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Sorption Equilibrium and Thermodynamic Properties of Palm Kernel

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Abstract: Equilibrium relative humidity – moisture content data for palm kernel at five different temperatures (40, 50, 60, 70 and 80°C) and moisture content values ranging from 8.6 to 24.7% (dry basis) were determined using the vapour pressure manometric method. A non-linear least squares regression programme was used to evaluate four moisture sorption models. The regression models were compared using the standard error of estimate, the mean relative percent deviation, the fraction-explained variation and residual plots. Modified Henderson model was found to be the best model for predicting both the equilibrium moisture content and equilibrium relative humidity of palm kernel. The experimental data was used to determine the thermodynamic characteristics of palm kernel. The heat of vaporization of moisture in the kernel decreased with increase in moisture content and approached the latent heat of pure water at a moisture content between 28 and 32% dry basis. The spreading pressure increased with increase in relative humidity and was not significantly affected by temperature. Net integral enthalpy decreased with increase in moisture content and became asymptotic in trend as the moisture content of 24% (db) was attained. Net integral entropy had positive values in the moisture range from 8.6 to 15% (db) and negative values from the moisture content of 15.3% (db) till 20% (db) was approached.

Key words: Palm kernel, equilibrium moisture content, equilibrium relative humidity, thermodynamics, heat of vaporization, integral enthalpy, entropy

Introduction

Palm kernel is a source of oil that is of significant importance to the industrial development of Nigeria. It is obtained as a by-product after the expression of palm oil from oil palm fruits. The kernel contains about 49 percent oil which is similar to coconut oil and is used in the manufacture of soaps, toiletries, surface active ingredients, bakery coatings, whipped creams and sugar confectionery. The efficient processing and storage of palm kernel requires that the moisture content be reduced to appropriate levels by drying. The proper modeling and optimization of drying process require the knowledge of equilibrium relative humidity – moisture content relationships at different temperatures, energy requirement as well as the state and mode of moisture sorbed within the product. The methods used for the determination of equilibrium moisture sorption isotherms of agricultural products can be classified into those in which the material is brought into equilibrium with air of fixed temperature and relative humidity and the moisture content of the material is measured (Equilibrium Moisture Content EMC or gravimetric method); and those in which air is brought into equilibrium with the material at a fixed temperature and the moisture content and relative humidity of the air determined (Equilibrium Relative Humidity ERH method). Rao and Pfost (1978) developed the equilibrium moisture sorption isotherms for some 20 agricultural products and concluded that the Equilibrium Relative Humidity methods are simpler and faster. The most commonly used ERH methods are the dew point method and the vapour pressure manometric methods (VPM). The dew point method has been used to obtain the equilibrium moisture sorption isotherms of rapeseed (Sokhansanj *et al.,* 1986) and wheat flour (Henderson and Pixton, 1982). The VPM method has been used to obtain the equilibrium moisture isotherms of apples (Singh and Lund 1984), dry milk (Sood and Heldman 1974) and sesame seed (Ajibola and Dairo 1998). Labuza *et al.* (1976) observed that the VPM method is one of the best methods of determining the sorption isotherm of materials as it measures directly the vapour pressure exerted by the moisture in the kernels of previously evacuated jar. Devices and procedures that are based on this method have been described by Labuza (1976).

Several theoretical, semi – theoretical and empirical models have been proposed and used by investigators for fitting equilibrium moisture content data (Vanden Berg and Bruin, 1981). Chirife and Iglesias (1978) reviewed part of these models and discussed 23 commonly used equations for fitting the sorption isotherms of different food materials. Many of these models have been tested and their constants evaluated for the sorption data of many agricultural crops. The sorption data of palm kernel however, appear to be unavailable.

Thermodynamics has been reported as one of the three approaches used to understand the properties and calculate the energy requirements of heat and mass transfer in biological systems (Rizvi and Benado 1984; Fasina *et al.,* 1997 and Fasina *et al.,* 1999).Others are the structural approach, which describes the mechanism of hydrogen bonding and the molecular positioning obtained using spectroscopic techniques, and the dynamic approach, which involves the analysis of the motion of water molecules and their contribution to the hydrodynamic properties of the system. The use of structural and dynamic approaches are limited in biological systems application due to limited information on the theory of the behavior of water associated with solid biological materials (Rizvi and Benado 1984).

