, respectively [6].

Measurement of thermal conductivity can be done by steady-state, transient-state or quasi-steady state methods. Generally custom made experimental setups and equipment are employed for measuring thermal properties of agricultural products due to lack of standard techniques available. However, several methods and techniques are known for measuring these important properties [7]. Measurements of thermal conductivity are much more difficult than those of specific heat capacity because the heat flow pattern in the sample must be carefully identified and defined [8]. Inconsistent heterogeneous structure poses difficulty in predicting its thermal properties of food grains [2, 9]. Among various steady state methods known, thermal conductivity of granular materials can be measured simply and conveniently using the coaxial dual cylinder method compared to other experimental techniques provided that the sample can be filled appropriately in the annular space of cylinders [10]. This technique has been used previously to predict the thermal conductivity of liquids [11], paddy [4], freeze dried skim milk [12] and aqueous solutions of glucose, sucrose, gelatin and egg albumin [10].

In the past, many investigations have been carried out by various researchers to predict the thermal conductivity of food grains using both steady state and unsteady state methods such as: white wheat and dent corn [13], sorghum [14], peanut [15], soybean pod [16], chicken, flour, and apple [17], pulses [18], malting barley [19], bulk wheat [20] and roasted Bengal gram flour [21]. They observed and reported the effect of moisture content, bulk density, temperature and porosity of the above cited food products on their thermal conductivities.

The objectives of this study were to determine the bulk thermal conductivity of freshly harvested wheat (Triticum aestivum), paddy (Oryza sativa L.), Bengal gram (Cicer aritinum L.) and black gram (Vigna mungo L.) by co-axial dual cylinder apparatus based on steady-state method and to check the suitability of developed apparatus for measuring thermal conductivity of cereals and pulses.

Materials and Methods

The experimental materials were freshly harvested whole grains of wheat (*Triticum aestivum*), paddy (*Oryza sativa L*), Bengal gram (*Cicer aritinum L*) and black gram (*Vigna mungo L*). The grains were procured from University Farm, Pantnagar, India and damaged grains, broken and dust was removed carefully. Hot air oven method was used for determination of moisture content of the grains for which samples of 5 g weight were heated to 130°C for one hour. The measurements were repeated five times for each observation. Bulk density is defined as the density of material when packed or stacked in bulk, and represented as the mass per total volume of solid and air void. Simple measuring cylinder method was used for determination of bulk density. A cylinder of known volume was taken and filled with the grain sample. Then the weight was measured by digital analytical balance. The measurements were repeated five times for each observation.

Experimental setup

The thermal conductivities of grain samples were determined by using steady state method with coaxial dual cylinder apparatus. **Figure 1** shows the line diagram of the developed setup. The setup consisted of a hollow brass cylinder having 245 mm height and an inner diameter of 110 mm. A heating rod of 1000 W capacity was carefully placed at the central axis of cylinder. The heating rod was enclosed in a hollow steel tube with a gap to avoid short circuiting. The hollow brass cylinder was jacketed for cold water circulation to keep the cylinder surface at a constant temperature. For this purpose submersible pump was used to force circulate the water through a tank to hollow brass cylinder. The annular space between heating rod and brass cylinder was provided for filling the test material. The space between brass cylinder and outer cylinder is filled by glass wool to avoid heat loss from sides to the surroundings. A covering plate of asbestos sheet was placed at top and bottom to avoid any heat loss. The top plate was provided with holes at different radial locations for measuring the temperature by inserting the nib of thermometer. A voltage current stabilizer (dimmer stat) was used to supply controlled voltage to the heating rod through 220 V power supply. It was found that grains were getting burned at high voltages, so readings were limited up to 25 V. The voltmeter and ampere meter used had a least count of 0.5 V and 0.05 A, respectively. Ampere meter and voltmeter was used to get the reading of current and voltage to find out the actual heat supplied to the grain.

Submersible pump dipped in water tank forced stored water to the bottom of the brass cylinder jacket. Water from the top portion was collected by collection pipes. Temperature of water at the outlet was measured at different intervals to know when the steady state has been reached. Almost constant temperature of outlet water indicates the point of reach of steady state and at that moment temperature readings of grain were recorded simultaneously at different radial distances. For measuring temperatures at different radial distances, holes were done on the upper asbestos sheet by drilling machine. The nib of digital thermometers were inserted in these holes and readings were taken when steady state has been achieved. The digital thermometers had a least count of 0.1°C and a good temperature range. The formulas applicable for this method are applicable only under the condition of steady state and radial heat flow. For radial heat flow care should be taken towards the correct vertical instalment of heating rod. The heating rod should not come in contact with the steel cylinder to prevent short circuiting. For this vertical installation of heater and cylinder are necessary. **Figure 2** shows the developed coaxial dual cylinder apparatus.

