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MODELING THE MOISTURE DEPENDENT THERMAL PROPERTIES OF MULTIPLIER ONION (*Allium Cepa* L. var *Aggregatum*)

Gomathy Kamalakkannan*[1], Balakrishnan Murugesan[1], Thirupathi Venkatachalam[1], Duraiswamy Mueasimangalam Ramasamy[2]

[1] *Tamil Nadu Agricultural University,*
Department of Food and Agricultural Process Engineering, Coimbatore, India
[2] *Tamil Nadu Agricultural University,*
Department of Physical Science & Information Technology, Coimbatore, India

Abstract: The thermal properties of multiplier onion namely thermal conductivity, thermal diffusivity and specific heat were determined in the moisture range of 80.87 to 88.84 % w.b. Thermal conductivity was determined using a line heat source transient heat transfer method whereas the thermal diffusivity was determined by Dickerson method using the thermal diffusivity probe. The thermal conductivity and specific heat of onion increased whereas the thermal diffusivity decreased with increase in moisture content. The thermal conductivity, thermal diffusivity and specific heat of onion ranged from 0.17 ± 0.01 to 0.53 ± 0.03 W/mK, 4.32 x 10^{-7} ± 0.58 to 2.01 x 10^{-7} ± 0.11 m^2/s and 1.01 to 5.75 J/kg.K, respectively. Mathematical modeling was done using the linear regression analysis to predict the specific heat of onions. Among the different models developed, the empirical equation which involved the thermal diffusivity and moisture content predicted the specific heat of onion with a R^2 of 0.974.

Key words*: multiplier onion, thermal conductivity, thermal diffusivity, specific heat, moisture content, modeling*

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* Corresponding author. E-mail: gomsfoodlife@gmail.com

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INTRODUCTION

Onion is one of the agricultural commodities that have an important role in human diet. Onions (*allium cepa* L.) are highly valued as flavouring agents. *Aggregatum* onion (*Allium Cepa* L.Var. *aggregatum*) also known as multiplier onion, is one of the important types of onion grown extensively in southern states of India. Tamil Nadu onions are very sensitive to weather conditions. If not cured properly after harvest the storage life of onions would be reduced due to physiological loss in weight, decay, fungal and mould growth, rotting and sprouting. This in turn leads to a heavy loss to farmers. Curing is being traditionally followed by heaping the onion for a period of two weeks by spreading on the floor in shade or under field conditions. However this traditional curing is not possible during monsoon periods. Artificial curing plays a vital role under such situations. The knowledge on the thermal properties of onion bulbs is required not only to quantify the thermal processes but also to design the artificial curing and storage systems. Specific heat, thermal conductivity and thermal diffusivity are the most important moisture-dependent thermal properties.

The thermal properties namely thermal conductivity, thermal diffusivity and specific heat capacity each can be measured by several well-established methods. The two methods for measuring thermal conductivity include the steady and line heat source transient state heat transfer methods. This line heat source transient heat transfer method has frequently been used in recent years for the determination of thermal conductivity of maize and cowpea [3], banana [2] and berberies fruit [10].

The thermal diffusivity can be measured by either a thermal conductivity probe or a thermal diffusivity tube. The thermal diffusivity probe and tube method had been followed for determining the thermal diffusivity of sweet potato [13] and egusi melon [6], respectively. Specific heat is an important thermal property used in heat transfer and energy balance calculations [7]. There are several methods to measure specific heat of foods. In the method of mixtures the error is caused by heat of solution of soluble matter in the sample. This method has been used by researchers such as barley [5] and for straw mushroom [19]. Another method is the differential scaning calorimeter (DSC) which is more precise but more expensive and requires specific sample preparation.The specific heat can also be calculated using the experimental thermal conductivity and thermal diffusivity data.

Thermal property data of various biological materials have been reviewed and reported so far, however, data pertaining to the thermal properties of multiplier onion bulbs are very limited and scanty. Hence the study was undertaken to determine the thermal properties of multiplier onion with the objective to determine the thermal conductivity, specific heat capacity and thermal diffusivity of multiplier onion as a function of moisture content and to develop a linear regression model to determine the specific heat as a function of thermal diffusivity, thermal conductivity and moisture content.

