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Influence of moisture content and temperature on thermal properties of acha grains: Application of response surface methods

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ABSTRACT

In this paper, influences of moisture content (MC) and temperature (T) on thermal properties of acha (*Digitaria exilis* Stapf) grains such as thermal conductivity (Y_k), thermal diffusivity (Y_α) and specific heat (Y_{Cp}) were investigated. The experiments were carried out at 5 %, 10%, 15 %, 20 % and 30%wb and 25, 30, 35, 40, 45 and 50 ^oC moisture content and temperature respectively, using a dual-needle line-heat-source (DNL) device. A central composite rotatable design (CCRD) was used to model the thermal conductivity, thermal diffusivity and specific heat of the acha grains. The Y_k, Y_α and Y_{Cp} varied from 0.160 to 0.309 W/mK, 0.121 and 0.179 $x10^{-6}$ m^2/s and 0.94 to 3.082 kJ/kg^oC, respectively. All the thermal properties were significantly influenced ($p<0.05$) by linear, interaction and quadratic effects of MC and T, except the interaction effect that was not significant ($p>0.05$) for thermal diffusivity only. The coefficients of determination were 0.955, 0.970 and 0.988 for Y_k, Y_α and Y_{Cp}, respectively. The correlation coefficients (R^2) for the observed and predicted values were 0.819, 0.948 and 0.881 for Y_k, Y_α and Y_{Cp}, respectively, indicating a good fit for the model. The CCRD was found appropriate in predicting thermal properties of acha.

Keywords: Thermal conductivity, Thermal diffusivity,Specific heat, Acha grains, Response surface methods

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I. INTRODUCTION

It is an understatement that the knowledge of thermal properties and how they change as a function of moisture content and temperature are fundamental to modeling, simulation and equipment design of various food processing operations involving heat transfer phenomena (Tang *et al*., 1991; de Moural *et al*., 1998; Shrivastava and Datta, 1999; Singh and Goswami, 2000; Aviara and Haque, 2001). Mohsenin (1980), Rao and Rizvi (1986) and others too numerous to mention had made concerted efforts in documenting data on thermal properties of various food and agricultural materials. Knowledge of these thermal properties such as thermal conductivity, specific heat and thermal diffusivity are essential for equipment design and heat transfer operations such as drying, heating, refrigeration and freezing (Mohsenin, 1980). However, data on thermal properties of acha popularly known as white fonio (*Digitaria exilis* Stapf) which is also variously called fundi, findi, hungry rice, and Asian millet (NRC 1996) are still limited in literatures.

This boycott could stem from the fact that the cereal was tagged an underutilized crop but are currently receiving increased attentions in research and development (Irving and Jideani, 1997; Jideani 1990, 1999; Adoukonou-Sagbadja *et al*., 2004; PhilipandItodo 2006; Ayo and Nkama, 2006; Jideani *et al*., 2000, 2007, 2008; Taylor, 2008; Agu*et al*., 2008, 2009). They are part of the indigenous African cereal-based diets which have been discovered healthy and cheap addition to diets, while at the same time generating incomes for local producers in Africa (Dury *et al*., 2007). The genus *D. exilis* forms the staple foods in some of the producing areas where it is processed into various kinds of menu such as tuwo, djouka, couscous, wete, acha jollof, kunuacha, breakfast acha e.t.c especially in West Africa sub region (Jideani, 1990, 1999).

Moisture content and temperature are two main parameters that greatly influence the specific heat, thermal conductivity and thermal diffusivity of biological materials (Alagusundaram *et al*., 1991; Hobani and Tolba, 1995; Singh and Goswin, 2000) owing to the relatively high specific heat, thermal conductivity and heat of sorption of water. Generally, specific heat is expressedas a function of moisture content using linearrelations (Mohsenin, 1980). The effect of temperature onthermal is still limited in theliterature concerning agricultural materials (Tang *et al*., 1991).

