Some Thermo-physical Properties of Yam Cuts of Two Geometries

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ABSTRACT

The effects of variation of temperature (-18 to 33^{O}C) and geometries (slab and cylinder) on some thermo-physical properties of white yam were investigated. The measured parameters were density, specific heat, and thermal diffusivity at constant moisture level of 72.7% ± 0.69 (wet basis) using transient heat transfer method. Both the density and specific heat of the sample increased with increase in temperature to maximum levels after which further increase led to a reduction of the values of these parameters; however, they were independent of sample's geometry. The rate of heat diffusion per second for the yam as measured was between 2.365 to 11.86 x 10^{-8} m^2 and 2.676 to 8.062 x 10^{-8} m^2 for slab and cylinder respectively. The thermal diffusivity and computed thermal conductivity were found to increase with increase in temperature. Conclusively, these thermo-physical properties were correlated with temperature using polynomials of the third order empirical model.

Keywords: Thermo-physical properties, density, specific heat, thermal conductivity thermal diffusivity,yam, Nigeria

1. INTRODUCTION

Knowledge of the thermo-physical properties of foodstuffs such as density, specific heat, thermal conductivity and thermal diffusivity, are fundamentally important in mathematical modeling studies for the design and optimization of food processing operation involving heat and mass transfer, best exemplified by food drying. However, the mathematical modeling approach has been faced with drawbacks imposed by the general lack of data on these important properties of foodstuffs, especially as a function of temperature and geometry.

Existing predictive equations for thermal conductivity of foodstuffs were reported by Miles et al. (1983) and Sweat (1986); however, these models may be applied only to specific foodstuffs for which they were developed. This is because substantial differences in the chemical and physical make-up of foodstuffs exist, which implies that each food material must have its own predictive equation (Mohsenin, 1980). Tung et al. (1989) compiled thermal diffusivity values for different food products from the literature, reported mostly at a certain moisture level and not including tropical foodstuffs at both geometry and temperature levels. In other words, much work has been done on thermo-physical properties of foodstuffs whether fresh or processed. In the tropics, however, little or nothing has been done especially on yam which is economically important and used as staple food in various forms viz: pounded, boiled, mashed, fried, or roasted. The under exploitation of the root and tuber crops which abound in the tropics and the very low level of the mechanization of their processing could be traced to the fact that data on the thermo-physical properties of these local foodstuffs are not available. Thus, their processing cannot be made amendable to the rapidly increasing range of new technologies serving the process industries.

The present study is concerned with the development of mathematical models to describe the changes in some thermo-physical properties of white yam as a function of geometry and temperatures. The temperature ranges investigated include ambient temperatures values and values below freezing point of the food samples. This invariably gives a wider application of these thermo-physical data.

2. MATERIALS AND METHODS

2.1 Materials

The white yam *(Dioscoreae rotundata*) used for this study was purchased from Kuto – a local market in Abeokuta, Ogun state, Nigeria. The sample was prepared by peeling, washing and slicing to two different geometrical shapes (slab and cylindrical) The Slab (or block) measured 3cm length x 2cm width x 1cm thickness while the cylinders are of 3cm length x 1cm diameter. The average initial moisture content (m.c) of the sample was determined to be 72.7 ± 0.69% using AOAC (1984) technique.

2.2 Experimental Procedure

2.2.1 Solid density (ρ) Measurement Equal mass (5.0g) of the sample was weighed and put into 100ml measuring cylinder containing 50ml water (as floatation liquid) using simple floatation principles (Nwanekezi and Ukagu, 1999). The difference in volume was noted and was equal to the volume occupied by the 5.0g sample. The density was derived from the mass of sample divided by volume occupied.

$$\rho = \frac{\text{Mass of sample (kg)}}{\text{Volume occupied by the sample (m}^3\text{)}} \qquad (1)$$

2.2.2 Specific Heat (Cp) Measurement The method of Mohsenin (1980) was adapted with the use of a lagged copper calorimeter. About 100g of heated water were weighed into the inner cylinder. When the temperature of the water and cylinder had equilibrated to the required temperature of $50^{O}C$, a 5.0g sample was placed in the cylinder and then covered. The cylinder content was stirred at 2 minutes intervals using a copper stirrer and the temperature of the water was monitored at regular interval for 1 hour.

$$C_p = 1/M_p \; [M_w C_w G_w/G_p - M_c C_c]/60 \qquad (2)$$

where, M_p, M_w and M_c are the masses of sample, water and calorimeter, respectively; C_w and C_c are the specific heat capacity of water and calorimeter, respectively; G_w and G_p are the slope of cooling curve for water and sample respectively (McPrond and Lund, 1983).