Thermodynamic functions are readily calculated from moisture sorption isotherms and this enables the thermodynamic approach to allow the interpretation of experimental results in accordance with the statement of the theory (Iglesias *et al.*, 1976). These functions include free energy, heat of vaporization (differential heat of sorption), integral enthalpy and integral entropy. They determine the end point to which food must be dehydrated in order to achieve a stable product with optimal moisture content, and yield a figure for the theoretical minimum amount of energy required to remove a given quantity of water from food. They also provide insight into the micro structure associated with food and a basis for the theoretical interpretation of physical phenomena occurring at the food - water interface (Rizvi, 1986).

Fish (1958) studied the thermodynamics of water in potato starch gel and noted that starch at very high moisture content is thermodynamically similar to pure water. Iglesias *et al.* (1976) studied the thermodynamics of water vapor sorption by sugar beet root and advanced hypotheses, which were mainly concerned with configurational modification of the adsorbents during the course of sorption, to explain the values and trends observed. Viollaz and Rovedo (1999) determined the equilibrium moisture sorption isotherms of starch and gluten and proposed a new method of calculating the isosteric heat (differential heat of sorption) at different temperatures. Fasina and Sokhansanj (1993), Fasina *et al.* (1997), Fasina *et al.* (1999), Aviara *et al.* (2002) and Aviara and Ajibola (2002) respectively calculated the thermodynamic functions of moisture sorption in alfalfa pellets, winged bean seed and gari, sesame seed and gari and cassava, from their moisture sorption isotherms.

The main aim of this study was to establish the experimental ERH/EMC data for palm kernel at different temperatures. Other objectives include the evaluation of the ability of four EMC/ERH models to fit the data obtained, and the determination of the thermodynamic functions of the product using the moisture sorption isotherms.

Materials and Methods

The palm kernel used in this study was purchased from the local market. A bulk quantity of the kernels were cleaned and milled in a hammer mill. The moisture content of the milled kernels was determined by oven - drying at 130°C for 6 hours as recommended by Young *et al.* (1982) for oilseeds with high oil contents. Samples of the product were conditioned to different moisture levels by the addition of calculated amounts of water, storing in clearly labelled cellophane bags and keeping in the refrigerator for about 7 days. Before use, the samples were brought out of the refrigerator and stored for at least 2 hours in the laboratory to enable them to acquire the room temperature. A fraction of the samples was set aside for moisture content determination.

Fig. 1 shows the VPM apparatus consisting of a Dymak MK1 vacuum pump (Charles Auston Pumps Ltd.) (A), a Budenburg vacuum/pressure gauge (Broadhealth, Manchester) (B), a Gallenkamp WF - 455 compenstat water bath (C), a Gilmont G - 1500 - A micromanometer (Cole - palmer Instrument Company) (D), two 25/40 top quickfit flasks (E, F), two mercury thermometers (G, H), rubber tubings and 2 - and 3 - way stopcocks. The water bath has a temperature range of between 20 to 100 °C in 5 °C divisions while the micromanometer has a range of 0 to 5 mm in 0.05 mm divisions with sensitivity of 0.0125 mm. The manometer oil with specific gravity determined as 0.82 was obtained from Cole - palmer, while $CaCl_2$ was used as the desiccant as suggested by Nunes *et al.,* (1985).

