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Determination of specific heat and thermal conductivity of mushrooms (*Pleurotus florida*)

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Abstract

The specific heat and thermal conductivity of mushrooms (*Pleurotus florida*) was determined for a moisture content (MC) range of 10.24–89.68% w.b. (wet basis) and temperature range of 40–70°C. A third variable of bulk density (BD) was added with its three levels (111.06, 383.49, and 655.86 kg/m^3) to see its effect in combination with other two input variables on thermal conductivity of mushrooms. Both the thermal properties increased almost linearly with the increasing levels of input variables. Multiple regression models with high R^2 values were developed to correlate these properties as a function of input variables. An analysis of variance (ANOVA) revealed that the moisture content had a highly significant effect on specific heat and thermal conductivity of mushrooms. Bulk density was also found to be highly significant affecting thermal conductivity of mushrooms.

Notation

β	Slope of temperature vs. ln time plot
BD	Bulk density (kg/m^3)
C_p	Specific heat (kJ/kg°C)
C_w	Specific heat of water (1 cal/g°C)
H	Heat capacity (cal/°C)
I	Current (A)
k	Thermal conductivity
L	length of the heater wire (m)
M	Mass (g)
MC	Moisture content (% w.b.)
Q	Power input (W)
T	Temperature (°C)
V	Voltage supplied (V)

Subscripts

c	Test capsule
cw	Cold distilled water
e	Equilibrium condition of mixture
f	Flask calorimeter
hw	Hot distilled water
m	Mushroom sample

1. Introduction

Specific heat and thermal conductivity are the most commonly used thermal properties which affect heating or cooling of foods. Computer aided heat transfer analysis techniques have brought about a need for a better knowledge of variation in thermal properties. Previous methods were restricted to uniform and constant thermal properties, but computer techniques can handle varying thermal properties. Therefore, it is necessary to know the effects of temperature, density, and moisture content for applications where these factors change (Rao & Rizvi, 1986).

Data on specific heats of various food materials have been reported in ASHRAE (1985). Sweat (1974) reported the thermal conductivity values of nearly 25 fruits and vegetables. An exhaustive compilation of data on both these thermal properties has been done by Mohsenin (1980) and Rao and Rizvi (1986). But mushrooms which are considered as one of the most nutritive and proteinaceous vegetables, were not found in the above refereed literature. However, Ordinanz (1946) has reported the average specific heat of mushrooms (3.935 kJ/kg°C) at 90% water content for 0–100°C temperature range.

The objective of this investigation was to determine the specific heat and thermal conductivity of mushrooms at various levels of input process variables, i.e. moisture content, temperature, and bulk density.

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2. Materials and methods

2.1. Preparation

Freshly harvested mushrooms of *Pleurotus florida* variety were selected for the investigation and procured from local market at Kharagpur and Midnapore towns of West Bengal, India. Mushrooms were subjected to mild washing in a plastic basket under running tap water to remove the dust and other foreign matter adhered to them. After draining out the water, the mushrooms were spread on blotting paper sheets to remove the surface moisture. Cleaned mushroom fruiting bodies were cut into small pieces to facilitate the determination of thermal properties.

2.2. Moisture content determination

Moisture content of mushroom pieces was determined by hot air oven method (AOAC, 1984). About 3–8 g sample was taken in a pre-weighed moisture box and was weighed again accurately to give the exact weight of sample. It was kept in hot air oven maintained at 102 ± 2°C for about 18 h to get the bone dry weight of sample. Amount of moisture evaporated was calculated and moisture content (MC) was expressed as % w.b. (wet basis). The method described above was adopted for all MC determinations using three replicates to get an average value of MC for any sample. Fresh mushroom pieces used in this investigation had an initial MC in the range of 88–91% w.b.

2.3. Experimental plan

Three levels of input variables viz. moisture content, temperature, and bulk density were selected to simulate the variation in thermal properties as affected by the actual process conditions to be used during the dehydration of mushrooms. Samples with three moisture contents viz. high (initial fresh, about 90% w.b.), medium (partially dried, about 50% w.b.) and low (nearly dried, about 10% w.b.) were obtained for the experiments to cover the full range of moisture content. Bulk density at desired level was achieved by filling a calculated mass of sample pieces upto a certain height. The actual values of different input variables are given below:

Levels of moisture content (% w.b.)	⇒	10.24, 49.96, 89.68
Levels of temperature (°C)	⇒	40, 55, 70
Levels of bulk density (kg/m^3) (only for k)	⇒	111.06, 383.49, 655.86
Experimental design	⇒	$3^2/3^3$ complete factorial

2.4. Experimental procedure for determination of specific heat

One of the most suitable method for biological materials – the method of mixtures (Mohsenin, 1980) was adopted for determination of specific heat of mushrooms. In this technique, certain assumptions were required as (i) there was no heat loss from the capsule containing the material, during transfer from the hot air oven to the calorimeter (ii) the capsule and the mushrooms attained uniform temperature throughout the mass at the end of heating (iii) there was no evaporation loss in the calorimeter during equilibration period, and (iv) the heat capacities of the calorimeter and the capsule remained constant within the range of temperature studied.

