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Modeling and simulation of freeze-drying behaviors of local cheese

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ABSTRACT

The freeze drying behaviour of local cheese was modeled using conservation laws of mass and energy balances such as Fick's law of mass transfer, Fourier's law of heat conduction and the Ideal gas equation. The three models developed and simulated are the drying rate, the moisture content and the energy balance models. Three different samples of cheese labeled A, B and C obtained from Bida, Suleja and Kontagora respectively all in Niger State of Nigeria were used to investigate the drying characteristics of local cheese. The analysis of the moisture contents showed that the moisture contents decreased with drying time and that the final moisture content at any time depends on the initial moisture content. Sample A with initial moisture content of 0.0124 kg has a final moisture content of 0.00097kg after 5 hours of drying, while samples B and C with initial moisture contents of 0.009kg and 0.0104kghave their final moisture contents of 0.00001kg and 0.00010kg respectively at the end of 5 hours. When the effect of temperature on moisture loss was studied, it was observed that the moisture loss increased as the freeze drying temperature was increased from 278 to 298K. Results also revealed that moisture loss depends on the initial moisture contents of samples. For this investigation, Samples A, Band C with initial moisture contents of 0.0124kg, 0.0138kg and 0.0104kg have moisture losses of 0.00420kg, 0.00440kg and 0.00363kg respectively at the highest freeze drying temperature of 298K. When the drying rates of samples was investigated, it was found that the drying rates decreased as the moisture contents decreased and which is also a function of the initial moisture contents of samples. The validation of the model was done by carrying out statistical precision analysis which compared the experimental results with those of the output of the models. From the results, the drying rate model showed 75 % agreement with the experimental results (i.e R^2 value of 0.75), with a standard error of $3.27X10^{-5}$ and a variance of $5.37X10^{-8}$, the moisture content model interprets about 98.44 % of the experimental results with a standard error of $7.04X10^{-4}$ and the variance of $2.79X10^{-6}$, while the energy balance model showed about 99.0 % agreement with the experimental results with a standard error of $2.16X10^{-5}$ and a variance of $3.32X10^{-7}$.

Introduction

Drying is a process during which water or other liquids are removed from a solid material to reduce the content of residual liquid to an acceptable value. In most technological processes involving conversion of raw materials to finished product, drying is usually the final step in a series of operations, and the product from a dryer is often ready for final packaging (Warren, Julius and Peter, 2005). Conventional drying methods may affect partially or totally the quality of a product (Ratti, 2001). Drying of heat-sensitive biomaterials such as fruits, vegetables, and functional foods, requires special drying methods so as to avoid degradation in quality of the end product due to thermal decomposition, oxidation, or enzymatic browning(Marques and Freire, 2005).The main qualities of food products that determine consumer acceptability are texture, color and aroma. During processing, these values may be lost or altered depending on the water content in the foods, particularly in dried foods(Marques and Freire, 2005).

The recent development in drying technology of drying is freeze drying which is a multiple operation usually performed in three stages(Nastaj and Witkiewicz, 2009).The first stage is the pre-freezing of the wet product and this is followed by primary drying when direct sublimation of the frozen solvent takes place in vacuum conditions. The final stage is the secondary drying when residual bound water is desorbed from the material matrix (Nastaj and Witkiewicz, 2009).In freeze drying, the vapor pressure driving force is very low because of low temperature of the frozen material and these results in longer drying time. High investment in freeze-drying operation can be justified by the cost saving realized by eliminating the need of continuous refrigeration for preservation of foodstuffs coupled with substantial weight reduction which is beneficial for transportation and also maintaining the original quality (Chakraborty, Saha and Bhattacharya, 2006). Despite the huge interest in freeze drying for food preservation, the technology is still not popular especially in the developing nations due to lack of proper understanding of interaction between the various parameters that influence its performance. Hence, there is need to investigate the methods of food preservation. Modeling and simulation of the preservation process is considered as the perfect route of investigating the drying behavior of food which is the purpose of this study.

Cheese is one of the dairy products with a growing consumer demand. Cheese making serves as a method of

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preserving milk or its nutritional components for human consumption (Africa and Susana, 2011). Some variety of cheese, such as fresh local cheese, has a short shelf- life due to its high moisture content of about 65 %. Because of their rapid spoilage, they do not meet food industry demands when they are needed as ingredients in some food processing (Africa and Susana, 2011;Charles, 1993).Reducing the moisture content of local cheese to a minimum value and storing it in an air-tight condition can tremendously improve its shelf-life for several months. Hence development of mathematical models that predicts the freeze drying characteristics of local cheese in a freeze dryer will aid better understanding of the drying process in the dryer. The developed models will be simulated using MathCad andthe simulated results will be compared with the experimental results for the purpose of ascertaining the conformity of the developed models with experimental data.

Materials And Methods

Materials

The raw materials (Cheese) were sourced from three different markets in Niger State Nigeria. The equipment used are: Vacuum Freeze dryer (Refrigerant 502), Vacuum pump (J D 120), Refrigerator/Freezer (HR-170 T), Electronic weighing balance (ARRW 60) and Oven (SG 97-03-243).

Methodology

Freezing

Fresh Cheesewas purchased from Bida, Minna and Kontagora in Niger State Nigeria. The cheese samples were cut into rectangular shapes of dimensions 0.035m $\times$ 0.025m $\times$ 0.02m and each sample was weighed and placed on a clean crucible. The crucible and its content was then transferred to a refrigerator freezer operating at -20^{o}C (Thermo-cool HR-170 T) for 8 hours.