The procedure suggested by Lewicki *et al.,* (1978) was used for the determination of equilibrium relative humidity. Thirty grammes of the sample were put into the sample flask and an equal amount of desiccant into the desiccant flask. The two flasks were sealed into the system apparatus. They were put into the water bath and sample flask was allowed to equilibrate with the water temperature. The whole system was then evacuated excluding the sample flask. After evacuation, the stopcock above the desiccant flask (V3) was closed and the stopcock over the sample flask (V4) was opened to connect the sample with the evacuated air space. The system was again evacuated for between 60 and 90 seconds. After evacuation, the stopcock across the manometer (V5) was closed causing the level of the oil in the micromanometer to respond to the vapour pressure exerted by the sample. When the oil level reached a steady value, the difference was recorded as H1. After equilibration, the stopcock over the sample was closed and the desiccant stopcock was opened such that the system was connected with the desiccant flask. The moisture in the air space was then absorbed by the desiccant, and this caused a change in the height of the manometric oil. After the oil has reached a constant height, the reading of the micromanometer was recorded as H2.

The sample was thereafter removed from the system and the moisture content determined using the standard oven method of drying at 130°C for 6hours.The apparatus excluding the sample flask was then evacuated for the next equilibrium relative humidity determination. The above procedure was followed at five temperature levels of the water bath (40, 50, 60, 70, 80°C) and different moisture levels between 8 and 25% (dry basis). Two replications were performed for each test condition. The moisture content of samples measured after each equilibrium relative humidity determination was observed to be different from the moisture content before the determination. Equilibrium relative humidity was calculated from equation (1) given by Lewicki *et al.* (1978).

$$\frac{RH\cdot}{100} = \frac{\dfrac{(H1-H2) * (273+Ts)}{(273+To)}}{Ps} \qquad (1)$$

where RH is the equilibrium relative humidity (%)

H1 is the micromanometer reading with the sample flask connected to the system (mm of manometric oil)

H2 is the micromanometer reading with the desiccant flask connected to the system (mm of manometric oil)

T_s is the temperature of the water bath taken as the temperature of the sample (°C)

T_o is the temperature of the environment surrounding the micromanometer (°C) and P_s is the saturated water vapour pressure at the sample temperature (mm of manometric oil).

Analysis of Data

Moisture Sorption Isotherms: The experimental data were fitted to four commonly used models, namely the Modified Henderson (Thompson, 1972), Modified Chung – Pfost (Pfost *et al.,* 1976), Modified Halsey (Iglesias and Chirife, 1976a) and Modified Oswin (Chen, 1988) models. All of them are three parameter models that can be solved explicitly for relative humidity as a function of temperature and moisture content, or for moisture content as a function of temperature and relative humidity.

The Modified Henderson ERH and EMC models are:

$$RH = 1.0 - \exp[-A*(T+C)*M^{B}] \qquad (2)$$

$$M = \frac{[-Ln(1.0 - RH)]^{1/B}}{A*(T+C)} \qquad (3)$$

The Modified Chung – Pfost ERH and EMC models are:

$$RH = \exp[-A/(T+C)]*\exp(-B*M) \qquad (4)$$

$$M = (-1.0/B)*Ln[-(T+C)/A]*Ln(RH) \qquad (5)$$

The Modified Halsey ERH and EMC models are:

$$RH = \exp[-\exp(A+B*T)*M^{-c}] \qquad (6)$$

$$M = \frac{[-Ln(RH)]^{1/c}}{\exp(A+B*T)} \qquad (7)$$

The Modified Oswin ERH and EMC models are:

$$RH = \frac{1.0}{\left[\dfrac{(A+B*T)}{M}\right]^{C} + 1} \qquad (8)$$

$$M = (A+B*T)*\left[\frac{RH}{1-RH}\right]^{1/C} \qquad (9)$$

where

M = equilibrium moisture content (% dry basis)
RH = equilibrium relative humidity (decimal)
T = temperature (°C)
A, B, C = constants of the models.

The NLIN procedure (SAS, 1986), a non-linear regression analysis procedure that minimizes the sum of squares of deviations in a series of iterative steps was used to fit the four moisture sorption isotherm models to the moisture sorption data. The procedure requires that the initial parameter estimates be chosen close to the true values. These estimates were obtained by linearization of the models through logarithmic transformation and application of linear regression analysis using the REG procedure (SAS, 1986). Model parameters were estimated for the models first by taking the equilibrium relative humidity (ERH) to be the dependent variable and secondly by taking the equilibrium moisture content (EMC) as the dependent variable. The goodness of fit of each of the models was evaluated using an estimate of the residual mean square (standard error) calculated by the procedure, mean relative percent error, fraction explained variation and residual plots.