2.2.3 Thermal Diffusivity (α) Measurement The thermal diffusivity of the sample at constant moisture content was determined by the method of Tong et al. (1993). The probe was connected by K – thermocouple wires to an Alda AVD 890C+ digital multimeter. The temperature history of each sample was determined by insertion of the probe into the centre, that is, at the radial axis of the sample. The sample packaged in polythene was placed in a water bath at constant temperature of $50^{O}C$ and the temperature history was recorded at 10 seconds intervals for about 5 minutes. The basic equation underlying this method was generated from the Fourier's equation, thus:

$$\delta T/\delta t = \alpha[\, 1/r\, (\delta T/\delta r + r\delta^2 T/\delta r^2)] \quad (3)$$

$$\delta T/\delta t = \alpha[\, 1/z\, (\delta T/\delta z + z\delta^2 T/\delta z^2)] \quad (4)$$

Equation (3) was used for cylindrical shape

Equation (4) was used for slab (or block) shape

$(0 < r < a;\ 0 < z < a)$

At Fourier 0.1, the solutions to the heat transfer equation for an infinite geometry using Eqns. (3) and (4) is as follows:

$$\mathrm{Ln}\left(\frac{T_s - T}{(T_s - T_i)}\right) = \mathrm{Constant} - \left(\frac{5.783\,\alpha}{r^2}\right) t \quad (5)$$

where, T_s is the medium temperature (^{O}C); T_i is the initial temperature of the sample (^{O}C), T is the temperature of the sample at time, t (^{O}C), r is the radius or half the thickness of the sample (Carslaw and Jaegar, 1959).

The thermal diffusivity was then calculated from the slope of a plot of the natural logarithm of the unaccomplished temperature Vs time.

2.2.4 Statistical Analysis The thermo-physical data obtained were subjected to analysis of variance (ANOVA) to give a suitable correlation in order to explain the variation of the thermo-physical properties against temperature by evaluating the coefficient of determination (R^2) and standard error (S.E)

3. RESULTS

3.1Moisture Content

The average initial moisture content (m.c) obtained for the yam sample was 72 ± 0.69% as shown in Table 1.

Table 1. Overall average initial moisture content of yam

Sample label	$M.C_{yam}$ (%)
A	74.00
B	72.60
C	72.40
D	72.00
E	72.40

F	72.60
Overall Average[a]	72.7±0.69

[a] mean of six replicates with standard deviation.

3.2 Thermo Physical Properties of Yam at Different Temperatures

Using the method proposed by Nwanekezi and Ukagu (1999), the density of the sample were determined as presented in Table 2 as a function of temperature in the range of -18 to 33^oC. Table 2 also shows the mean experimental values for the specific heat at temperature range of –18 to 33^OC using the data obtained for heat loss of the frozen and unfrozen yam sample at initial water temperature of 50^OC according to McProd and Lund (1983). The specific heat of the yam used in this study ranged from 1.177 to 3.015 kJ/kg^OC for the various temperatures. The mean experimental values for the thermal diffusivity of yam - slab and cylindrical geometries using the procedure recommended by Tong et al. (1993) ranged from 2.365 x 10^{-8} to 11.862 x 10^{-8} m^2/s and 2.676 x 10^{-8} to 8.062 x 10^{-8} m^2/s, respectively (Table 2). When the density, thermal diffusivity and specific heat of the sample are combined, its thermal conductivity (λ) was computable for various temperature studied as shown in Table 2. The interraction of the themophysical properties with temperature was best explained in Figure 1.

Table 2. Measured and computed thermo physical properties of yam at different temperatures