Determination of Initial moisture content of frozen cheese

ThePetri dish was washed and dried in an ovum and its weight (w_1g) was determined. The frozen cheese was then placed on it. The weight of the dish and the content (w_2g) was then taken after which it was transferred to an ovum (Gallikamp SG-97-03-243) operating at 70^{o}C for 2 hours interval until a constant weight (w_3g) was achieved. The moisture content was determined using Equation (1) (Gregory, 2005).

$$\text{Moisture content} = \frac{w_3 - w_1}{w_2 - w_1} \times 100 \quad (1)$$

Determination of effect of drying temperature on the freeze drying of local cheese

At a fixed chamber pressure of 26.7N/m^2 and a fixed drying time of 1 hour, the chamber temperature was varied at 5, 10, 15, 20 and 25^{o}C. At the end of each time interval, the dried cheese was removed and weighed and the moisture removed was calculatedby subtracting the weight of dried sample from the initial weight of wet sample. The temperature that gaves the highest moisture loss was selected as the working temperature (Richardson *et al.*, 2002).

Determination of drying behavior of cheese

The frozen cheese was placed in the drying chamber of the freeze dryer (armfield, Refrigerant 502). The vacuum pump (Javac J D-120) was then switched on. The chamber pressure was set at 26.7N/m^2 and the chamber temperature maintained at 25^{o}C using the temperature control switch. The sample was allowed to dry for a period of 1 hour after which it was removed and weighed using an electronic weighing balance (Adventure ARRW 60). The moisture loss was calculated by subtracting the weight of dried sample from the initial weight of wet sample.The moisture content and drying rate were calculated using Equations (2) and (3) respectively. The experiment was continued by increasing the drying time at intervals of 1 hour for a maximum of 5 hours (Emmanuel, 2010)

$$X = \frac{M_{wi} - M_L}{S_w} \quad (2)$$

$$N = \frac{S_d\, dX}{A\, dt} \quad (3)$$

Development of mathematical models

Freeze-drying is a drying process where the solution, normally aqueous, is first frozen, thereby converting most of the water to ice, and the ice is removed by sublimation in a very high vacuum (10 to 40 N/m^2) and at a low temperature of 240 to 260K during the primary drying stage of the process (Richardson et al., 2002). Sublimation occurs at the interface between the frozen and dry material and starts at the top of the material. The interface moves through the material until only a dried porous material remains at the end of primary drying. Water vapor flows out of the material through the pores of the material and is then collected on a condenser operating at very low temperatures (-45^{o}C). The process of primary freeze drying is shown in Figure 1.

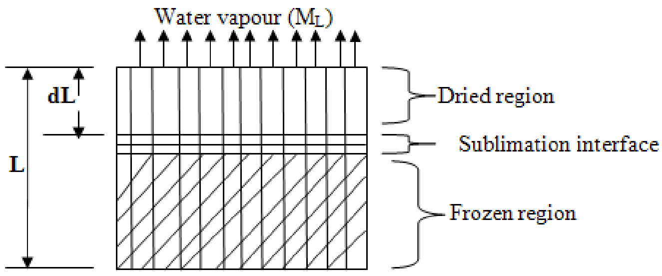

Figure 1: Schematic diagram for Primary freeze drying process

The following assumptions were made during the development of the models:

1. Fick's law of mass transfer holds for the sublimation of ice to water vapour which diffuses through the solid cheese to the condenser and the water vapour is assumed to be an ideal gas.
2. Fourier's law of heat conduction holds for the transfer of heat within the cheese through both the dried and frozen regions. Also Heat transferred to the cheese is only by conduction and radiation since the system operates at very low pressure (almost vacuum).
3. Sublimation occurs at the interface between the dried and the frozen regions whose thickness is infinitesimal.
4. The frozen region is considered to remain at temperature equal to that of the interface.
5. Only water vapour diffuses through the dried region. Inert gases dissolved are neglected. In the porous region, the solid cheese and the enclosed water vapour are in thermal equilibrium.
6. The mass and heat transfer through the sides of the solid cheese is assumed negligible, both transfers occur only at the upper part of the solid cheese while only heat transfer takes place at the lower surface in contact with the heating source.
7. The thickness of the dried layer is proportional to the fraction of moisture evaporated.
8. The mass of ice that sublimes to form vapour and residual bound moisture (M_{mix}) is directly proportional to the moisture loss by the cheese slab and inversely proportional to the final moisture content.

9. Only 5% of the heat radiated by the heating surface is absorbed at the upper part of the solid cheese.

Material balance

The equation of continuity or mass balance is (William, 1996):

$$\left\{\text{Mass flow into System}\right\} - \left\{\text{Mass flow out of system}\right\} = \left\{\begin{matrix}\text{Time rate of change of mass}\\ \text{inside the system}\\ \text{(Accumulation)}\end{matrix}\right\} \quad (4)$$

In freeze drying there is no input of moisture. Therefore Equation (4) becomes;

(Accumulation of moisture) = - (Output of moisture) (5)

$$\text{Accumulation} = \frac{dM_w}{dt} \quad (6)$$

From the first assumption, i.e Fick's law holds, hence diffusion of water vapor the through solid Cheese is(Treybal, 1981);

$$\text{(Output of moisture)} = N_{wo} = -D_{wv}\frac{dC_w}{dL} \quad (7)$$

Since water vapour is assumed to be an ideal gas, the following ideal gas equation holds (Onkar, 2009).