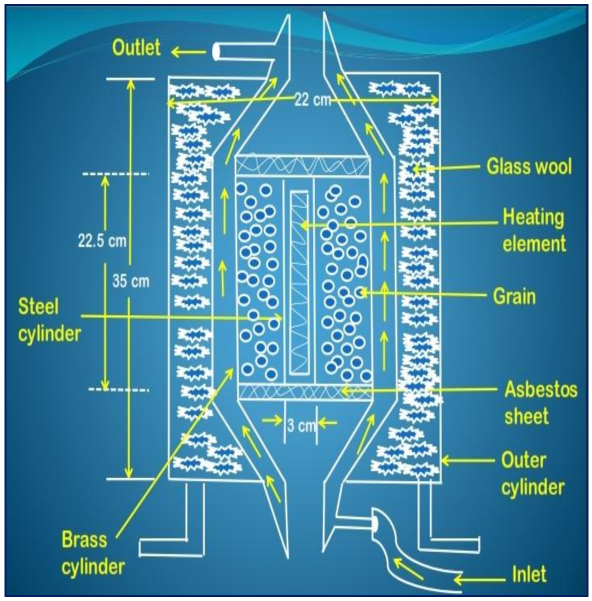

Figure 1 Line diagram of coaxial dual cylinder apparatus

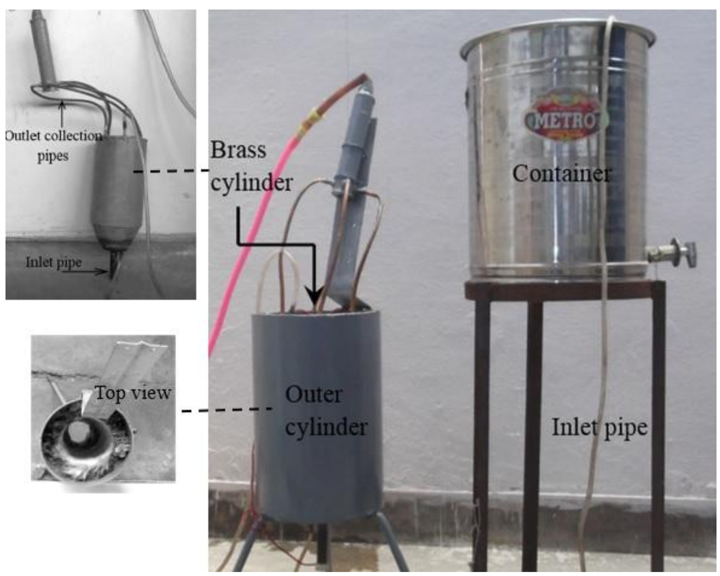

Figure 2 Developed coaxial dual cylinder apparatus

Experimental procedure

For each experiment, the upper asbestos sheet was opened and different samples of whole grains with predetermined moisture content and bulk density were filled between hollow brass cylinder and steel cylinder. Then upper asbestos sheet was placed above the test material with some glass wool insulation packed above it to avoid any heat loss to the surroundings. Electrical connections of dimmer stat, voltmeter, ampere meter, and heater were done systematically. Cold tap water was circulated around the cylinder to keep the cylinder surface at a constant temperature. Tap water was stored in a water drum, which was pumped with the help of submersible pump.

At first, dimmer stat was adjusted to 10 V and at the instant when the temperature of outlet water become constant (i.e. steady state has been reached), nib of digital thermometer was placed vertically at different radial distances from the heater and readings were recorded. Similar procedure was repeated at 15 and 25 V of supply by adjusting the dimmer stat. Time to achieve steady state was found to be around 1.5 hours.

Let $Q = V \times I$ = heat flow under steady state, which is equal to that generated by heater rod; V and I are the voltmeter and ampere meter readings, respectively; L = length of cylinder; T_i= temperature corresponding to radial distance (r_i) on upper asbestos sheet; k = thermal conductivity of material.