2.4.1. Determination of heat capacity of flask calorimeter

Since the calorimeter used (ordinary vacuum thermoflask of 250 ml capacity) was a composite of glass, metal and insulating material, it was easier to determine the heat capacity of the calorimeter experimentally, rather than determining the mass and specific heat of each material separately and combining them. This method consisted of determining the temperature change of distilled water contained in the flask calorimeter at a higher temperature, when a known quantity of distilled water at a known lower temperature was added to it. The system was assumed to be adiabatic. Therefore, the heat capacity of the flask calorimeter was given by (Sreenarayanan, 1983):

$$H_f = \frac{M_{cw}C_w(T_e - T_{cw}) - M_{hw}C_w(T_{hw} - T_e)}{(T_{hw} - T_e)} \quad (1)$$

2.4.2. Determination of heat capacity of test capsule

The heat capacity of cylindrical aluminium test capsule (58 mm height, 23 mm internal diameter and 2.5 mm wall thickness) was also determined experimentally. This consisted of determining the temperature change of water contained in the calorimeter when the empty capsule at higher temperature was added to it. The heat capacity of test capsule was given by (Sreenarayanan, 1983):

$$H_c = \frac{(H_f + M_{cw}C_w)(T_e - T_{cw})}{(T_c - T_e)} \quad (2)$$

2.4.3. Determination of specific heat of mushrooms

After maintaining the higher uniform desired temperature, the test capsule containing mushroom pieces was dropped into distilled water contained in the flask calorimeter at room temperature. Considering the heat balance during the process, the specific heat of mushroom as calculated using the following heat balance equation (Sreenarayanan, 1983):

$$C_p = \frac{(H_f + M_{cw}C_w)(T_e - T_{cw}) - H_c(T_m - T_e)}{M_m(T_m - T_e)} \times 4.1868 \quad (3)$$

Values of H_f and H_c used in above equation were the average values of five replications. The specific heat of mushrooms was determined for samples with different combinations of moisture content and initial sample temperature as indicated under experimental plan.

2.5. Experimental procedure for determination of thermal conductivity

The thermal conductivity of sample was determined by the thermal conductivity probe method (Sweat & Haugh, 1974; Sweat, 1976; Mohsenin, 1980; Rao & Rizvi, 1986) using line-heat source principle. However, in reality, the probe method deviates from the line-heat source method for the reasons as (i) finite length of the line-heat source (ii) finite size of the sample, and (iii) finite radius of the line-heat source (Mishra, 1996).

Thermal conductivity probe (Fig. 1) used by Mishra (1996) was employed to determine thermal conductivity of mushrooms. The probe was made of a brass tube of 1.5 mm diameter and 50 mm length. Line-heat source in the form of 0.75 mm Nichrome wire insulated with Teflon was fused at one end of the brass tube. Calibrated copper-constantan thermocouple wire (1 mm diameter) was placed inside the brass tube with its tip positioned just outside the centre of the brass tube.

Small cut pieces of mushrooms at desired MC were taken in an insulated test container with the desired level of bulk density. The probe was inserted through the centre of the sample mass to prevent any other heat source coming in contact with the sample from the ambient. A constant d.c. power source of 2.22 V and 0.66 A was supplied to the Nichrome wire as the heat input source. The sample in the insulated test container was heated to about 2–3°C below the desired temperature level. Then again the heating started and stopped at about 2–3°C below and above that particular temperature level, respectively. During this heating, the temperature of the sample was recorded as a function of elapsed time at the interval of every 5 s with the help of a data logger. Recorded temperature values were then plotted against the natural logarithm (ln) of elapsed time and subsequently thermal conductivity was calculated by using the Eqs. (4) and (5) (Rao & Rizvi, 1986; Mishra, 1996):

$$k = Q/4\pi\beta, \quad (4)$$

where

$$Q = VI/L \quad (5)$$

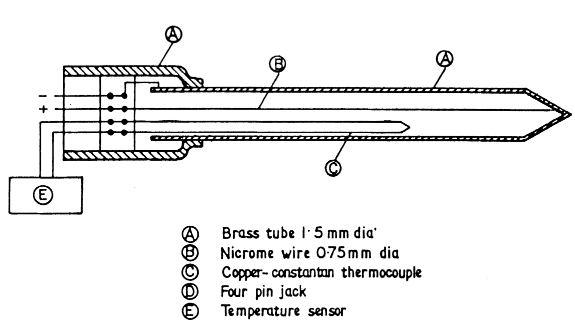

Fig. 1. Thermal conductivity probe.