Better understanding of the effects of moisture content and temperature on the thermal properties of biological materials is obtained if the experimental data were analysed by multiple regression as described by Snedecor and Cochran (1967) rather than the one-variable-at-a-time method of experimentation. The latter is inappropriate in many circumstances especially where there are more than one input factors controlling the response or output of a process or system (Tayeb *et al*., 1992; Iwe, 2001, 2010, Goyal *et al*., 2008). In the foregoing, response surface methodology (RSM) will be useful in this particular situation where the thermal properties under investigation are high influenced by moisture content and temperature. This method of analysis has been well adopted in many multi-factored processes (Tayeb *et al*., 1992; Iwe, 2001, 2010, Carley *et al*., 2004; Goyal *et al*., 2008). Therefore, the objective of the study was to determine the thermal conductivity, thermal diffusivity and specific heat of acha grain as a function of moisture content and temperature applying response surface analysis.

II. MATERIALS AND METHODS

2.1 Preparation of materials

The experimental material was achaotherwise known as fonio grain (*Digitaria exilis* Stapf) purchased from a local market in Kaduna, Northern Nigeria. The grains were cleaned manually by winnowing to remove all foreign materials, broken and immature seeds. The cleaned seeds were oven dried at 45 ^{o}C and thereafterstored for one month in a refrigerator. The initial moisture content of the dried grain (5.18 %wb) was determined by the ASAE (1998) standard (S 352.2) involving oven-drying method at 103 ± 1 ^{o}C for 72 hours.Other four grain moisture levels investigated in this study were: 10, 15, 20 and 25 ± 0.2 %wb These moisture content levels were arrived at by adding amounts of distilled water calculated based on the sample's initial moisture content according to AACC method 26-95 (AACC, 2003). After conditioning, every sample was sealed in separate polyethylene bags. All samples were stored in a refrigerator for at least 2 days to allow the moisture to distribute uniformly throughout the sample.

2.2 Dual-needle line-heat-source method

A dual-needle line-heat-source **(**DNL) device consists of 2 needle probes in parallel (Campbell *et al*., 1991; Bristow *et al*., 1994; Fontana *et al*., 1999). The primary probecontains a line heater and a thermocouple, while the second probecontains a thermocouple only. An epoxy material of high thermal conductivity fills the gap between the heatingwire or the thermocouple and the needle. A short duration pulse is applied to the heater and thetemperature of the thermocouple is monitored.This probe has been individually used for thermal conductivity measurement in conventional conditions (Sweat, 1974; Mohsenin 1980; Murakami *et al*., 1996; Denys *et al*., 2000; Zhu *et al*., 2007). Theoretically this method is based on non-steady-state heat conduction caused by a constant line heat source to an infinite medium. The thermal conductivity (k, W/m°C) of the medium tested is obtained as (Campbell *et al*., 1991):

$$k = \frac{q}{4\pi S} \qquad 1$$

where q is heat input (W/m) and S is a slope determined by linear regression of measured temperatures against the natural logarithm of time (^{o}C).

From the other probe, if a heat pulse is applied to the heater, the response of the thermocouple will be a temperature peak after a certain time, which depends on the thermal property of the test sample.This can be used to estimate the thermal diffusivity (α, m^2/s) ofthe tested medium by the following expression (Kluitenberg *et al*., 1993; Bristow *et al*., 1994):

$$\alpha = \frac{r^2}{4}\left(\frac{t_m^{-1} - \left(t_m - t_0\right)^{-1}}{\ln\left(t_m\right) - \ln\left(t_m - t_0\right)}\right) \qquad 2$$

where r is the distance from the line source (m), t_o is the duration of the heat pulse (s), and t_m is the time from the start of heating to the temperature reaching maximum (s).and calculate the volumetric heat capacity.