MATERIAL AND METHODS

Raw material. Field harvested onions (CO-4) were used for all the experiments in this study. The onion harvested during 2014 growing season at the farmer’s field of

Ottanchatram, Tamil Nadu, India was procured for the study. The onions were cleaned manually wherein all foreign matter such as dust, dirt, stones, and chaff as well as immature and spoiled onions were removed. Moisture content of the onion was determined using AOAC 1996 method [1]. Onion samples were dried using hot air oven at 105°C until a constant weight was obtained. The average moisture content was found to be 84.46 % w.b. Onion samples were dried and conditioned to obtain different moisture contents ranging between 80.87 and 88.84 % w.b. A cabinet drier (M/s. Macneill and Magor limited, Calcutta, India) was used for decreasing the moisture content of the onions. To condition the onion samples to higher moisture content, a calculated quantity of distilled water was added [5].The sample was equilibrated at room temperature (30±2°C) before conducting different tests [15].

Thermal conductivity. Thermal conductivity was determined using the transient state heat transfer method (Fig. 1).The test cylinder made of 26 gauge aluminium of size 201 mm x 460 mm contained the onion samples. The probe inside the test cylinder consisted of a 26 gauge thick constantan heating wire of resistivity 15.4 ohms per meter length. The heating wire was insulated with teflon tape and encased in a 6 mm diameter brass tube. The heating wire was attached at lower end of the brass tube. A copper- constantan thermocouple was inserted into the brass tube up to 13 cm from the top, for the measurement of sample temperature, for calculating its thermal conductivity. Power for heating the wire was supplied by a variable DC power supply unit of 1 to 30V and 0 to 2A capacity. A 35 ohms rheostat was used to control the current flow in the circuit. A 5A ammeter was used to measure the current in the circuit.

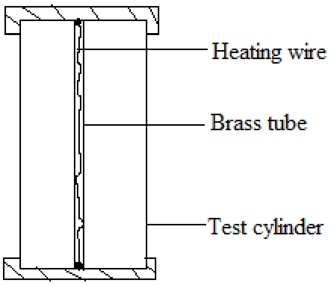

Figure1. Schematic arrangement of test apparatus for measuring thermal conductivity

The thermal conductivity of the sample was calculated using the following Eq. 1:

$$K = [q / 4\pi(T_2 - T_1)] \ln[(Q_2 - Q_0)/(Q_1 - Q_0)] \qquad (1)$$

Where, q = Heat supplied per unit length of thermal conductivity probe (W/m), T_1 = Temperature of thermocouple at time Q1 (°C), T_2 = Temperature of thermocouple at time Q_2 (°C), Q_0 = Time correction for finite diameter of probe (s), Q_1 and Q_2 = Time corresponding to temperatures T_1 and T_2 (s).

Thermal diffusivity. The thermal diffusivity was determined using Dickerson apparatus (Fig.2). A cylindrical probe of 56 mm diameter and 243 mm long made of copper and coated with chromium was used to hold the sample. The teflon lid was used to cover the top and bottom of the cylinder in order to ensure only radial heat transfer. Through the centre of the top lid, a thermocouple junction was inserted and placed at the centre of the probe. Another thermocouple was placed at outside surface of the probe. After filling the onion samples in the probe, the top lid with thermocouple was positioned. The probe was placed within the agitated water bath and the rise in temperature was noted by both thermocouples until the difference between these became constant. The thermal diffusivity of the sample was calculated using the Eq. 2.

The thermal diffusivity was determined using the following equation:

$$D = \frac{AR^2}{4(T_1 - T_2)} \tag{2}$$

Where, D- Thermal diffusivity (m^2/s), R- Inner radius of cylinder (m), T_1- Surface temperature of probe(° C), T_2- Centre temperature of onions (° C), A- Slope.

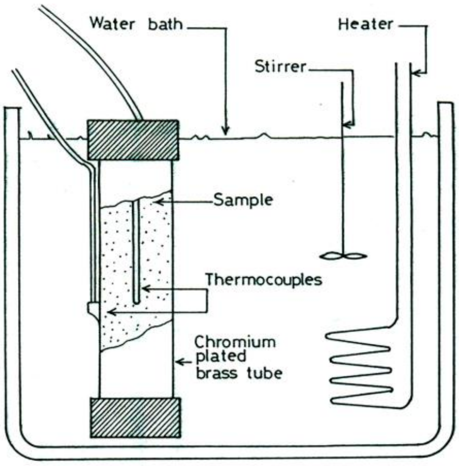

Figure 2. Schematic arrangement of test apparatus for measuring thermal diffusivity

Specific heat. From the thermal diffusivity and thermal conductivity values, the specific heat of onion was calculated using the Eq. 3:

$$C_p = \frac{K}{\rho\sigma} \tag{3}$$

Where, C_p = Specific heat (J/kg.K), K = Thermal conductivity (W/mK), ρ = Bulk density, (kg/m^3)· σ = Thermal diffusivity (m^2/s).