3. Results and discussion

3.1. Specific heat

The variation in specific heat with moisture content and temperature of mushrooms is presented in Table 1 and Fig. 2. The specific heat of mushrooms varied from 1.7158 to 3.9498 kJ/kg°C for the experimental range of variables studied. The table shows that specific heat increased with the increase in moisture content and temperature of mushrooms. Specific heat (C_p) was modeled through a linear multiple regression equation as a function of moisture content (MC) and temperature (T_m) as follows

$$C_p = 1.0217 + 0.0247\ \mathrm{MC} + 0.0092\ T_m \quad (R^2 = 0.989) \quad (6)$$

Since the prediction equation was a first order linear model, the response surface is almost flat as shown in Fig. 2. To analyse the individual effect of moisture content and temperature on specific heat, analysis of variance (ANOVA) table was constructed as shown in Table 2. It was evident that the effect of moisture content was highly significant (high F-value), while temperature affected specific heat at 5% level of significance. The behaviour of response surface in Fig. 2 also confirmed this inference. High F-value of regression con-

Table 1
Variation in specific heat of mushrooms with moisture content and temperature

Moisture content (% w.b.)	Temperature (°C)	Specific heat (kJ/kg°C)
10.24	40	1.7158
10.24	55	1.8441
10.24	70	1.9645
49.96	40	2.5026
49.96	55	2.6472
49.96	70	2.7827
89.68	40	3.6478
89.68	55	3.8096
89.68	70	3.9498

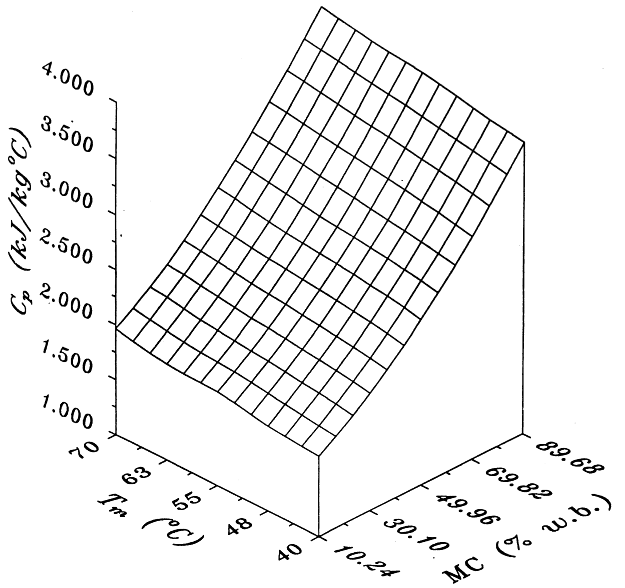

Fig. 2. Effect of moisture content and temperature on specific heat of mushrooms.

firmed the adequacy of fitted model which accounted for 98.9% variation is specific heat within the experimental range of input variables studied (Gomez & Gomez, 1984).

The average observed value of specific heat (3.8024 kJ/kg°C) at 89.68% MC (w.b.) for all temperatures studied has been found close to the value reported (3.935 kJ/kg°C) at 90% MC (w.b.) for 0–100°C temperature range by Ordinanz (1946).

3.2. Thermal conductivity

The thermal conductivity of mushrooms varied from 0.2084 to 0.5309 W/m°C depending upon the moisture content, bulk density and temperature within the experimental range of these variables studied (Table 3). Values of thermal conductivity determined in this investigation were comparable to thermal conductivities of other fruits and vegetables reported in published literature (Sweat, 1974). Based on the findings of previous researchers (Sweat, 1974; Mohsenin, 1980; Rao & Rizvi, 1986), a possible linear multiple regression equation was developed to predict the variation of thermal conductivity as a function of moisture content, bulk density and temperature as follows:

$$k = 0.151 + 0.0037\ \text{MC} + 3.971 \times 10^{-5}\ \text{BD} + 2.348 \times 10^{-4}\ T_{\text{m}} (R^2 = 0.998) \quad (7)$$

The analysis of variance table (Table 2) clearly indicates the greatest effect of moisture content (highest F-value) on thermal conductivity followed by bulk density and temperature. The magnitudes of respective regression coefficients in Eq. (6) also confirmed this result. The above model seems adequately fitted based on the observation of high F-value as well as high coefficient of determination (R^2). The model accounted for 99.76% variation in thermal conductivity within the experimental range of input variables studied (Gomez & Gomez, 1984).