The volumetric heat capacity (C_{pV}, J/m^{3o}C) can be calculated from the thermal conductivity and diffusivity values obtained (Fontana *et al*., 1999):

$$C_{pV} = \frac{k}{\alpha} \qquad 3$$

and subsequently specific heat (C_p, J/kg^{o}C) as:

$$C_p = \frac{C_{pV}}{\rho} \qquad 4$$

where ρis bulk density (kg/m^3) of the tested material i.e. acha. The bulk density of the acha grain in the above relation was substituted from Eq. (11) an outcome of preliminary experiment:

$$\rho_b = 0.349M^2 - 19.601M + 973.80$$

$$(R^2 = 0.99) \qquad 5$$

where M is the moisture content of acha grain (% wet basis) and R^2 is the coefficient of determination.

2.3 Determination of bulk density

Bulk density of acha grains was determined according to the method described by Jaliliantabar*et al.* (2011) at different moisture contents (Table 1) by filling a plastic container ofpredetermined volume. Theplastic container was measured 10.5 cm height and 4.3 cm inside diameter. At different moisture contents, grains in the sample holder were shaken and tapped around the container various numbers of constant times, followed by dropping the container thrice from a 10 cmheight at each one-third filling. The bulk density (ρ_b) of grains was obtained by calculating the ratio of the mass (M) of grains in the plastic container to the container's volume (V) as expressed by Equation (7):

$$\rho_b = M/V \qquad 6$$

2.4 Thermal properties determination

The dual needle heat pulse probe according to the method described by Zhu *et al.* (2007) was used with modifications in this study to measure the thermal properties of acha. The DNHP probe was connected to ThermoLink® (Decagon devices Inc., Pullman, WA 99163 USA) is a hand-held device, which consist of controller (case size 15.5 cm by 9.5 cm by 3.5 cm) with a display of 3 cm by 6cm, keypad of 6 keys, sealed membrane and a dual-needle sensor of 1.3 mm diameter by 6 cm long which is inserted into any material under investigation.

Dual-needle line-heat-source (DNL) device was used to determine the thermal conductivity (k), thermal diffusivity (α) and volumetric specific heat capacity (C_{pv}) of acha.

$$y_k = \beta_0 + \sum_1^2 \beta_i x_i + \sum_{i=1}^2 \beta_{ii} x_i^2 + \sum_{i=1}^1 \sum_{j=i+1}^2 \beta_{ij} x_i x_j \qquad 7$$

$$y_\alpha = \beta_0 + \sum_1^2 \beta_i x_i + \sum_{i=1}^2 \beta_{ii} x_i^2 + \sum_{i=1}^1 \sum_{j=i+1}^1 \beta_{ij} x_i x_j \qquad 8$$

$$y_{c_p} = \beta_0 + \sum_1^2 \beta_i x_i + \sum_{i=1}^2 \beta_{ii} x_i^2 + \sum_{i=1}^1 \sum_{j=i+1}^1 \beta_{ij} x_i x_j \qquad 9$$

A central composite rotatable design according to Lorezen and Anderson (1993) with two variables was adopted (Table 1and 2). The experimental design was made up of four (2^2) factorial points, four-star points to form a central composite design and five replications at the centre point. The experiments were conducted in a randomized order to minimise the effect of unexpected variability in the observed responses i.e. due to extraneous factors. Independent variables such as moisture content (MC) and temperature (T) and thermal conductivity (Y_k), thermal diffusivity (Y_α) and specific heat (Y_{cp}) with their corresponding values and the coded factor levels are given in Table 1and 2.

DNL uses the transient line heat source method (as described above) to measure the thermal properties. After moisture equilibration in the refrigerator for 24 hours, the samples were randomly brought for test according to experimental plan. The independent variables were moisture content (MC; 5, 10, 15, 20 and 25 ±0.2 %wb) and temperature (T; 25, 30, 35, 40 and 25 ±1°C) as shown in Table 1. The samples were allowed to attain test temperature in thermostatically controlled water bath (12 – 15 minutes) before carrying out the experiment and it was assumed that the temperature of water bath and acha were equal. The SH-1 probe was inserted through the centre of the removable top cover and a fixed bottom base stainless-steel container of 3.5cm by 5 cm which contained the weighed acha.In each experimental run, thermal conductivity (y_k), thermal diffusivity (y_α) and specific heat (y_{cp}) were measured as readout as output (readout) from the screen of the KD 2 Pro thermal properties analyzer in duplicate at intervals of 15 mins as shown in Table 2.