The experiments were conducted in triplicate and was analyzed using Analysis of Variance (ANOVA) followed by Least Significant Difference (LSD) Test using the AGRESS software version 7.01. The Factorial Completely Randomized Design (FCRD) was followed for the ANOVA estimation.

Modeling the specific heat. The specific heat (C_p) was modeled using single or multiple linear regression analysis as proposed for modeling the mass of banana fruit [16]. Thermal diffusivity (σ), thermal conductivity (K) and moisture content (m) data were analyzed to predict the specific heat of onion bulbs. Five linear regression equations were predicted. In all the equations A and B indicate the coefficient of independent variable and C is the constant. Modeling was done using SPSS 16.0 and the suitability of the model was selected based on the highest R^2 (Coefficient of determination) and lowest standard error of estimate.

RESULTS AND DISCUSSION

The thermal properties namely thermal conductivity, thermal diffusivity and specific heat have been determined at a moisture range of 80.87 to 88.84 % w.b. and are represented in Tab. 1. As the moisture content increased, the thermal conductivity of onion bulbs significantly increased ($P<0.1$) from 0.17 ± 0.01 to 0.53 ± 0.03 W/mK. This is due to the decreasing porosity of the onions with increasing moisture content. Water and air have the highest and lowest thermal conductivity respectively, as compared to dry agricultural materials. Therefore the moisture content increased the volume of the pores reduced resulting in a higher thermal conductivity. The positive linear dependence of thermal conductivity on moisture content has also been reported for ginger [8], banana [16], cowpea and maize [3].

As the moisture content increased from 80.87 to 88.84 % w.b., the thermal diffusivity of onion bulbs significantly decreased ($P<0.1$) from $4.32 \times 10^{-7} \pm 0.58$ to $2.01 \times 10^{-7} \pm 0.11$ m^2/s. The decrease in thermal diffusivity with moisture content has also been reported for pea nut pod and kernel [4], egusi Melon [6] and rice flour [9].

The specific heat of onion bulbs varied from 1.01 to 5.75 J/Kg. K at moisture content ranging between 80.87 to 88.84 % w.b. The specific heat increased significantly ($P<0.1$) with increasing moisture content. The increased specific heat with increasing moisture content is due to the high specific heat of water compared to the dry material, and the tendency of water to occupy the air-filled pores at a faster rate [13]. The result was in line with fermented ground cassava [12] and pistachio nuts [17].

Table 1. Effect of moisture content on the thermal properties of onion bulb

Thermal properties	*Moisture content, % w.b.*	*Mean*	*S.D*	*S.E*
Thermal conductivity (W/mk)	80.87	0.17^{d}	0.01	0.005
	82.91	0.23^{c}	0.02	0.011
	85.25	0.43^{b}	0.06	0.034
	88.84	0.53^{a}	0.03	0.017
Thermal diffusivity (m^2/s)	80.87	$4.32^{a} \times 10^{-7}$	0.58	0.334
	82.91	3.49^{b} x 10-7	0.45	0.259
	85.25	$3.16^{b} \times 10^{-7}$	0.2	0.115
	88.84	$2.01^{c} \times 10^{-7}$	0.11	0.063
Specific heat (J/kg.K)	80.87	1.01^{d}	0.87	0.502
	82.91	1.56^{c}	0.55	0.317
	85.25	3.02^{b}	0.12	0.069
	88.84	5.75^{a}	0.95	0.548

All data represent the mean± standard deviation (S.D). a-d letters indicate the statistical difference in same columns ($P<0.05$)

The results of the mathematical modeling *viz.* model coefficient, coefficient of determination R^2, Adjusted R^2 and the Error Sum of Estimate (ESE) for the thermal conductivity, thermal diffusivity and specific heat are provided in Tab. 2, 3 and 4, respectively. Fig. 3-5 represents the fit of various models to the thermal properties as a function of moisture content. The best model was selected based on the highest R^2 and lower ESE values.