T(^0C)	ρ (kg/m^3)	Cp (kJ/kg^oC)	α_{slab}x10^{-8}(m^2/s)	$\alpha_{cylinder}$x10^{-8}(m^2/s)	λ_{slab}(W/mK)	$\lambda_{cylinder}$(W/mK)
- 18	1053.19 ± 0.289[a]	1.177 ± 0.537[a]	2.364 ± 0.293[a]	2.676 ± 0.425[a]	0.029 ± 0.042[a]	0.033 ± 0.042[a]
- 10	1064.51 ± 1.041	3.015[b] ± 0.465	4.431[b] ± 0.389	4.630[b] ± 0.272	0.120[b] ± 0.096	0.149[b] ± 0.040
-5	1076.09 ± 0.764	2.204 ± 0.484	5.049 ± 0.389	4.128 ± 0.289	0.120 ± 0.095	0.098 ± 0.039
0	1087.91 ± 0.577	2.582 ± 0.480	5.486 ± 0.758	6.307 ± 0.284	0.154 ± 0.041	0.177 ± 0.049
5	1139. 24 ± 0.577	2.809 ± 0.797	6.156 ± 0.811	7.539 ± 0.726	0.197 ± 0.031	0.241 ± 0.036
27	1125.00 ± 0.500	2.152 ± 0.431	7.673 ± 0.333	7.695 ± 0.742	0.186 ± 0.084	0.186 ± 0.065
33	1100.00 ± 0.289	2.056 ± 0.337	11.862 ± 0.887	8.062 ± 0.423	0.268 ± 0.033	0.182 ± 0.063

[a] mean of three replicates with standard deviation.
[b] critical point/departure from the observed trend

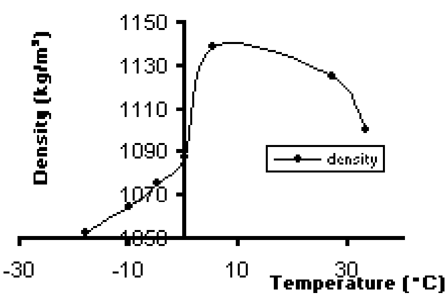

Fig. A:Plot of density as function of temperature

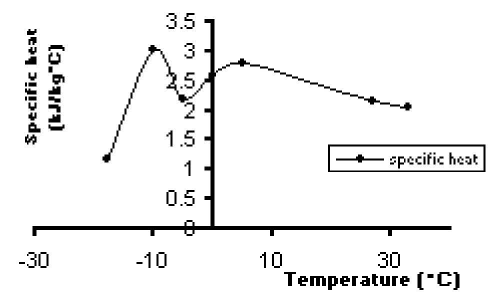

Fig.B:Plot of specific heat as function of temperature

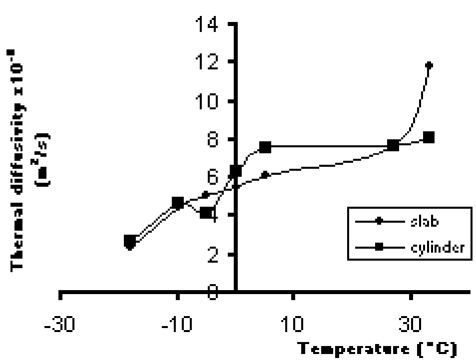

Fig.C:Plot of Thermal diffusivity as function of temperature

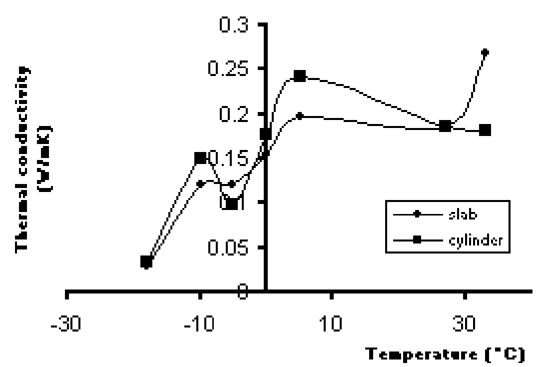

Fig.D:Plot of Thermal conductivity as function of temperature

Figure1. Plots of some selected engineering properties of yam as functions of temperature

4. DISCUSSION

The average value of initial moisture content obtained is in agreement with the published data (Paul and Southgate, 1978; Dorosh, 1988), however, with very little variation of numerical values. This variation might be due to the type of species used, climatic and environmental conditions in which the sample was subjected prior to processing. However, the higher moisture content of the fresh sample (72.7± 0.69%) may contribute to microbial proliferation and subsequent degradation.

It was observed that the density of the sample increased with increase in temperature up to 5^{O}C after which a subsequent increase in temperature led to decrease in density because of the anomalous behaviour of water in the frozen state. This was principally due to the gradual change in the proportion of water frozen as a function of temperature. The magnitude of change in density was proportional to the moisture content of the product as reported by Singh and Heldman (1993). Based on the statistical analysis done, an empirical model was considered:

$$\rho_{yam} = 1100.490 + 4.107T + 0.004T^2 - 0.004T^3 \quad (6)$$

$$(R^2 = 0.89;\ S.E=14.68)$$

The specific heat increases with increase in temperature up to a peak (freezing state) and then decreases (heating state) with further increase in temperature. This corroborates the results reported by Taiwo et al. (1995). However, the method used was independent of geometries (McPrond and Lund, 1983). Changing state of the ice, i.e freezing front influences the specific heat at a critical temperature of -10^{o}C in the sample. Below – 10^{o}C, there was a sharp drop for the sample as shown in Table 2 while subsequent value increased with further increase in temperature. This further affected the thermal diffusivity and thermal conductivity especially that of cylindrical geometry of the sample. However, in processing foodstuffs, higher values of specific heat usually lead to more energy transfer and improved heat transfer conditions.