2.5 Experimental design

According to Goyal *et al.* (2008), RSM is defined as the statistical method that uses quantitative data from an appropriate experimental design to determine and simultaneously solve multivariate equations. It is advantageous by reducing the number of experiments needed to evaluate multiple parameters and their interactions. Hence, RSM was adopted to study the effects of moisture content (x_1) in %wb and temperature (x_2) in °C on thermal properties such as thermal conductivity (y_1), thermal diffusivity (y_2) and specific heat (y_3) of acha (white fonio). Experimental data were fitted to the following second-order polynomial equations.

Table 1: Experimental variables and their levels

Experimental variable	Symbol		Level				
	Original	Coded	-2	-1	0	+1	+2
Moisture content(%wb)	MC	x_1	5	10	15	20	25
Temperature (°C)	T	x_2	25	30	35	40	45

III. RESULTS AND DISCUSSION

The experimental responses of thermal conductivity, thermal diffusivity and specific heat of acha are recorded in Table 2 with original and coded variable levels. Using Design Expert 11 (Stat Ease Inc.), a multiple regression model with all the thermal properties acha as a function of moisture content and temperature T, were fitted to the experimental data. Sequential model sum of squares suggested the linear effects, quadratic and cross-effect of moisture content and temperature.

3.1 Thermal conductivity, y_k

The thermal conductivity of acha obtained experimentally within the moisture content and temperature ranges of 5 - 25 %wb and 25 - 45 °Crespectively, was found to lie between 0.160 and 0.309 W/mK (Table 2). Analysis of variance for the response surface quadratic model for thermal conductivity is given in Table 3. It is evident there are positive significant ($p < 0.05$) relationship between the response (thermal conductivity) and the input variables for all effects except linear effect of moisture content that is negative as shown in Eq. (10).

$$Y_k = 0.263 + 0.0282x_1 + 0.0338x_2 + 0.0195x_1x_2 - 0.0120x_1^2 + 0.0103x_2^2 \qquad 10$$

Table 2: Experimental design used to obtain different combinations of variables[a].

Run[b]	Moisture content (%wb)	Temperature (°C)	*k (W/m°C)	*α (x10^{-6} m^2/s)	*c_p(kJ/kg°C)
1	15 (0)	35 (0)	0.268	0.144	2.446
2	25 (+2)	35 (0)	0.279	0.129	3.082
3	20 (+1)	30 (-1)	0.201	0.121	2.306
4	15 (0)	35 (0)	0.265	0.146	2.394
5	15 (0)	35 (0)	0.269	0.145	2.445
6	15 (0)	45 (+2)	0.294	0.179	2.167
7	15 (0)	25 (-2)	0.160	0.128	1.651
8	20 (+1)	40 (+1)	0.309	0.153	2.803
9	10 (-1)	30 (-1)	0.188	0.149	1.553
10	15 (0)	35 (0)	0.266	0.143	2.453
11	5 (-2)	35 (0)	0.162	0.188	0.974
12	15 (0)	35 (0)	0.268	0.147	2.404
13	10 (-1)	40 (+1)	0.218	0.179	1.499

[a] Central Composite Rotatable Design with five levels and two factors, 13 experiments.
[b] Does not necessarily corresponded to the order of experiment.
*Average values of three replicates

The second order polynomial model is highly significant ($p < 0.0001$) with high adjusted R^2 and predicted R^2 values of 0.955 and 0.819, respectively are in reasonable agreement i.e. the difference is less than 0.2 which suggests that the model Eq. (4) is adequate to navigate within the design domain (5 %wb ≤MC ≤ 25 %wb and 25 °C ≤ T ≤ 45 °C) as shown in Figure 2a. This was in agreement with the investigations of other workers (Kazarian and Hall, 1965; Sharma and Thompson, 1973; Moraulis *et al*., 1990; Hsu *et al*., 1991) on some other food materials. This may imply that heat transmission in acha grains is better when wet than when they are dried as inferred by Sadiku and Bamgboye (2014). The representation of the response surface is given in Figure 1a.