Several authors have used these parameters to evaluate the fitting ability of EMC – ERH equations. Ajibola (1986a, 1989) and Ajibola *et al.,* (2003) used the standard error of estimate to evaluate different models. Boquet *et al.,* (1979) used the mean relative percent deviation to compare the fitting ability of different models, Pappas and Rao (1987) used the fraction-explained variation to compare the fitting ability of several models, while Chen and Morey (1989) and Mazza and Jayas (1991) used the standard error of estimate, mean relative percent deviation and residual plots to evaluate the fitting ability of models.

The mean relative percent deviation is defined as:

$$P = \frac{100}{N} \times \sum \frac{|Y-Y'|}{Y} \qquad (10)$$

The standard error of estimate (S.E) is defined as

$$S.E = \sqrt{\frac{\sum(Y-Y')^2}{df}} \qquad (11)$$

The fraction - explained variation (FEV) is defined as:

$$F.\,E.\,V. = \frac{\text{Sum of squares due to model}}{\text{Total sum of squares}} \qquad (12)$$

where

Y = the measured value
Y' = the value predicted by the model
N = the number of data points
df = degrees of freedom on regression model.

The residual plots were plots of residuals (the differences between measured and predicted values of ERH or EMC) against the predicted values. A model was considered acceptable if the residuals were uniformly scattered around the horizontal value of zero showing no systematic tendencies towards a clear pattern. A model is considered better than another if it has a lower standard error, lower mean relative percent deviation and higher fraction explained variation.

Heat of Vaporization: The heat of vaporization of moisture (L) in palm kernel was estimated by applying the Clausius – Clapeyron equation to the sorption isotherms. This, after some mathematical manipulations (Aviara and Ajibola, 2000) yielded the expression

$$\mathrm{Ln}(P_o) = \frac{L}{h_{fg}}\,\mathrm{Ln}(P_s) + C_1 \qquad (13)$$

where P_o = actual water vapor pressure in the material (Pa)
P_s = saturated water vapor pressure (Pa)
h_{fg} = latent heat of vaporization of free water (J/kg)
and C_1 = constant.

A plot of $Ln(P_o)$ vs $Ln(P_s)$ yielded the ratio of the heat of vaporization of moisture in the material to the latent heat of saturated vapor from the slope of the straight line obtained. The saturation vapor pressure at different temperatures was obtained from Rogers and Mayhew (1981) and the vapor pressure in the material was obtained from the equation

$$P_o \doteq P_s(ERH) \qquad (14)$$

The values of ERH were obtained from the Modified Henderson model, which gave the best fit for palm kernel ERH. This model is given in equation (2) and for palm kernel; it can be expressed as follows:

$$RH = 1 - \exp[-1.82 \times 10^{-6}(T + 35.1)M^{2.92}] \qquad (15)$$

Net Integral Enthalpy and Entropy: The integral enthalpy of sorption and desorption of water in food products provides an indication of the binding strength of water molecules to the solid and has some bearing on the energy balance of drying and freezing operations (Gal 1975). The equation for calculating net integral enthalpy was derived from the first law of thermodynamics following the procedure reported by Rizvi (1986), as

$$\frac{d[Ln(RH)]_\phi}{d(1/T)} = \frac{-Q_{in}}{R} \qquad (16)$$

where Q_{in} = net integral enthalpy (J kg^{-1})
R = gas constant of water vapor (0.462kJ kg^{-1})
ϕ = spreading pressure (J m^{-2})

A plot of Ln(RH) vs 1/T at constant spreading pressure yielded the net integral enthalpy from the slope. The spreading pressure, which is the surface excess free energy, was estimated using an analytical procedure similar to the ones described by Iglesias *et al.* (1976) and Fasina *et al.* (1999), from the relationship:

$$\phi = \frac{KT}{A_m} \int \frac{\theta \, d(RH)}{RH} \qquad (17)$$

where

$$\theta = \frac{M}{M_m} \qquad (18)$$

K = Boltzmann constant (1.380 x 10^{-23} J kg^{-1})
A_m = area of water molecule (1.06 x 10^{-19} m^2, Mazza, 1980)
M_m = monolayer moisture content (% dry basis).