$$PV = nRT \quad (8)$$

and

$$\frac{n}{V} = C = \frac{P}{RT} \quad (9)$$

Substituting Equation (9) into Equation (7)

$$N_{ow} = \frac{-D_{wv}}{RT}\cdot\frac{dP}{dL} \quad (10)$$

Integrating Equation (10) to obtain

$$N_{ow}dL = \frac{-D_{wv}}{RT}\int_{P_V}^{P_C} dP \quad (11)$$

$$N_{ow}dL = \frac{-D_{wv}}{RT}(P_c - P_v) \quad (12)$$

By rearranging (12) gives:

$$N_{ow} = \frac{-D_{wv}}{RT}\frac{(P_C - P_v)}{\Delta L} \quad (13)$$

Equation (13) represents the drying rate of cheese in (moles/m^{2}s). To obtain the drying rate in kg/m^{2}s Equation (13) is multiplied by the molar mass of water MM_w(kg/moles) to give:

$$N_{ow} = \frac{-D_{wv}}{RT}\frac{(P_c - P_v)}{dL}.MM_w \quad (14)$$

Equation (14) represents the rate or mass of moisture removed in kg/m^{2}s through a thickness (dL) of the dried region.

Since (dL) could not be determined experimentally, a model can be developed to represent it. Since it was assumed that the thickness of the dried layer is proportional to the fraction of moisture evaporated, (dL) can be represented mathematically by:

$$dL = \frac{(X_i - X)}{X_i}.L \quad (15)$$

Since it has been reported that the rate of water vapour removed is proportional to the porosity of solid being dried (Chakrabortyet *al*., 2006) and also the movement of the vapour through the solid cheese dependson its viscosity and density (McCabe *et al*., 1993). Putting Equation (15) into Equation (14) and introducing the constants σ = Porosity of cheese and N_{sc}= Schimdt Number for water vapour (A function of viscosity and density of water vapour), we obtain:

$$N_{ow} = \sigma\frac{-D_{wv}}{RT}\frac{(P_c - P_v)}{\frac{(X_i - X)}{X_i}.L\,N_{sc}^{a}}.MMw \quad (16)$$

Equation (16) is the predictive model Equation for the drying rate of cheese in kg/m^{2}sia a freeze dryer.

The constant (σ) in Equation (16) which represents the porosity can be estimated from the relationshipin Equation (17)(Vasilikiet *al*., 2011).

$$\sigma = 1 - \frac{\rho_b}{\rho_t} \quad (17)$$

The Schmidt number according to McCabe *et al*(1993) is

$$Nsc = \frac{\mu}{\rho D_v} \quad (18)$$

Also the constant **(a)**in Equation (16) is a function of the pH of the moisture and the initial moisture content whose mathematical relationship is given by:

$$a = pH_w + X_i \quad (19)$$

The model also named in this study is the mathematical model equation that can be used to predict the moisture content of the dried cheese in a freeze dryer. The model can be achievedby substituting Equations (16) and (6)into Equation (5);

$$\frac{dM_w}{dt} = \sigma\frac{D_{wv}}{RT}\frac{(P_c - P_v)}{\frac{(X_i - X)}{X_i}.L\,N_{sc}^{a}}.MMw \quad (20)$$

On integrating Equation (20) we have:

$$\int_{M_{w2}}^{M_{w1}} dM_w = \sigma\frac{D_{wv}}{RT}\frac{(P_c - P_v)}{\frac{(X_i - X)}{X_i}.L\,N_{sc}^{a}}.MMw\int_0^t dt \quad (21)$$

$$M_{w1} - M_{w2} = \sigma\frac{D_{wv}}{RT}\frac{(P_c - P_v)}{\frac{(X_i - X)}{X_i}.L\,N_{sc}^{a}}MM_w.t \quad (22)$$

Since the right hand side of Equation (22) is in kg/m^2, multiplying it by the surface area of the dried cheese (A) in m^2 and simplifying we get;

$$M_{w2} = M_{w1} - \underbrace{\sigma\frac{D_{wv}}{RT}\frac{(P_c - P_v)}{\frac{(X_i - X)}{X_i}.L\,N_{sc}^{a}}MM_w.A.t} \quad (23)$$

Amount of moisture removed in (kg) at any time (t)

Substituting Equation (16) intoEquation(23)

$$M_{w2} = M_{w1} - N_{ow}.A.t \quad (24)$$

Equation (24), represents the predictive model for the moisture content of the dried solid in (kg) at any time (t) during freeze drying.

Heat transfer

Figure 2 represents the heat transfer during the freeze drying of local cheese. Since in freeze drying, drying is carried out at a very low pressure (26.7 N/m^2), it is assumed that no heat is transferred by convection but only by radiation at the upper surface of the slab. Also, heat transfer is by conduction at the lower surface of the slab in contact with the heating source as shown in Figure 2:

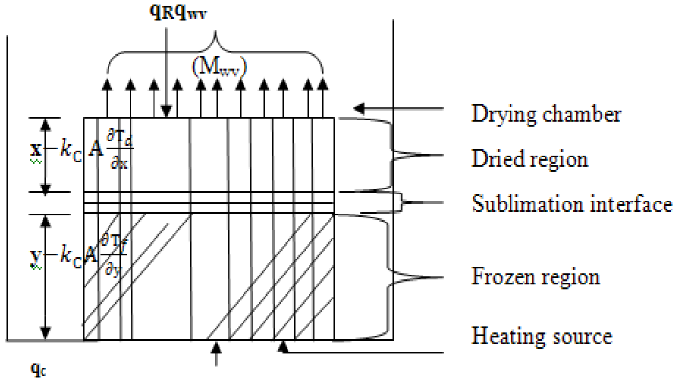

Figure 2. Schematic diagram of Heat transfer in freeze drying of cheese

Considering Figure 2, heat radiated(q_R) is transferred by radiation to the dried surface and subsequently conducted through the dried region to the sublimation front. Heatsupplied by water vapour (q_{wv}) is transferred to the drying chamber by the water vapour escaping from the dried region due to sublimation of ice at the sublimation front. The last component of heat, which is the conductive heat(q_C) from the heating source is transferred by conduction through the frozen region to the sublimation front.

Energy balance

Assuming no heat is generated within the system represented in Figure 2, the energy balance on the system (slab of cheese) according to Eduardo (2010) and Onkar (2009) is;

{Input of heat by Conduction and Radiation} - {Output of heat by water vapourthe cheese} = {Heat accumulated within} (25)

Heat accumulated within cheese slap is given by:

$$(q_C + q_R) - q_{wv} = \frac{dq}{dt} \quad (26)$$

Heat conducted through the surface in contact with heating source into the frozen region is given by:

$$q_c = -k_C\, A \frac{\partial T_f}{\partial y} \quad (27)$$

Heat radiated to the dried surface from the Drying chamber and conducted through the dried region is:

$$q_R = -k_C\, A \frac{\partial T_d}{\partial x} \quad (28)$$

Heat transferred to the drying chamber by water vapour is given by:

$$q_{wv} = M_{mix} Cp_{wv} \frac{\partial T_d}{\partial t} \quad (29)$$

Since it was assumed that M_{mix}, that is the mass of ice that sublimes to form vapour and residual bound moisture is directly proportional to the moisture loss by the cheese and inversely proportional to the final moisture content, then M_{mix}can be mathematically expressed by the relationship shown in equation (30):

$$M_{mix} \alpha \frac{M_L}{X} \quad (30)$$

Since the porosity (σ) is a factor that determines the amount of moisture removed from the dried Cheese, porosity is then introduced into Equation (30) as constant of proportional ityand Equation (30) becomes;

$$M_{mix} = \sigma \frac{M_L}{X} \quad (31)$$

Substituting Equation (31) into Equation (29) gives:

$$q_{wv} = \sigma \frac{M_L}{X} Cp_{wv} \frac{\partial T_d}{\partial t} \quad (32)$$

By substituting Equations(27), (28) and (32) into Equation (26), an expression for the change in heat content of the cheese dried with freeze dryer is obtained as:

$$\frac{dq}{dt} = -k_C\, A\left(\frac{\partial T_d}{\partial x} + \frac{\partial T_f}{\partial y}\right) - \sigma \frac{M_L}{X} Cp_{wv} \frac{\partial T_d}{\partial t} \quad (33)$$

Equation (33) represents the predictive model for the accumulation of heat or the heat content of the cheese.

Energy balance on the dried surface is given by:

Input of heatby radiation to the dried surface = output of heat by water vapour from the dried surface

$$q_R = \sigma \frac{M_L}{X} Cp_{wv} \frac{\partial T_d}{\partial t} \quad (34)$$

In terms of radiating heat transfer coefficient (h_R), the heat radiated (q_R) in Equation (32) is given by;

$$q_R = h_R(T_R - T_d)Af_R \quad (35)$$

Substituting Equation (35) into Equation(34) gives;

$$h_R(T_R - T_d)Af_R = \sigma \frac{M_L}{X} Cp_{wv} \frac{\partial T_d}{\partial t} \quad (36)$$

Rearranging Equation (36) to obtain;

$$\frac{\partial T_d}{\partial t} = \frac{h_R(T_R - T_d)A\, f_R X}{\sigma M_L Cp_{wv}} \quad (37)$$

Model equation (37) can be used to predict the moisture loss(M_L)by the cheese at any given drying time (t).

Notation

N_{ow} = Rate of water removed in kg/m^{2}s.
σ = Porosity of the solid being dried.
D_{WV} = Diffusivity of water vapour in m^2/s.
P_V = Vapour pressure of water in N/m^2.
P_C = Chamber pressure in N/m^2.
R = Universal gas constant (8.314 J/moles K).
T = Temperature of water Vapour in Kelvin (K).
MM_w = Molar mass of water in (kg/moles).
X_i = Initial moisture content of frozen solid (cheese) (%)
X = Final moisture content of dried solid (cheese) (%)
N_{sc}= Schimdt Number for water vapour
(a) = constant depending on dried material
ρ_b = Bulk density of cheese (kg/m^3)
ρ_t = True density of cheese (kg/m^3)