However, the positive linear effects of moisture content and temperature on thermal conductivity was far more profound (<0.0001) than the second order effects ($p > 0.001$). The linear incremental effect of temperature on thermal conductivity was also reported by other researchers (Rao and Rizvi, 1986; Singh and Goswami, 2000; Aviara and Haque, 2001). It is observed that this trend especially with temperature is in agreement with Fourier's equation of heat conduction that higher temperature gives rise to increased thermal conductivity.

The interaction effect of the two factors as it is evidently shown from response surface (Figure 1a) that there is steep increase in thermal conductivity at high moisture content and temperature under investigation. The same effect though much greater was also reported by Singh and Goswami (2000) for cumin seeds.

3.2 Thermal diffusivity, y_α

The variation of thermal diffusivity of acha at different moisture content-temperature (5 - 25 %wb and 25 - 45 °C) is as recorded in Table 2. The values were found to range between 0.121 x 10^{-6} and 0.179 x10^{-6} m^2/s. Analysis of variance for the response surface quadratic model for thermal conductivity is given in Table 4.

Table 3: Analysis of variance for thermal conductivity (k) of acha using composite design

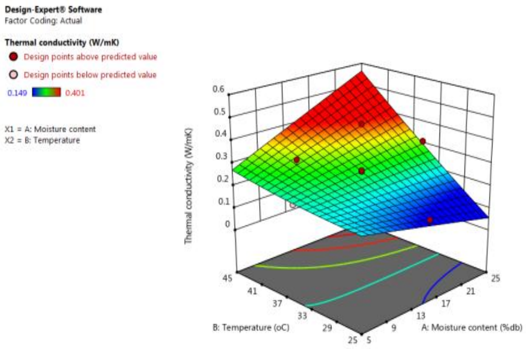
Source	Sum of squares	df	Mean square	F-value	p-value
Model	0.0293	5	0.0059	51.82	<0.0001
Linear					
x_1	0.0095	1	0.0095	84.32	<0.0001
x_2	0.0137	1	0.0137	121.65	<0.0001
Quadratic					
x_{11}	0.0033	1	0.0033	29.02	0.0010
x_{22}	0.0024	1	0.0024	21.67	0.0023
Interaction					
x_{12}	0.0015	1	0.0015	13.47	0.0080
Residual	0.0008	7	0.0001		
Lack-of-fit	0.0008	3	0.0003	96.25	0.0003
Pure error	0.0000	4	0.0000027		
Correlation total	0.0300	12			
R^2	0.974				
Adjusted R^2	0.955				
Predicted R^2	0.819				

It can be observed that there was second order polynomial relationship between thermal diffusivity of acha grains and input variables ($p < 0.05$). The linear terms of both the variables had higher significant effect on thermal diffusivity at 5% level, but no cross relationship ($p > 0.05$), removal of the insignificant terms did not improve the model. The relationship between the thermal diffusivity and variables can be expressed by the following regression equation:

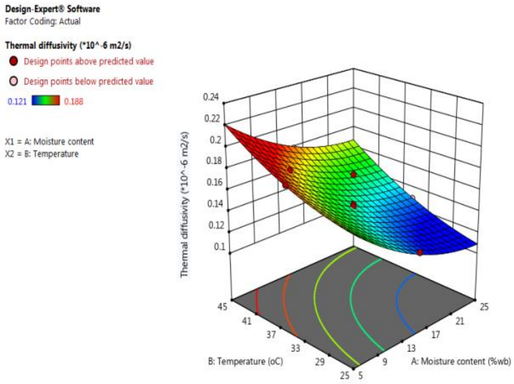
$$Y_\alpha = 0.145 - 0.0143x_1 + 0.0137x_2 + 0.0005x_1x_2 + 0.0034x_1^2 + 0.0021x_2^2 \qquad 11$$

The predicted R² of 0.948 is close to the adjusted R² of 0.988 i.e. the difference is more than 0.2. Therefore, the model (Eq. 6) can be used to navigate the design space under investigation as also shown in Figure 2b that there exists good relationship between the predicted values and experimental measurements.