The monolayer moisture content was obtained by applying the BET equation (Brunauer *et al.*, 1938) to the experimental data on equilibrium moisture relations of the material. The BET equation is stated as

$$\frac{RH}{M(1 - RH)} = \frac{1}{M_m C_2} + \frac{C_2 - 1\,(RH)}{M_m C_2} \qquad (19)$$

where C_2 is a constant.
A plot of RH/(1 – RH)M vs RH yielded a straight line with slope and intercept on the Y-axis from which M_m was

calculated.

The spreading pressure calculated using equation (17) was found to be indeterminate at the RH = 0, therefore, the lower limit employed was RH = 0.05. The computed values of spreading pressure were adjusted by adding the values corresponding to the interval RH = 0 to RH = 0.05, which was calculated by assuming that a linear relationship (Henry's law) exists between RH and è within this relative humidity range. For the interval of RH = 0 to RH = 0.05, equation (17) becomes

$$\phi = \frac{Kt\theta}{A_m} \qquad (20)$$

Integral entropy describes the degree of disorder, randomness of motion and other statistical approach related to water sorption by food products (Mazza and Le Maguer, 1978). It was determined using the integral enthalpy in the following equation:

$$S_{in} = \frac{-Q_{in}}{T} - R\ln(RH^{*}) \qquad (21)$$

where S_{in} = net integral entropy (J/kgK), and RH* = the geometric mean relative humidity obtained at constant spreading pressure.

Results and Discussion

The moisture content of palm kernel measured after each equilibrium relative humidity determination was observed to be lower than the moisture content before the determination. The difference is believed to be due to loss of moisture that accompanied the evacuation process during equilibrium relative humidity determination. Similar observation was made by Labuza (1976) and Lewicki *et al.* (1978). The moisture content after evacuation was always considered to be in equilibrium with the measured relative humidity. The experimental values of equilibrium relative humidity for palm kernel at different conditions considered were taken each as the average of two readings and are presented in Table 1. These were used to estimate the parameters in both the ERH and EMC models.

Table 2 shows the parameter estimates for the ERH models in which the ERH is taken as the dependent variable. Table 3 shows the parameter estimates for the EMC in which the EMC is taken as the dependent variable. The different analyses provide flexibility in that the user can select the model and associated parameter values that best suit the particular application. The tables also show the parameters used in comparing the models namely the standard error of estimate, the mean relative percent error; the fraction-explained variation and the nature of the residual plots. An examination of the tables indicates that the parameter estimates obtained with the ERH models were not the same as the corresponding parameter estimates obtained with the EMC models. These differences have also been noted for other crops by Duggal *et al.* (1982), Ajibola (1986a, 1986b, 1986c, and 1989) Ajibola and Adams (1986), Ajibola and Dairo (1998) and Ajibola *et al.* (2003). The EMC models were obtained by logarithmic transformations of the ERH models and in the non-linear regression analysis, the errors were assumed to be normally and independently distributed. These caused some distortions in the models, thereby causing the corresponding model constants to take on different least square values.

Using the residual plot criterion, all the models were found acceptable in predicting equilibrium relative humidity but only the Modified Henderson and Modified Chung - Pfost were found acceptable in predicting equilibrium moisture content. The Modified Henderson model was found to be the best equation for predicting the equilibrium relative humidity as it gave the lowest standard error of estimate of ERH, an acceptable mean relative percent deviation and the highest fraction explained variation. From Table 3, of the two models found acceptable, the lower standard error of estimate of EMC, the lower mean relative percent deviation and the higher fraction explained variation were obtained by using the Modified Henderson model. It was noted that though the model is the best one to predict temperature dependency in the moisture sorption isotherms of palm kernel, it is only applicable in the low relative humidity range.