μ = Viscosity of water vapour
ρ = Density of water vapour (kg/m^3)
D_v = Volumetric diffusivity of water vapour (m^2/s)
pH_w = pH of pure water
M_{w1} = Initial moisture content in (kg)
M_{w2} = Final moisture content in (kg)
N_{ow} = Drying rate in kg/m^2s
A = Cross-sectional area of dried solid in (m^2)
t = Time of drying in seconds (s)
h_R = Radiation heat transfer coefficient ($w/m^2.K$)
T_d = Temperature of dried region (K)
T_f = Temperature of frozen region (K)
K_c = Thermal conductivity of cheese (J/m s .K)
A = cross sectional area of cheese (m^2)
M_{mix}= Mass of ice that sublimes to form vapour and residual bound moisture (kg)
M_L = Moisture loss (kg)
Cp_{wv} = Specific heat capacity of water vapour (J/kg.K)
∂x = Change in thickness of dried region (m)
∂y = Change in thickness of frozen region (m)
f_R = Fraction of the radiated heat absorbed by the surface of the cheese (%)
w_1= Initial weight of the empty dish (g)
w_2 = Weight of dish + frozen cheese before drying (g)
w_3 = Final of weight dish + frozen cheese after drying (g)
S_d= Mass of dry solid cheese (kg)
S_d= Mass of wet solid cheese (kg)
dX = Change in moisture content of cheese (%)
dt = Change in time of drying (s)

Results And Discussion

Moisture contents

The results of the experimental and simulated moisture contents were plotted against drying time as shown in Figure 1 for Samples A, B and C. As can be seen from the figure, the moisture contents decreased with time and as could be expected during the initial stage of drying, there was a rapid moisture removal from the product which later slowed down with drying time. This was as a result of high concentration of moisture within the cheese at the initial stage of the drying operation which decreases with increase in drying time. This was also reported by Boughali*et al* (2009).

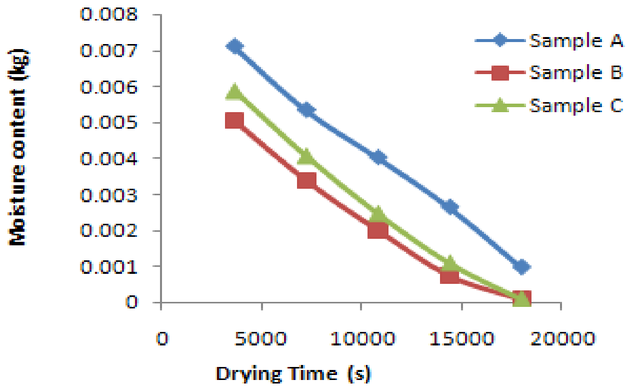

Figure 1: Experimental moisture contents Vs time for Samples A, B and C.

When the moisture content model was simulated, the results obtained were used to plot simulated moisture contents against time on the same axis with the experimental moisture contents as presented in Figures 2, 3 and 4 for samples A, B and C. Results as presented indicate that the curves have the same shapes with those of the experimental results but with higher values of moisture contents when compared with their corresponding experimental values.

This is because the experimental drying rates are greater than their corresponding simulated drying rates predicted by the drying rate model. This difference is due to the fact that only 74.64 % of the experimental results were captured by the drying rate model.

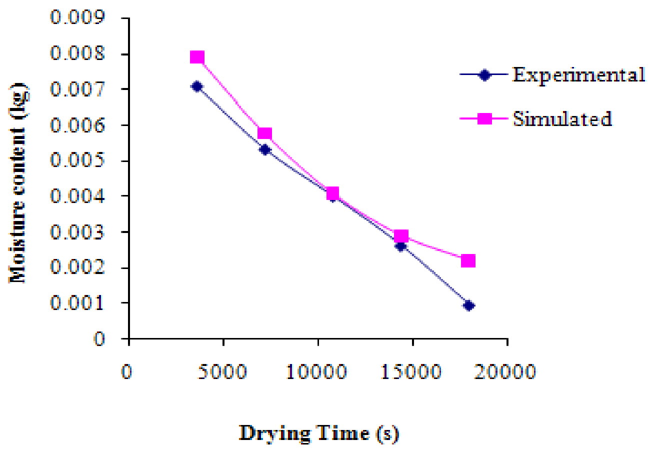

Figure 2: Experimental and simulated moisture content Vs time for sample A

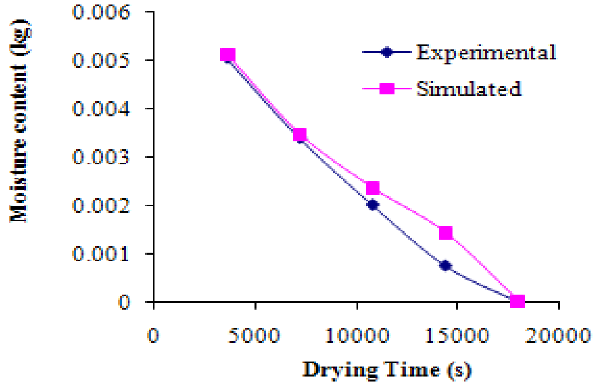

Figure 3: Experimental and simulated moisture content Vs time for sample B

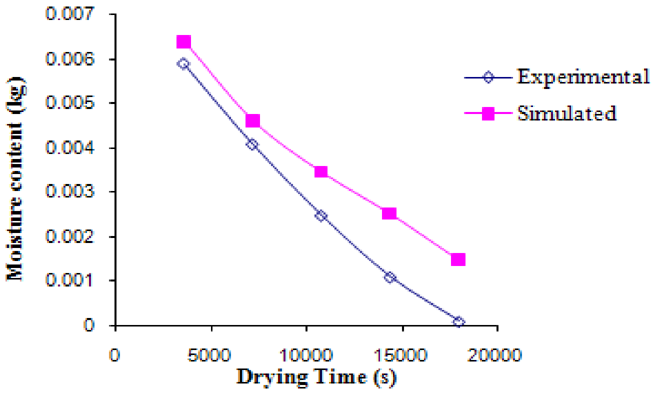

Figure 4: Experimental and simulated moisture content Vs time for sample C

The validity of the moisture content model was revealed by the result of statistical analyses results presented in Table 1. The average correlation coefficient, the R- square, variance and standard error values are 96.81 %, 98.44 %, $2.79X10^{-6}$ and $2.34X10^{-4}$ respectively. The high values of average correlation coefficient and R- square denote high response of the model in predicting the experimental results and the low values of the variance and standard error also reveal that the model is accurate.