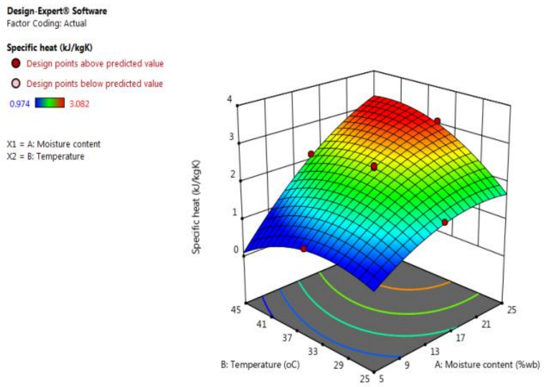
The effect of moisture contents and temperature on thermal diffusivity of acha is shown in Figure 1b. As can be seen, the thermal diffusivity decreased with increase in moisture content this trend and the values range are in agreement with the outcomes for corn and wheat (Kazarian and Hall, 1965) and cumin seeds (Singh and Goswami, 2000).



a

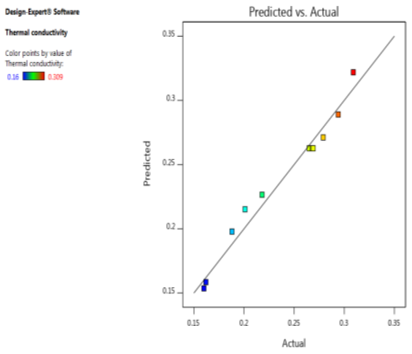


b



c

Figure 1: Response surface and contours for (a) thermal conductivity (b) thermal diffusivity and (c) specific heat as functions of moisture content and temperature of acha.



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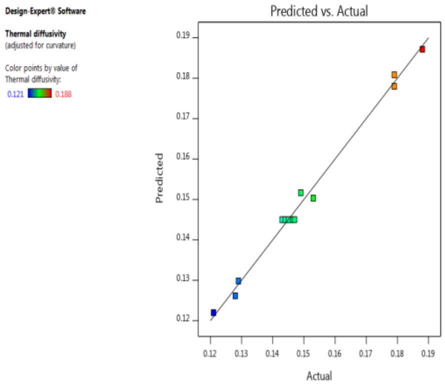

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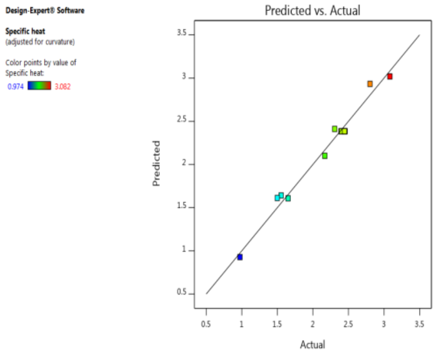

c

Figure 2: Predicted value versus actual measurements for (a) thermal conductivity (b) thermal diffusivity and (c) specific heat of acha grains.

Table 4: Analysis of variance for thermal diffusivity (α) of acha using composite design

Source	Sum of squares	df	Mean square	F-value	p-value
Model	0.0050	5	0.0010	203.99	<0.0001
Linear					
x_1	0.0025	1	0.0025	502.64	<0.0001
x_2	0.0022	1	0.0022	456.97	<0.0001
Quadratic					
x_{11}	0.0003	1	0.0003	53.21	0.0002
x_{22}	0.0001	1	0.0001	21.10	0.0025
Interaction					
x_{12}	0.000001	1	0.000001	0.2039	0.6653
Residual	0.0000	7	4.905E-06		
Lack-of-fit	0.0000	3	8.111E-06	3.24	0.1427
Pure error	0.0000	4	2.500E-06		
Correlation total	0.0050	12			
R^2	0.993				
Adjusted R^2	0.988				
Predicted R^2	0.948				

3.3 Specific heat capacity

The experimental values obtained at different moisture contents and temperatures are shown in Table 2 and Figure 1c. The specific heat capacity of acha grain increased from 0.94 to 3.082 kJ/kg^{o}C with increase moisture content and temperature within the experimental domain (5 %wb ≤MC ≤ 25 %wb and 25 ^{o}C ≤ T ≤ 45 ^{o}C) as shown in Table 2.