The plots of Ln(Po) vs Ln(Ps) for palm kernel at various moisture levels are presented in Fig. 2. The ratio of the heat of vaporization of water in palm kernel to the heat of vaporization of saturated water was obtained from the slope of the straight line at each moisture content. The non-linear regression procedure in SPSS 9.0 for windows was used to fit equation (22) to the data obtained and relate L to the material moisture content.

$$\frac{L}{h_{fg}} = 1 + a^{*}\exp(-bM) \qquad (22)$$

The values of the coefficients 'a' and 'b' obtained were 0.5335 and 9.64 with standard errors of 0.019 and 0.386 respetively.The standard error of estimate for L/h_{fg} was 0.008.

Equations in the form of equation (22) have been used by many researchers to relate the heat of vaporization of moisture in agricultural products to their moisture content

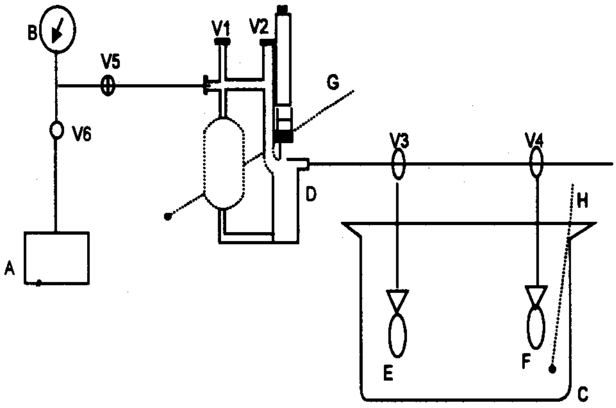

Fig. 1: Schematic diagram of the VPM apparatus A, vaccum pump, B, vaccum gaugel C, water bath; D, micromanometer; E, desiccant; F, sample flask; G, H, the momenters, V1 to V6, stop cocks.

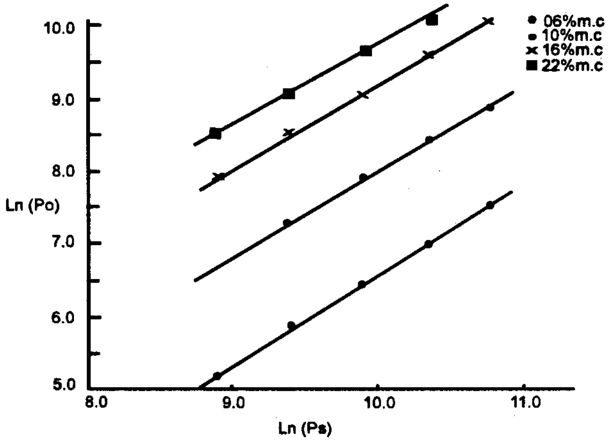

Fig. 2: Relationships between Ln (Po) and Ln (Ps) for palm kernel at various moisture contents.

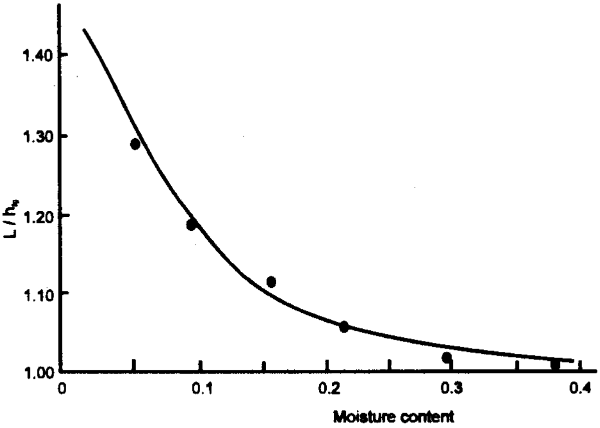

Fig. 3: Effect of moisture content on the heat of vaporization of moisture palm kernel