The rate of heat flow through the cylindrical annular section of apparatus can be predicted as:

$$Q = -k\,A\;dt/dr = -k(2\pi rL)\,dt/dr \tag{1}$$

$$-Q\int_{r_1}^{r_2}\frac{dr}{r} = 2k\pi L\int_{T_1}^{T_2} dt$$

$$-Q\;ln(r_2/r_1) = -2k\pi L(T_2 - T_1)$$

$$k = Q\,ln(r_2/r_1)/2\pi L(T_1 - T_2)$$

also, $Q = V \times I$, therefore,

$$k = VI\,ln(r_2/r_1)/2\pi L(T_1 - T_2) \tag{2}$$

The steady state temperatures at four different locations can be used to calculate six values of the thermal conductivities corresponding to different annular zones and voltage. Let the temperature corresponding to the five locations r_1, r_2, r_3, r_4 and r_5 be T_1, T_2, T_3, T_4 and T_5, respectively. Then the thermal conductivity of the sample material between the two consecutive points $k_{i,\,i+1}$ is

$$k_{i,i+1} = V\,I\;ln(r_{i+1}/r_i)/2\pi L(T_i - T_{i+1}) \tag{3}$$

Corresponding to a particular set voltage six readings of thermal conductivity were calculated from four radial distances r_1, r_2, r_3 and r_4. These are k_{12}, k_{13}, k_{14}, k_{23}, k_{24}, k_{34}. Then the average of these is calculated (say k_{avg1}). Similar procedure was repeated at 15 V and 25 V settings of dimmer stat to calculate k_{avg2} and k_{avg3}. Then the mean thermal conductivity of sample was calculated as:

$$k_{avg} = (k_{avg1} + k_{avg2} + k_{avg3})\,/\,3 \tag{4}$$

Values of radial distances of holes on upper asbestos sheet from central axis are: r_1 = 2.5 cm, r_2 = 3.5 cm, r_3 = 4 cm, r_4 = 5 cm

Results and Discussion

The experiments were conducted by the co axial dual cylinder apparatus to evaluate the thermal conductivities of different food grains by steady state method. The steady state method was used because of its simplicity, accuracy and ease in the mathematical processing of the results. **Table 1** shows the specifications of the developed coaxial dual cylinder apparatus.

Table 1 Specifications of the developed coaxial dual cylinder apparatus

Components		**Dimension (mm)**
Outer cylinder	Diameter × Height	220 × 350
Brass cylinder	Outer Diameter × Inner Diameter × Height	140 × 110 × 245
Steel cylinder	Diameter × Height	30 × 225
Heating rod (1000 W)	Length	235

Moisture content of wheat, paddy, Bengal gram and black gram was found to be 9.7±0.30%, 10.5±0.20%, 10.3±0.35% and 11.4±0.20%, respectively on wet basis. The calculated values are cross checked with the readings obtained from infrared moisture meter. The bulk densities of wheat, paddy, Bengal gram and black gram were found to be 765.4±16, 535.6±20, 721.5±15 and 740.7±25 kg m^{-3}, respectively.

Thermal conductivity of wheat (Triticum aestivum)

Table 2 shows the recorded temperature readings of wheat (T_1, T_2, T_3 and T_4) at different radial distances (r_1, r_2, r_3 and r_4) corresponding to 10, 15 and 25 V settings of dimmer stat. **Table 3** shows the values of thermal conductivity of wheat for different annular zones and average value of thermal conductivity at different voltage settings at which experiments were performed. From Table 3, it is evident that the thermal conductivities of wheat at 10, 15, 25 V settings were 0.2213, 0.2524 and 0.2415 Wm^{-1} $^{o}C^{-1}$ respectively. The average thermal conductivity of wheat was found to be 0.2384 Wm^{-1} $^{o}C^{-1}$ at moisture content (wb) and bulk density of 9.7±0.30% and 765.4±16 kg m^{-3}, respectively. According to the range given by [22], the range of thermal conductivity of wheat is around 0.1801-0.213 $Wm^{-1}\,^{o}C^{-1}$ at 12.5-23% moisture content (wb).