Table 2. Models predicting thermal conductivity as a function of moisture content

S.No.	Model	Equations	R^2	Adjusted R^2	ESE
1.	Linear	$K= -3.713+ 0.048* m$	0.948	0.923	0.047
2.	Logarithmic	$K= -17.749+ 4.078 \ln m$	0.951	0.926	0.046
3.	Quadratic	$K= -18.142+ 0.388 *m - 0.002 * m^2$	0.958	0.873	0.060
4.	Power	$K= 1.154E\text{-}25 * m^{12.679}$	0.927	0.891	0.175
5.	Exponential	$K= \mathrm{Exp}\,(1.057E\text{-}06 + 0.149 *m)$	0.922	0.883	0.182

From Tab. 2, the logarithmic model with a $R^2 = 0.951$, adjusted $R^2 = 0.926$ and ESE = 0.046 was found to be the best fit model for prediction of thermal conductivity as a function of moisture content

The linear, logarithmic and quadratic models predicted the thermal diffusivity of the onions with a $R^2 = 0.979$ and ESE = 0.000 as represented in Tab. 3. Any one of the above models could be considered for determining the relationship between moisture content and thermal diffusivity of onions.

Table 3. Models predicting thermal diffusivity as a function of moisture content

S.No.	Model	Equations	R^2	Adjusted R^2	ESE
1.	Linear	$\sigma = 2.663E\text{-}06\text{-} 2.76E\text{-}08* m$	0.979	0.968	0.000
2.	Logarithmic	$\sigma = -1.075E\text{-}05\text{-}2.35E\text{-}06 * m$	0.979	0.968	0.000
3.	Quadratic	$\sigma = 3.323E\text{-}06 - 4.32E\text{-}08* m - 9.165E\text{-}01* m^2$	0.979	0.936	0.000
4.	Power	$\sigma = 4.444E\text{-}08 * m^{-7.866}$	0.966	0.949	0.073
5.	Exponential	$\sigma = \mathrm{Exp}\,(0.001 - 0.093* m)$	0.969	0.954	0.069

Table 4. Models predicting specific heat as a function of moisture content

S.No.	Model	Equations	R^2	Adjusted R^2	ESE
1.	Linear	$C_p = -48.766+ 0.611* m$	0.971	0.957	0.441
2.	Logarithmic	$C_p = -1.075E\text{-}05 - 2.350E\text{-}06* m$	0.966	0.950	0.476
3.	Quadratic	$C_p = 260.058 - 6.669* m - 0\ .043* m^2$	0.998	0.995	0.154
4.	Power	$C_p = 1.154E\text{-}36 * m^{18.842}$	0.993	0.989	0.078
5.	Exponential	$C_p = \mathrm{Exp}\,(1.671E\text{-}08 + 0.222* m)$	0.991	0.987	0.086

Table 5. Specific heat models of multiplier onion

S.No.	Equations	A	B	R^2	C	ESE
1.	$C_p = \sigma A+ C$	-2.143 E07	-	0.936	9.790	0.657
2.	$C_p = K A+ C$	11.984	-	0.907	-1.239	0.791
3.	$C_p = \sigma A+ m B+C$	7.674 E06	0.823	0.974	-69.198	0.595
4.	$C_p = KA+ m B+C$	1.778	0.696	0.972	-55.369	0.612
5.	$C_p = \sigma A+ K B+C$	-1.32 E07	4.811	0.955	5.587	0.782

The power law model is adjudged as the best fit model to predict the relationship between specific heat and moisture content with a $R^2 = 0.993$, adjusted $R^2 = 0.989$ and ESE = 0.078 as shown in Tab. 4.

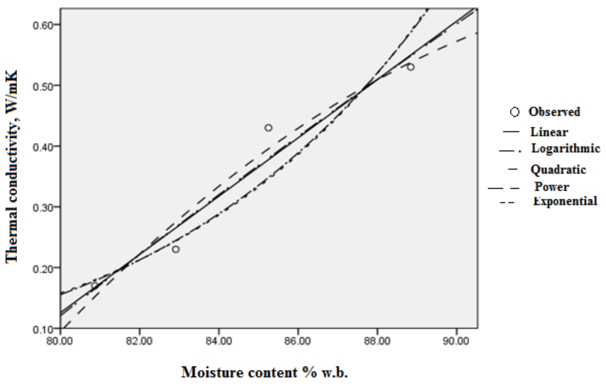

Figure 3. Models predicting the effect of moisture content on the thermal conductivity of onion bulbs