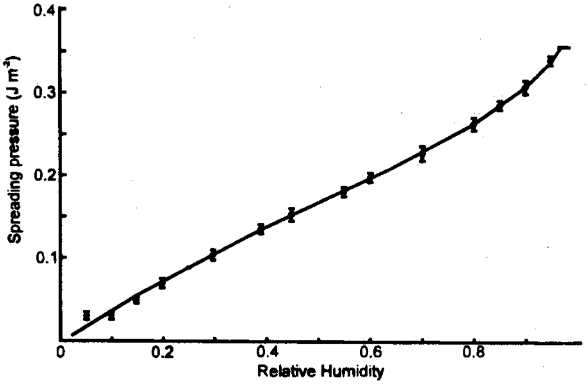

Fig. 4: Average spreading pressure isotherm of palm kernel in the temperature range of 40 to 80°C

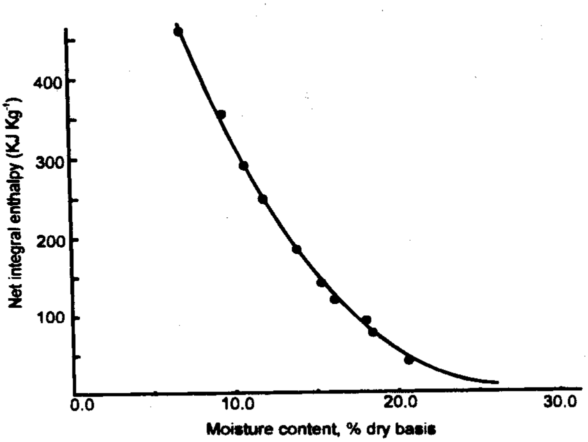

Fig. 5: Net integral enthalpy of palm kernel as a function of moisture content

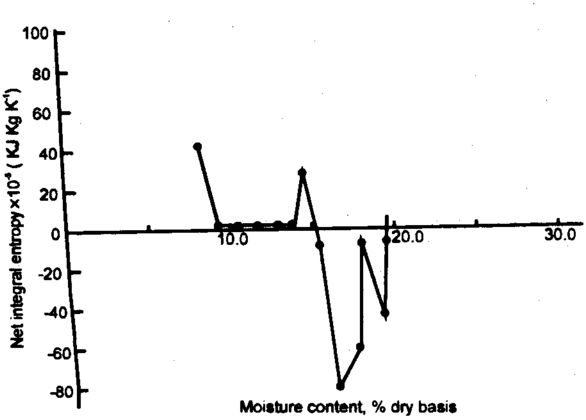

Fig. 6: Net integral entropy of palm kernel as a function of moisture content

Table 1: Observed ERH/EMC data for palm kernal

Temperature °C	ERH %	EMC %	Temperature °C	ERH %	EMC %
40	13.1	11.7	60	33.1	13.8
40	20.3	13.2	60	51.2	18.1
40	31.5	15.8	70	9.4	8.9
40	47.4	18.5	70	10.7	9.1
50	10.8	10.1	70	18.7	10.2
50	15.5	11.7	70	27.2	12.4
50	27.2	14.8	70	42.4	14.5
50	41.7	17.2	80	8.7	8.6
50	53.4	19.1	80	10.4	8.9
60	10.3	9.6	80	15.6	9.1
60	12.6	9.8	80	24.9	10.3
60	19.1	11.3	80	32.3	12.1

Table 2: Estimated parameters and comparison criteria for equilibrium relative humidity models of data for palm kernel

	Modified Henderson	Modified Chung-Pfost	Modified Halsey	Modified Oswin
A	1.82E-6	1.23E3	6.30	22.32
B	2.92	0.15	-9.72E-3	-9.2E-2
C	35.1	78.7	-2.15	0.26
S.E	4.63	5.07	6.22	4.9
F.E. V	0.984	0.981	0.971	0.982
P	14.8	14.8	14.6	11.48
Residual plot	Random	Random	Random	Random

A, B, C = Regression constants

F. E. V. = Fraction explained variation

S.E. = Standard Error

P = Mean relative percent deviation

Table 3: Estimated parameters and comparison criteria for equilibrium moisture content models of data for palm kernel