The experimental values of C_p as a function of temperature at constant moisture content of the sample was best explained by the following empirical equation:

$$C_{pyam} = 2750.890 + 2.693T - 2.925T^2 + 0.069T^3 \quad (7)$$

$$(R^2 = 0.67;\ S.E = 489.06)$$

It was observed that the values obtained for thermal diffusivity of yam are less than 1.00 and these agree with thermal diffusivity values which were published for some other foods as reported earlier (Singh, 1982; Wallapapan et al., 1984; Singh and Heldman, 1993; Rapusas and Driscoll, 1995; Nwanekezi and Ukagu, 1999).

The thermal diffusivity, which increased with an increase in temperature below the initial freezing point were best explained by the following empirical equations:

$$\alpha_{yam(slab)} = 5.54E-8 + 1.89E-11T - 4.78E-11T^2 + 3.11E-12T^3 \quad (8)$$

$$(R^2 = 0.98;\ S.E = 0.00)$$

$$\alpha_{yam\ (cylinder)} = 6.104E-8 + 1.650\ E-9T - 2.274E-11T^2 - 3.622E\text{-}13T^3 \quad (9)$$

$$(R^2 = 0.92;\ S.E = 0.00)$$

The effect of changing state of the freezing front influences the thermal conductivity at a critical point of $-10^{O}C$ in both geometries of the sample after which there was a drop in thermal conductivity values as shown in the Table 2. It was also observed that geometry had only very little effect on these values, and therefore, the three thermo-physical properties are greatly influenced by their composition or constituents.

The effect of temperature variation on the thermal conductivity of this sample at constant moisture content were best explained by the following empirical models:

$$\lambda_{yam\ (slab)} = 0.164 + 0.001T - 0.000T^2 + 7.676T^3 \quad (10)$$

$$(R^2 = 0.92;\ S.E = 0.03)$$

$$\lambda_{yam\ (cylinder)} = 0.183 + 0.005T - 0.00T^2 - 3.152\ E-7\ T^3 \quad (11)$$

$$(R^2 = 0.79;\ S.E = 0.04)$$

Then, it can be deduced that thermal conductivity increased with an increase in density for constant moisture content and, therefore, more mass of the sample was contained per unit volume. The greater the density of a sample, the lower the volume of air in the particle interstices. Since air is a poor conductor of heat, the less the quantity present, the better the conduction. In addition, the greater the density, the greater the contact between particles, hence, higher thermal conductivity. Wallapapan and Sweat (1982) and Taiwo et al. (1995) also reported the same trend for defatted soy flour and ground and hydrated cowpea, respectively.

5. CONCLUSIONS

An evaluation has been carried out on the effects of temperature variation and geometry of yam sample on the thermo-physical properties of yam. Temperature was varied between -18 and $33^{O}C$ for two geometries: slab (measuring 3cm x 2cm x 1cm) and cylindrical (measuring 3cm in length and 1cm in diameter). The thermo-physical properties of the yam of these geometries were measured at constant moisture level.

The values of specific heat in this work were found to be high, running into thousands of joules per kilogramme for a unit change in temperature. This translates to the fact that a lot of energy is required to heat or cool yam foods, and that once it is heated or cooled, it will retain its temperature for a long time. This is as a result of large moisture contents of the root and tuber crops. Water retains its temperature for long time because of its high specific heat value (Lamb, 1976).

The values of thermal conductivity and thermal diffusivity of yam obtained in this study are low. This means that yam is a poor conductor of heat. Heat energy diffusion or transfer during drying, refrigeration, freezing, thawing, evaporation, etc, are likely to be very slow. Good conductors like metals have high thermal conductivities and low specific heat values. The low thermal diffusivities of the samples imply that they do not heat up or cool down rapidly. Going by the values obtained, therefore, movement or diffusion of heat energy from one point to another in these foods is generally at very low rate when heat is being transferred. The variation of these thermo-physical properties with temperature was best described by polynomials of the third order empirical model.

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