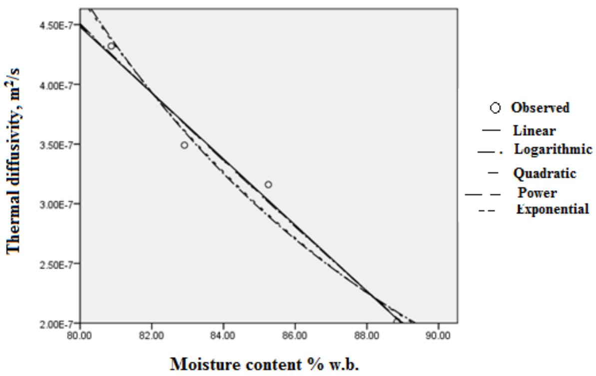

Figure 4. Models predicting the effect of moisture content on the thermal diffusivity of onion bulbs

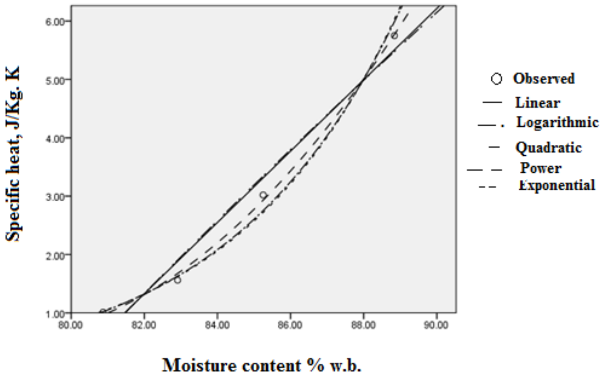

Figure 5. Models predicting the effect of moisture content on the specific heat of onion bulbs

Among the five regression models presented in Tab. 5, the following equation (6) predicted the specific heat with a $R^2 = 0.974$ and ESE = 0.595 and found to be the best fit model for calculating the specific heat of multiplier onion as a function of moisture content and thermal diffusivity.

$$C_p = 7.674E06(\sigma) + 0.823(m) - 69.198 \tag{4}$$

CONCLUSIONS

The thermal properties determined were used for modeling the specific heat of multiplier onion as a function of moisture content. The best fit model predicting the thermal properties was chosen based on coefficient of determination (R^2) and Error Sum of Estimate (ESE). The recommended linear regression model describing the specific heat of multiplier onion is:

$$C_p = \sigma K_1 + mK_2 + C$$

The thermal property data determined for the multiplier onions would be useful for designing an artificial curing and storage system and in the prediction of energy requirement involved in heat transfer operations.

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MODELIRANJE TERMIČKIH KARAKTERISTIKA LUKA (*Allium Cepa* L. var *Aggregatum*) U ZAVISNOSTI OD SADRŽAJA VLAGE

Gomathy Kamalakkannan[1], Balakrishnan Murugesan[1],
Thirupathi Venkatachalam[1], Duraiswamy Mueasimangalam Ramasamy[2]

[1] *Poljoprivredni univerzitet Tamil Nadu,*
Institut za procesni inženjering hrane i poljoprivrede, Coimbatore, India
[2] *Poljoprivredni univerzitet Tamil Nadu,*
Institut za fiziku i informatiku, Coimbatore, India

Sažetak: Termalne osobine luka, kao što su: toplotna provodljivost, toplotna difuzija i specifična toplota su određivane u opsegu vlage od 80.87 do 88.84%. Toplotna provodljivost je određena metodom prolaznog prenosa toplote dok je toplotna difuzija određena Dickerson metodom, korišćenjem toplotne difuzione sonde. Toplotna provodljivost i specifična toplota crnog luka porasle su dok je toplotna difuzija smanjena sa povećanjem sadržaja vlage. Toplotna provodljivost, toplotna difuzija i specifična toplota crnog luka u rasponu od 0,17 ± 0,01 na 0,53 ± 0,03 V/mK , 4.32 h 10-7 ± 0,58 do 2,01 k 10-7 ± 0,11 m^2/s i 1,01 do 5,75 J/kg.K , redom. Matematičko modeliranje je urađeno pomoću linearne regresione analize predviđene specifične toplote luka. Među različitim razvijenim modelima, empirijska jednačina koja uključuje toplotnu difuziju i sadržaj vlage predvidela je specificnu toplotu crnog luka sa R^2 od 0,974 .

Ključne reči: *luk, toplotna provodljivost, termička difuzija, specifična toplota, sadržaj vlage, modeliranje*

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