	Modified Henderson	Modified Chung-Pfost	Modified Halsey	Modified Oswin
A	8.2E-7	1.9E3	9.9	20.02
B	3.12	0.18	-1.42E -2	-6.76E-2
C	65.6	86.9	-3.46	0.21
S-E	1.06	1.27	1.78	1.30
F-E- V	0.995	0.993	0.985	0.992
P	6.3	6.6	10.6	6.8
Pesidual plot	Random	Random	Pattern	Pattern

A, B, C = Regression constants

F. E. V. = Fraction explained variation

S.E. = Standard Error

P = Mean relative percent deviation

(Cenkowski *et al.,* 1992; Fasina and Sokhansanj, 1993; Yang and Cenkowski, 1993; Fasina *et al.*, 1999; Aviara and Ajibola, 2002; Aviara *et al.*, 2002 and Ajibola *et al.*, 2003). The effect of moisture content on L/h_{fg} is shown in Fig. 3. From this figure, it can be seen that L decreased with increase in moisture content. This confirms the fact that at higher moisture levels, the strength of water binding decreases. However, L approached h_{fg} at the moisture content between 28 and 32% dry basis. Iglesias and Chirife (1976b) explained that the moisture level at which the heat of sorption approaches the heat of vaporization of water can be an indication of the point at which water exists in free form in the food product and Aviara *et al.* (2002) have denoted this point as the free water point. However, it may be noted that the presence of dissolved soluble components can cause the actual point to be masked.

The values of monolayer moisture content of palm kernel obtained from equation (19) at the temperatures of 40, 50, 60, 70 and 80°C were 10.3, 10.2, 10.1 and 10.0% dry basis, respectively. These show that the monolayer moisture content decreased only slightly with increase in temperature. There was also little effect of temperature on the values of the spreading pressure obtained using equations (17) and (20). Consequently, the spreading pressure values between the temperatures of 40°C and 80°C were averaged at any given relative humidity and the values obtained were used in further analysis. Fig. 4 shows the spreading pressure isotherm of palm kernel obtained using the average pressures.

The variation of net integral enthalpy with moisture content is shown in Figure 5. Net integral enthalpy of palm kernel was observed to decrease with increase in moisture content. The trend became asymptotic as the moisture content of about 25% (dry basis) was attained.

The variation of net integral entropy with moisture content is shown in Figure 6. Net integral entropy was positive in value and decreased with increase in moisture content till the moisture level of about 9.5% (dry basis) was reached. It remained constant within the moisture range from 9.5 to 14% (dry basis), and became negative in value from the moisture content of 15.3% (dry basis) till 20% (dry basis was approached.

Conclusion

The equilibrium moisture content of palm kernel determined using the vapour pressure manometric method increased with increase in equilibrium relative humidity and decreased with increase in temperature. 2. All the models tested, namely Modified Henderson, Modified Chung-Pfost, Modified Halsey and Modified Oswin Model were found acceptable for predicting the equilibrium relative humidity (ERH) of palm kernel. However, the Modified Henderson model, which gave the lowest standard error of estimate, an acceptable mean relative percent deviation and highest fraction explained variation was considered to be the best model for predicting the ERH of palm kernel. 3. The Modified Henderson and Modified Chung-Pfost were found acceptable for the prediction of the equilibrium moisture content (EMC). However, The Modified Henderson, which gave the lower standard error of estimate, lower mean relative percent deviation and higher fraction explained variation, was considered the best model for predicting the EMC of palm kernel, though the temperature dependence of the isotherms of the product can only be predicted more accurately at the low relative humidity range. 4. The heat of vaporization of moisture in palm kernel decreased with increase in moisture content and approached the latent heat of vaporization of pure water at a moisture content between 28 and 32% (dry basis). 5. The monolayer moisture content of palm kernel and the spreading pressure of moisture in the product were not significantly affected by temperature. 6. The net integral enthalpy decreased with increase in moisture content and the trend became asymptotic as the moisture content of 25% (dry basis) was attained, while the net integral entropy was positive in value in the moisture range of 8.6 to 15% (dry basis) and negative in value from 15.3% till the moisture content of 20% (dry basis) was approached.

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