Moisture loss

The effect of freeze drying temperature on the moisture loss was investigated in order to determine the working temperature for freeze drying of cheese. Figure 5 represents the curves of the plots of experimental moisture losses against freeze drying temperatures for samples A, B and C with initial moisture contents of 0.62, 0.69 and 0.52respectively.The variation in the initial moisture contents of the samples can be attributed to the haphazard nature of production of local cheese where the boiling temperature and time are not regulated. The variation can also be due to the composition of the raw milk used in producing the cheese. In all the three samples, moisture removal increase as the freeze drying temperature was increased. These results are similar to the findings of Junling*et al*, (2008) where drying blueberries using infrared radiation heating was studied. When the moisture losses of the three Samples were compared, it was observed that the greater the initial moisture content, the greater the moisture loss. At the highest freeze drying temperature of 298K, sample B with the initial moisture content of 0.69 has the highest moisture loss of 0.0044kg followed by sample A with initial moisture content of 0.62 and a moisture loss of 0.0042kg and lastly sample C with initial moisture content of 0.52 and a moisture loss of 0.00363kg. This implies that the variation in the moisture loss of the samples is as a result of the variation in the initial concentration of moisture in the wet samples.

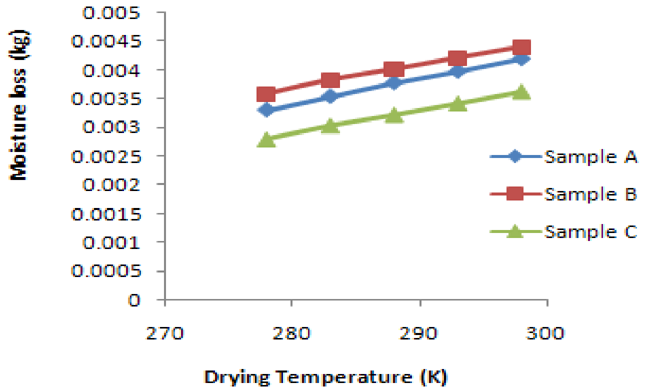

Figure 5: Experimental moisture contents Vs time for samples A, B and C

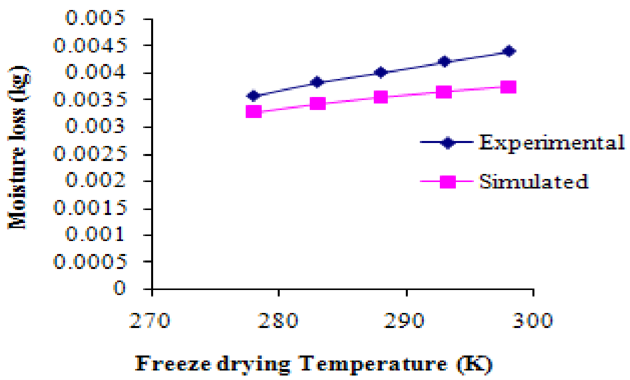

Figure 6. Simulated and Experimental Moisture loss versus freeze drying temperature for sample A

When the energy balance model was simulated, the simulated results obtained were used to plot the simulated moisture losses against freeze drying temperatures for samples A, B, and C. Figures 6, 7 and 8 compared the experimental to the simulated moisture losses against freeze drying temperatures for samples A, B and C respectively. In all the three cases, the values of the simulated results are lower than those of the experimental results. The results of the statistical analysis performed to check the validity of the energy balance model is shown in Table 1. The average correlation coefficient value obtained was 99.5%, which is quite high suggesting that the relationship between the predictors and response variables is linear. The average R-Square value of 99.0% implies that only 99.0% of the variability in the output could be captured and explained by this model. The results also revealed that the average variance and standard error in the model equation are $3.32X10^{-7}$ and $2.16X10^{-5}$.The low values of the variance and standard error show that the mathematical model is satisfactory.

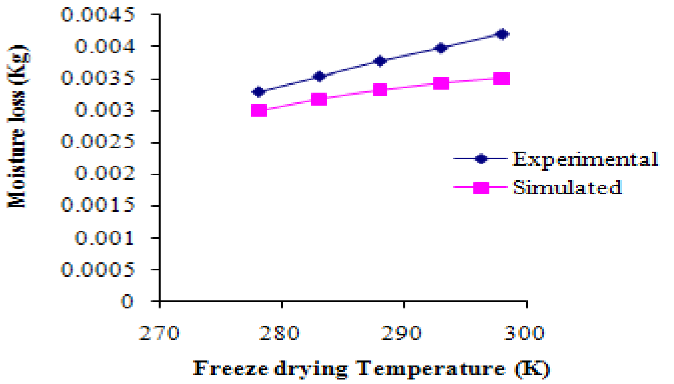

Figure 7. Simulated and Experimental Moisture loss versus freeze drying temperature for Sample B