The effect of the two most significant variables (moisture content and bulk density) on thermal conductivity of mushrooms is shown in Fig. 3 through response surface diagram for 40°C temperature. The nature of response surfaces for other two temperatures (55°C and 70°C) was found almost similar to that for 40°C temperature. Table 3 and Fig. 3 revealed that the thermal conductivity increased linearly with the increase in moisture content which is in general agreement with findings of some previous researchers (Sweat, 1974; Mohsenin, 1980; Rao & Rizvi, 1986). This may be due to the fact that the thermal conductivity of water ranges from 0.6106 to 0.6372 W/m°C at temperatures of 26.5–45.0°C (Mohsenin, 1980) which is much higher

Table 2
Analysis of variance (ANOVA) for effect of moisture content, temperature and bulk density on specific heat and thermal conductivity of mushrooms

Source of variation	Sum of squares	Degrees of freedom	Mean sum of squares	F_{cal}-value	Probability
Specific heat					
Regression	5.8829	2	2.9415	275.669***	0.0000
MC	5.7679	1	5.7679	540.556***	0.0000
T_{m}	0.1150	1	0.1150	10.781*	0.0167
Error	0.0640	6	0.0107		
Total	5.9470	8			
Thermal Conductivity					
Regression	0.3939	3	0.1313	3176.669***	0.0000
MC	0.3916	1	0.3916	9494.209***	0.0000
BD	0.0021	1	0.0021	50.958***	0.0000
T_{m}	2.23×10^{-4}	1	2.23×10^{-4}	5.403*	0.0293
Error	9.51×10^{-4}	23	4.13×10^{-5}		
Total	0.3948	26			

*** Highly significant.
* Significant at 5% level.

Table 3
Variation in thermal conductivity of mushrooms with moisture content, bulk density and temperature

Moisture content (% w.b.)	Bulk density (kg/m^3)	Temperature (°C)	Thermal conductivity (W/m°C)
10.24	111.06	40	0.2084
10.24	111.06	55	0.2115
10.24	111.06	70	0.2147
10.24	383.49	40	0.2179
10.24	383.49	55	0.2213
10.24	383.49	70	0.2258
10.24	655.86	40	0.2295
10.24	655.86	55	0.2328
10.24	655.86	70	0.2354
49.96	111.06	40	0.3415
49.96	111.06	55	0.3442
49.96	111.06	70	0.3488
49.96	383.49	40	0.3529
49.96	383.49	55	0.3569
49.96	383.49	70	0.3612
49.96	655.86	40	0.3660
49.96	655.86	55	0.3692
49.96	655.86	70	0.3724
89.68	111.06	40	0.5036
89.68	111.06	55	0.5077
89.68	111.06	70	0.5101
89.68	383.49	40	0.5142
89.68	383.49	55	0.5170
89.68	383.49	70	0.5196
89.68	655.86	40	0.5215
89.68	655.86	55	0.5275
89.68	655.86	70	0.5309

than that of air filled in pores following reduction in moisture.

Regarding the effect of bulk density, it may be noted that air is a poor heat conductor and has very low thermal conductivity, about 0.0272 W/m°C at about 38°C (Mohsenin, 1980), as compared to the solid particles of mushrooms and moisture. Therefore as the bulk density increased, the volume of the pores reduced resulting in a higher thermal conductivity value of mushrooms (Sreenarayanan, 1983).

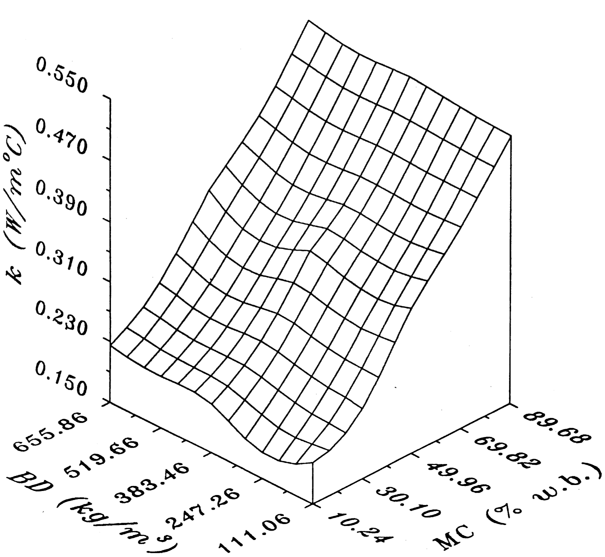

Fig. 3. Effect of moisture content and bulk density on thermal conductivity of mushrooms at 40°C temperature.

4. Conclusions

Results of this investigation clearly shows the significant variation in specific heat and thermal conductivity of mushrooms with changing moisture content, temperature, and bulk density. The conclusion drawn from this study agreed with the general principle that there is a strong linear correlation between thermal properties and water content, especially over the higher range of water contents (Rao & Rizvi, 1986). The developed models can be used to predict the thermal properties satisfactorily within the range of input variables studied.

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