Table 2 Temperature of wheat (*Triticum aestivum)* recorded at different radial distances

Voltage, V	Current, A	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)
10	0.30	48.1	45.4	43.6	41.7
15	0.41	59.4	54.3	52.1	47.4
25	0.46	75.5	63.2	59.1	51.6

Table 3 Thermal conductivity of wheat (*Triticum aestivum)* at different annular zones and average value of thermal conductivity

Voltage, V	Thermal conductivity at different annular zones, $W\,m^{-1}\,^{o}C^{-1}$							Average thermal conductivity, $W\,m^{-1}\,^{o}C^{-1}$
	k_{12}	k_{13}	k_{14}	k_{23}	k_{24}	k_{34}		
10	0.2645	0.2217	0.2299	0.1575	0.2046	0.2493	k_{avg1} = 0.2213	k_{wheat} = 0.2384
15	0.2871	0.2802	0.2514	0.2641	0.2249	0.2066	k_{avg2} = 0.2524	
25	0.2226	0.2332	0.2360	0.2650	0.2502	0.2421	k_{avg3} = 0.2415	

Thermal conductivity of paddy (Oryza sativa L)

Table 4 shows the recorded temperature readings of paddy (T_1, T_2, T_3 and T_4) at different radial distances (r_1, r_2, r_3 and r_4) corresponding to 10, 15 and 25 V settings of dimmer stat. **Table 5** presents the values of thermal conductivity of paddy for different annular zones and average value of thermal conductivity at different voltage settings at which experiments were performed. From Table 5, it is evident that the thermal conductivities of paddy at 10, 15, 25 V settings were 0.1106, 0.1278 and 0.1480 $Wm^{-1}\,^{o}C^{-1}$ respectively. The average thermal conductivity of paddy was found to be 0.1288 $Wm^{-1}\,^{o}C^{-1}$ at moisture content (wb) and bulk density of 10.5±0.20% and 535.6±20 kg m^{-3}, respectively. According to the range given by [22], the range of thermal conductivity of paddy is around 0.102-0.112 $Wm^{-1}\,^{o}C^{-1}$ at 10-20% moisture content (wb). Some fluctuations could be because of different variety of grains, heat loss from sides and top and also because of moisture evaporation from sample.

Table 4 Temperature of paddy (*Oryza sativa L*) recorded at different radial distances

Voltage, V	Current, A	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)
10	0.30	48.3	42.5	39.6	35.3
15	0.41	62.3	49.2	43.5	38.1
25	0.46	78.4	58.6	49.3	40.1

Table 5 Thermal conductivity of paddy (*Oryza sativa L*) at different annular zones and average value of thermal conductivity

Voltage, V	Thermal conductivity at different annular zones, $W\,m^{-1}\,^{o}C^{-1}$							Average thermal conductivity, $W\,m^{-1}\,^{o}C^{-1}$
	k_{12}	k_{13}	k_{14}	k_{23}	k_{24}	k_{34}		
10	0.1231	0.1146	0.1132	0.0977	0.1051	0.1101	k_{avg1} = 0.1106	k_{paddy} = 0.1288
15	0.1117	0.1088	0.1246	0.1019	0.1398	0.1798	k_{avg2} = 0.1278	
25	0.1383	0.1314	0.1472	0.1168	0.1569	0.1974	k_{avg3} = 0.1480	

Thermal conductivity of Bengal gram (Cicer aritinum L)

Table 6 presents the recorded temperature readings of Bengal gram (T_1, T_2, T_3 and T_4) at different radial distances (r_1, r_2, r_3 and r_4) corresponding to 10, 15 and 25 V settings of dimmer stat. **Table 7** shows the values of thermal conductivity of Bengal gram for different annular zones and average value of thermal conductivity at different voltage settings at which experiments were performed. From Table 7, it is evident that the thermal conductivities of Bengal gram at 10, 15, 25 V settings were 0.2075, 0.1832 and 0.2366 $Wm^{-1}\,^{o}C^{-1}$ respectively. The average thermal conductivity of Bengal gram was found to be 0.2091 $Wm^{-1}\,^{o}C^{-1}$ at moisture content (wb) and bulk density of 10.3±0.35% and 721.5±15 kg m^{-3}, respectively. According to the range given by [22], the range of thermal conductivity of Bengal gram is around 0.1535-0.3257 $Wm^{-1}\,^{o}C^{-1}$ at 7-25% moisture content (wb).