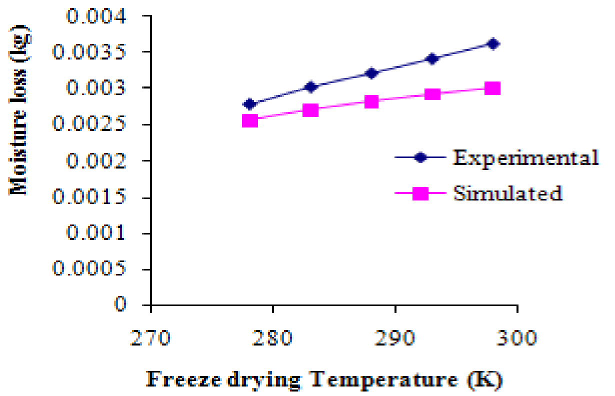

Figure 8. Simulated and Experimental Moisture loss versus freeze drying temperature for Sample C

Drying rates

The relationship of the experimental and simulated drying rates with moisture contents for sample A, B, and C with initial moisture contents of 0.62, 0.45 and 0.52 are presented in Figures 9, 10 and 11 respectively. The results show that the drying rates decrease with moisture contents in all the three samples. This is attributed to decrease in concentration of water with time due to moisture loss during freeze drying. This is in agreement with the literature on the study of freezedrying behaviours of apple where the drying rates decreased as the moisture content also decreased according to Tayfun*et al*.(2010). It can also be deduced from these results that the higher the initial moisture contents in sample the greater the drying rates. After the drying time of one hour, the drying rate of sample A with initial moisture content of 0.62 was $1.67X10^{-3}$ kg/m^2s, while that of sample B with initial moisture content of 0.45 is $1.25X10^{-3}$ kg/m^2s and that of sample C with initial moisture content of 0.52 has a drying rate of $1.432X10^{-3}$ kg/m^2s.At the end of drying time of 5 hours, samples B and C were completely dried with no moisture content, while sample A has residual moisture content of 0.05 due to its higher initial moisture content of 0.62. It was equally observed from the drying rate curves of the three samples under test that the drying rates took place only in the falling rate period and no constant rate period was observed.

Table 1: Summary of Statistical analyses results for comparing experimental to the simulated results for the developed models

	Model		
	Drying Rate	Moisture content	Energy balance
Correlation Coefficient	0.8273	0.9681	0.995
Adjusted Correlation Coefficient (R^2)	0.7464	0.9844	0.990
Standard Error	$3.27X10^{-5}$	$7.04X10^{-4}$	$2.16X10^{-5}$
Standard Deviation	$3.04X10^{-4}$	$2.34X10^{-4}$	$3.32X10^{-4}$
Variance	$5.37X10^{-8}$	$2.79X10^{-6}$	$3.32X10^{-7}$

This is because freeze drying is an unsteady state operation. This is in conformity with the work of Boughali*et al.*, (2009), Akanbi*et al.*, (2006) and Hawlader*et al.*, (1991).

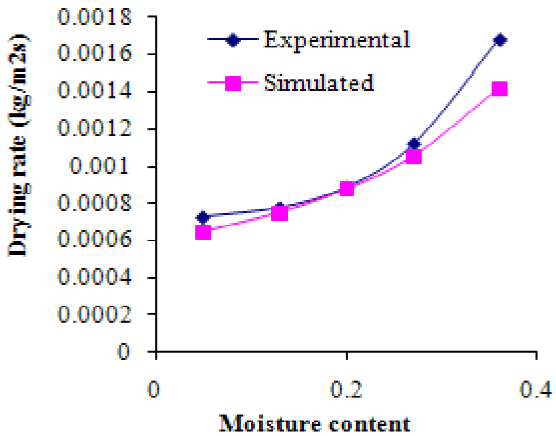

Figure 9: Experimental and Simulated drying rate Vs Moisture content for sample A

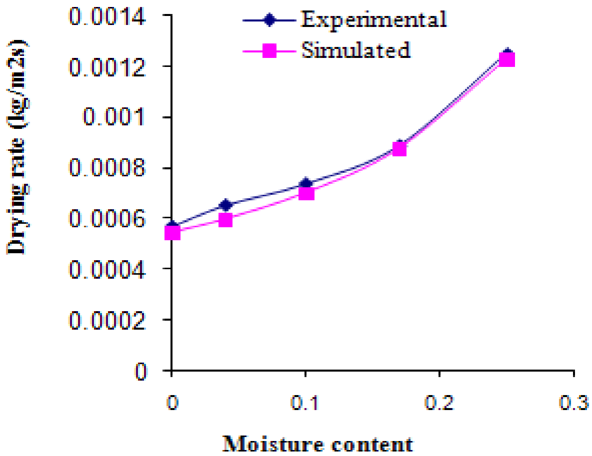

Figure 10: Experimental and Simulated drying rate Vs Moisture content for sample B

When the curves of the experimental and the simulated results were compared, the results of the simulated drying rates follow the same trend with that of the experimental but with lower values of drying rates being recorded. From the results in Table 1, the statistical analysis carried out showed that, the average correlation coefficient and the average R-square value are 82.73 % and 74.64 % respectively.