These values are similar to specific heats reported in the literature for other food crops such as 1.330 to 3.090 kJ/kgK for cumin seeds, 1.792 to 3.172 kJ/kgK for sheanut kernel. Though other terms are significant ($p<0.05$), specific heat (y_{Cp}) was modeled by second order polynomial as a function of moisture content (x_1) and temperature (x_2) with high $R^2 = 0.970$ as follows:

$$y_{c_p} = 2.38 + 0.523x_1 + 0.123x_2 + 0.138x_1x_2 -$$

R^2=0.970 12

The second order polynomial model is highly significant ($p < 0.0001$) with high adjusted R^2 and predicted R^2 values of 0.970 and 0.881, respectively are in reasonable agreement i.e. the difference is less than 0.2 which suggests that the model Eq. (4) is adequate to navigate within the design domain (5 %wb ≤MC ≤ 25 %wb and 25 ^{o}C ≤ T ≤ 45 ^{o}C) as shown in Figure 2a. Similar quadratic relationship trend was reported by Singh and Goswani (2000) for cumin seed against linear relationship reported by some researchers (Kazarian and Hall, 1965; Mohsenin, 1980; Murata *et al.*, 1987; Dutta *et al.*, 1988; and Hsu *et al.*, 1991).

Obviously, the increase in specific heat was more pronounced at higher moisture contents than at lower values at all temperatures (Figure 1c) which was also in agreement with the work of Tang *et al.* (1991), for lentil seed, Wang and Brennan (1993) for potato, Singh and Goswani (2000) for cumin. The increment in specific heat with moisture content is generally common to biological materials as earlier indicated. The cross effect of the two factors was significant as specific heat increased more rapidly with positive change in moisture content and temperature (Figure 1c).

Table 5: Analysis of variance for specific heat (c_p) of acha using composite design

Source	Sum of squares	df	Mean square	F-value	p-value
Model	4.05	5	0.8090	77.23	<0.0001
Linear					
x_1	3.28	1	3.28	313.02	<0.0001
x_2	0.1813	1	0.1813	17.31	<0.0042
Quadratic					
x_{11}	0.2423	1	0.2423	23.13	0.0019
x_{22}	0.4027	1	0.4027	38.45	0.0004
Interaction					
x_{12}	0.0759	1	0.0759	7.25	0.0310
Residual	0.0733	7	0.0105		
Lack-of-fit	0.0704	3	0.0235	31.60	0.0030
Pure error	0.0030	4	0.0007		
Correlation total	4.12	12			
R^2	0.982				
Adjusted R^2	0.970				
Predicted R^2	0.881				

IV. CONCLUSIONS

All thermal properties of acha are fitted to second order polynomial with all effects being significant ($p < 0.05$) except interactive effect of thermal diffusivity ($p > 0.05$) using response surface methodology by adopting central composite rotatable design and all the empirical models were found to be highly significant ($p < 0.0001$) within the experimental domain(5 ≤ MC ≤ 25 %wb and 25 ≤ T ≤ 45 ^{o}C) investigated.It can be concluded that the empirical models can be adequately used to predict the thermal properties i.e. bulk thermal conductivity, thermal diffusivity and specific heat of acha within the experimental domain since the actual and measured thermal properties were regressed and the correlation coefficients were found to reasonably high. Therefore, the results presented in this paper can be used in industrial applications of such processes as drying, tempering, or cooling, where heat transport properties of acha are indispensable.

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