Table 6 Temperature of Bengal gram (*Cicer aritinum L*) recorded at different radial distances

Voltage, V	Current, A	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)
10	0.30	49.8	46.8	44.6	42.9
15	0.41	60.8	52.3	48.5	44.3
25	0.46	78.4	65.9	61.6	54.1

Table 7 Thermal conductivity of Bengal gram (*Cicer aritinum L*) at different annular zones and average value of thermal conductivity

Voltage, V	Thermal conductivity at different annular zones, W m^{-1} °C^{-1}							Average thermal conductivity, W m^{-1} °C^{-1}
	k_{12}	k_{13}	k_{14}	k_{23}	k_{24}	k_{34}		
10	0.2381	0.1919	0.2132	0.1288	0.1941	0.2786	k_{avg1} = 0.2075	$k_{Bengal\ gram}$ = 0.2091
15	0.1722	0.1663	0.1828	0.1529	0.1940	0.2312	k_{avg2} = 0.1832	
25	0.2190	0.2276	0.2321	0.2527	0.2460	0.2421	k_{avg3} = 0.2366	

Thermal conductivity of black gram (Vigna mungo L)

Table 8 shows the recorded temperature readings of black gram (T_1, T_2, T_3 and T_4) at different radial distances (r_1, r_2, r_3 and r_4) corresponding to 10, 15 and 25 V settings of dimmer stat. **Table 9** shows the values of thermal conductivity of black gram for different annular zones and average value of thermal conductivity at different voltage settings at which experiments were performed. From Table 9, it is evident that the thermal conductivities of black gram at 10, 15, 25 V settings were 0.1458, 0.1348 and 0.1460 Wm^{-1} °C^{-1} respectively. The average thermal conductivity of black gram was found to be 0.1460 Wm^{-1} °C^{-1} at moisture content (w.b.) and bulk density of 11.4±0.20% and 740.7±25 kg m^{-3}, respectively. According to the range given by [22], the range of thermal conductivity of black gram is around 0.13-0.22 Wm^{-1} °C^{-1} at 10.3-21.4% moisture content (wb).

Table 8 Temperature of black gram (*Vigna mungo L*) recorded at different radial distances

Voltage, V	Current, A	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)
10	0.30	47.2	42.6	40.4	37.3
15	0.41	61.2	50.4	45.4	39.1
25	0.46	76.5	59.1	50.9	41.1

Table 9 Thermal conductivity of black gram (*Vigna mungo L*) at different annular zones and average value of thermal conductivity

Voltage, V	Thermal conductivity at different annular zones, W m^{-1} °C^{-1}							Average thermal conductivity, W m^{-1} °C^{-1}
	k_{12}	k_{13}	k_{14}	k_{23}	k_{24}	k_{34}		
10	0.1553	0.1467	0.1486	0.1288	0.1428	0.1528	k_{avg1} = 0.1458	$k_{black\ gram}$= 0.1460
15	0.1356	0.1294	0.1365	0.1162	0.1373	0.1541	k_{avg2} = 0.1348	
25	0.1573	0.1494	0.1593	0.1325	0.1612	0.1853	k_{avg3} = 0.1460	

Observations

The following observations were made during experimentation:

Moisture evaporation and suitability of the developed apparatus

Due to the applied heat input, there was considerable moisture evaporation from the sample, which condensed at the top covering plate. The moisture evaporation was more at the inner annular zone and decreased towards the outer zone. As, some energy was consumed in moisture evaporation, less heat was transferred to the consecutive annular sections. So, it was found to be not suitable for products containing high moisture content.

Heat loss from top plate

Some heat loss takes place from the upper asbestos sheet in spite of the glass wool insulation packed above it which resulted in less heat being transferred through consecutive annular sections. As the moisture evaporation and as well as heat loss were more at higher levels of heat input, therefore error could be expected to be increase in the measurement of thermal conductivity corresponding to the highest level of heat input.

Effect of heat input

The heat input should be limited to 25 V for the experiment, because at higher heat input the grains were getting burned and their properties were altered significantly.

Conclusions

On the basis of experimental work done following conclusions can be drawn:

- The developed coaxial dual cylinder apparatus based on steady state method can be widely applied to all types of cereals, pulses and different varieties of oilseeds.
- It was not considered suitable for products containing higher moisture content because of the moisture migration and condensation on the top covering plate. Time to achieve steady state was found to be around 1.5 hours. So, it was found to be not suitable for perishable food products that may change physically or chemically during the time.
- The bulk thermal conductivities of wheat, paddy, Bengal gram and black gram at moisture contents (wb) of 9.7±0.30%, 10.5±0.20%, 10.3±0.35% and 11.4±0.20% and bulk densities of 765.4±16, 535.6±20, 721.5±15 and 740.7±25 kg m^{-3}, respectively were found to be 0.2384, 0.1288, 0.2091 and 0.1460 Wm^{-1} $^{o}C^{-1}$, respectively.