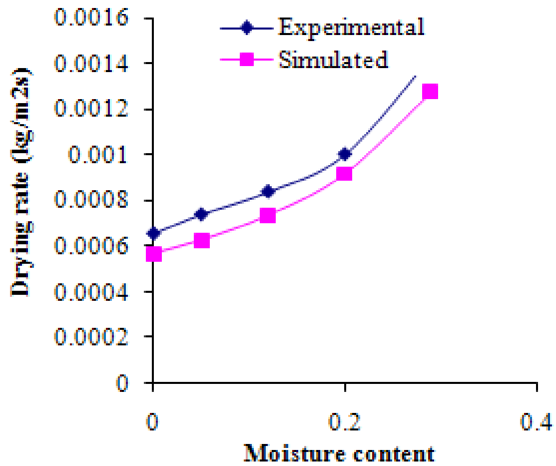

Figure 11: Experimental and Simulated drying rate Vs Moisture content for sample C

These high values reveal that there is strong relationship between the experimental and the predicted results by the drying rate model. The low average values of the variance and the standard error of $5.37X10^{-8}$ and $3.27X10^{-5}$ indicates the validity of the model.

Conclusion

The freeze drying behavior of local cheese in a freeze dryer was investigated and the process was modeled using conservation law of mass and energy balances. Three important models were developed and simulated using mathCad. These models include: The drying rate model, the moisture content model and the energy balance model. From the results of the validation of the models, the drying rate model showed about 75% agreement with the experimental results with variance and the standard error of $5.37X10^{-8}$ and $3.27X\ 10^{-5}$, while the moisture content model showed about 98% agreement with the experimental results with variance and standard error of $2.70X10^{-6}$ and $7.04X10^{-4}$respectively.The energy balance model interprets about 99 % of the experimental results with values of Variance and standard error of $3.32X10^{-7}$ and $2.16X10^{-5}$ respectively. With these results, the models can be said to be of high accuracy. The experimental and simulated results also revealed that drying rates decrease as the moisture contents decrease and took place during the falling rate period. The moisture contents decreased as the drying time increased, the moisture losses also increased as the drying temperature increased and all these are functions of the initial moisture contents of samples.

References

ÁfricaC, and Susana S. (2011). Heat pump drying kinetics of a pressed type Cheese: *LWT - Food Science and Technology* **44**, 489-494.

Akanbi, T., Remi, C., Sikiru, A. and Ademola, D.(2006). Drying characteristics and sorption isotherm of tomato slice: *Journal of Food Engineering***73**, 157–163.

Boughali, S, Benmousa, H, Bouchekima, B, Mennouche, D, Bouguettaia, H and Becki, D. (2009). Crop drying by indirect active hybrid solar- Electrical dryer in the eastern Algerian Septemtrional Sahara: *Journal of solar energy*, **83**, 2223- 2232,

Chakraborty R., Saha A.K. and Bhattacharya P. (2006). Modeling and simulation of parametric sensitivity in primary freeze-drying of foodstuffs, *Journal of Separation And Purification Technology*, **49**, 258–263.

Charles, C.O. (1993). *Traditional cheese making manual*, Addis Abbaba: international livestock centre for Africa.

Eduardo, C. (2010). *Heat transfer in process engineering*. New York, U.S.A: McGraw-Hill company incorporation.

Emmanuel C.N. (2000). *Performance evaluation of a laboratory freeze dryer*. A project submitted for the award of National Diploma in chemical Engineering at Federal polytechnic Bida.

Gregory I.O. (2005). *Food Analysis and instrumentation theory and practice*: first edition, Lagos: HG Support Nigeria Limited.

Hawlader, M.N.A., Uddin, M.S., HO, J.C., and Teng, A.B.W., (1991). Drying characteristics of Tomatoes. *Journal of Food Engineering*,**14**, 259–268.

Junling S., Zhongli P., Tara H. M., Delilah W., Edward H. and Don O.(2008). Drying and quality characteristics of fresh and sugar infused blueberries dried with infrared radiation heating. *LWT-Food and Science Technology*, **14**, 1962-1972.

Marques, L. G. and Freire, J. T. (2005).Analysis of freeze-drying of tropical fruits, *Journal of drying* Technology, **23**, 2169–2184.

McCabe W.L., Julian, C.S. and Peter, H. (1993).*Unit Operation of Chemical Engineering*, fifth edition, Singapore: McGraw-Hill Incorporation.

Nastaj J.F and Witkiewicz K. (2009). Mathematical modeling of the primary and secondary vacuum freeze drying of random solids at microwave heating: *International Journal of Heat and Mass Transfer*,**52**, 4796–4806.

Onkar, S. (2009).*Applied Thermodynamics*, third edition, New delhi: New age International (P) Limited.

Ratti, C.(2001). Hot air and freeze drying of high value foods: Journal of food engineering 49, 311–319.

RicardsonJ.F,Harker J.H. and Backhust J.R. (2002). *Chemical Engineering Volume 2*: Fifth Edition, Oxford: Butterworth Heinemann.

Tayfun M, Mustafa B. O. and Volkan K. (2010). Determination of freeze-drying behaviors of apples by artificial neural network: *Expert Systems with Applications*, **37**, 7669–7677.

Treybal, R.E (1981). *Mass transfer operations*, Mc-Graw-Hill Book Company, Singapore.

Vasiliki, P.O., Magdalini, K. K. &Vaios, T. K. (2011). Structural properties of freeze-dried rice. *J. Food Engineering*: **107**, 326–333.

Warren L.M., Julius C.S. and Peter H.(2005). *Unit Operations Of Chemical Engineering*. Seventh edition, New York: Mc-Graw-Hill Companies Incorporation.

William L.L.(1996). *Process modeling, Simulation and control for chemical Engineers*. Second edition, New York: McGraw-hill publishing company.