References

[1] Chang, C.S. (1986). Thermal conductivity of wheat, corn and grain sorghum as affected by bulk density and moisture content. Transactions of the ASAE, 29(5), 1447-1450.
[2] Tavman, S. and Tavman, I.H. (1998). Measurement of effective thermal conductivity of wheat as a function of moisture content. International Communications in Heat and Mass Transfer, 25(5): 733-741.
[3] Barbosa-Canovas, GV., Juliano, P., Peleg, M. (2006). Engineering Properties of Foods. In: GV Barbosa-Canovas, ed., Food Engineering. Encyclopedia of life support systems, 39-69. Oxford: EOLSS Publishers Co Ltd.
[4] Dua, K.K. and Ojha, T.P. (1969). Measurement of thermal conductivity of paddy grain and by products. Journal of Agricultural Engineering Research, 14(1):11-17.
[5] Mahapatra, A.K., Lan, Y. and Harris, D.L. (2011). Influence of moisture content and temperature on thermal conductivity and thermal diffusivity of rice flours. International Journal of Food Properties, 14(3): 675-683.
[6] Sahin, S. and Sumnu, S.G. (2006). Physical Properties of Foods. New York: Springer, pp: 110.
[7] Murakami, E.G. & Okos, M.R. (1989). Measurement and prediction of thermal properties of foods. In R.P. Singh, & A.G. Medina (Eds.), Food Properties and Computer-Aided Engineering of Food Processing Systems (pp. 3-48). Dordrecht: Kluwer Academic.
[8] Rao M.A. and Rizvi S.H., Datta Ashim, K. and Ahmed, J. (2014). Engineering Properties of Foods. 4th edition, Taylor and Francis publication, pp: 234-239.
[9] Wallapapan, K., Sweat, V.E., Diehl, K.G. and Engler, C.R. (1986). Physical and chemical properties of foods, Okos, M. R. (ed.), ASAE, St. Joseph, MI, pp: 78.
[10] Pongsawatmanit, R., Miyawaki, O. and Yano, T. (1993). Measurement of the thermal conductivity of unfrozen and frozen food materials by a steady state method with coaxial dual-cylinder apparatus. Bioscience, Biotechnology, and Biochemistry, 57(7): 1072-1076.
[11] Woolf, J.R. and Sibbitt, W.L. (1954). Thermal conductivity of liquids, Industrial and Engineering Chemistry, 46: 1947-1952.
[12] Gentzlerand, G.L. and Schmidt, F.W. (1972). Determination of thermal conductivity values of freeze-dried evaporated skim milk, Journal of Food Science, 37: 554-557.
[13] Kazarian, E.A. and Hall, E.H. (1965). Thermal properties of grain. Transactions of the American Society of Agricultural Engineers, 8(1): 33-37.
[14] Sharma, D.K. and Thompson, T.L. (1973). Specific heat and thermal conductivity of sorghum. Transactions of the American Society of Agricultural Engineers 16, 114-117.

[15] Bitra, V.S.P., Banu, S., Ramakrishna, P., Narender, G. and Womac, A.R. (2010). Moisture dependent thermal properties of peanut pods, kernels, and shells. Biosystems Engineering, 106: 503-512.
[16] Azadbakht, M., Khoshtaghaza, M.H., Ghobadian, B. and Minaei, S. (2013). Thermal properties of soybean pod as a function of moisture content and temperature. American Journal of Food Science and Technology, 1(2): 9-13.
[17] Huang, L. and Liu, L.S. (2009). Simultaneous determination of thermal conductivity and thermal diffusivity of food and agricultural materials using a transient plane-source method. Journal of Food Engineering, 95(1): 179-185.
[18] Bhawna, S.S. and Phirke, P.S. (2012). Thermal properties of different pulses. International Journal of Agricultural Engineering, 5(2): 278-283.
[19] Markowski, M. & Białobrzewski, I. (2013). Bulk thermal conductivity of malting barley. Industrial Crops and Products, 42: 369-372.
[20] Babbitt, J.D. (1945). Thermal properties of wheat in bulk. Canadian Journal of Research, 23(6): 388-401.
[21] Raigar, R.K. and Mishra, H.N. (2014). Effect of moisture content and particle sizes on physical and thermal properties of roasted Bengal gram flour. Journal of food processing and preservation, 39(6): 1839-1844.
[22] ASAE. (2003). ASAE D243.4: Thermal Properties of Grain and Grain Products. ASAE Standards 2000. St. Joseph. MI: ASAE.

Publication History

Received	29th Aug 2017
Revised	04th Sep 2017
Accepted	10th Sep 2017
Online	30th Sep 2017