Model for Computational Analysis of the Quantity of Water Evaporated during Initial Stage Drying of Wet Clay Designated for Production of Spark Plug Ceramic Component

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Abstract: A model has been derived for computational analysis of the quantity of water evaporated during initial drying of wet clay (designated for production of the ceramic component of spark plug). The drying process was carried out at the temperature range: 80-95^{0}C. The model;

$$\beta = \text{Antilog}[(0.9524 \text{ Log}(833/T)]$$

indicates that the quantity of evaporated water during the drying process is dependent on the drying temperature, the evaporating surface being constant. It was found that the validity of the model is rooted on the expression N Logβ = Log (A/T) where both sides of the expression are correspondingly approximately equal to 1. The maximum deviation of the model-predicted quantity of evaporated water from the corresponding experimental value is less than 11% which is quite within the acceptable deviation range of experimental results. It was observed that above 80^{0}C, both quantities of evaporated water as obtained from experiment and derived model show proximate agreement; both decreasing with increase in the drying temperature. Water evaporation per unit rise in the drying temperature evaluated from experimental and model-predicted results are -0.16 and -0.10g/^{0}C respectively, indicating proximate agreement. [Academia Arena, 2010;2(6):48-53] (ISSN 1553-992X).

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1. Introduction

Reed (1988) described firing as having three stages through which it proceeds; preliminary reactions which include binder burnout, elimination of gaseous product of decomposition and oxidation, sintering as well as cooling which may include thermal and chemical annealing.

Several works (Reed, 1988; Barsoum, 1997; Viewey and Larrly, 1978; Keey, 1978) have been carried out on shrinkage of clay during drying. In all these works, porosity has been shown to influence the swelling and shrinkage behaviour of clay products of different geometry. Past report (Reed, 1988) shows that drying occurs in three stages; increasing rate, constant and decreasing rate. The report pointed out that during the increasing rate; evaporation rate is high compared with evaporating surface hence more water is lost. At constant rate, the evaporation rate and evaporation surface are constant. The researcher posited that shrinkage occurs at this stage. Keey (1978) also in a similar study suggested that at this stage, free water is removed between the particles, and the inter-particle separation decreases, resulting in shrinkage. During the decreasing rate, particles make contacts as water is removed, which causes shrinkage to cease.

Model for calculating the volume shrinkage resulting from the initial air-drying of wet clay has been derived (Nwoye, 2008). The model;

$$\theta = \gamma^3 - 3\gamma^2 + 3\gamma \qquad (1)$$

calculates the volume shrinkage θ when the value of dried shrinkage γ, experienced during air-drying of wet clays is known. The model was found to be third-order polynomial in nature. Olokoro clay was found to have the highest shrinkage during the air drying condition, followed by Ukpor clay while Otamiri clay has the lowest shrinkage. Volume shrinkage was discovered to increase with increase in dried shrinkage until maximum volume shrinkage was reached, hence a direct relationship.

Nwoye et al. (2008) derived a model for the evaluation of overall volume shrinkage in molded clay products (from initial air-drying stage to completion of firing at a temperature of 1200^{0}C). It was observed that the overall volume shrinkage values predicted by the model were in agreement with those calculated using conventional equations. The model;

$$S_T = \alpha^3 + \gamma^3 - 3(\alpha^2 + \gamma^2) + 3(\alpha + \gamma) \qquad (2)$$

depends on direct values of the dried γ and fired shrinkage α for its precision. Overall volume shrinkage was found to increase with increase in dried and fired shrinkages until overall volume shrinkage reaches maximum.

Nwoye (2009a) derived a model for calculating the quantity of water lost by evaporation during oven drying of clay at 90^0C. The model;

$$\gamma = \exp[(\ln t)^{1.0638} - 2.9206] \qquad (3)$$

indicated that the quantity of evaporated water γ, during the drying process is dependent on the drying time t, the evaporating surface being constant. The validity of the model was found to be rooted in the expression $(\text{Log}\beta + \ln\gamma)^N = \ln t$.

Model for predictive analysis of the quantity of water evaporated during the primary-stage processing of a bioceramic material sourced from kaolin has been derived by Nwoye et al. (2009a).

The model;

$$\alpha = e^{(\ln t/2.1992)} \qquad (4)$$

shows that the quantity of water α, evaporated at 110^0C, during the drying process is also dependent on the drying time t, where the evaporating surface is constant. It was found that the validity of the model is rooted on the expression $(\ln t/\ln\alpha)^N = \text{Log}\beta$ where both sides of the expression are correspondingly approximately equal to 3. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value was found to be less than 22% which is quite within the acceptable deviation range of experimental results.

Model for quantifying the extent and magnitude of water evaporated during time dependent drying of clay has been derived (Nwoye, 2009b). The model;

$$\gamma = \exp((\ln t/2.9206)^{1.4}) \qquad (5)$$

indicates that the quantity of evaporated water γ during the drying process (at 90^0C) is dependent on the drying time, t the evaporating surface being constant. It was found that the validity of the model is rooted in the expression $\ln\gamma = (\ln t/\text{Log}\beta)^N$ where both sides of the expression are correspondingly almost equal.

A model was derived (Nwoye, 2009b) for predicting the quantity of water evaporated during initial stage drying of wet clay designated for production of bricks. The drying process was carried out at a temperature range 80-110^0C. The model;

$$E = \exp[0.3424(\text{Log}T)^{2.3529}] \qquad (6)$$

indicates that the quantity of evaporated water during the drying process is dependent on the drying temperature, the evaporating surface being constant. The validity of the model is rooted in the expression $(\ln E \times \text{Log } \beta)^N = \text{Log } T$ since both sides of the expression are correspondingly approximately equal to 2. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value is less than 20% which is quite within the acceptable deviation range of experimental results, hence depicting the usefulness of the model. Water evaporation per unit rise in the drying temperature evaluated from experimental and model-predicted results are 0.078 and 0.0502g/^{0}C respectively, indicating proximate agreement.

The present work is to derive a model for computing the quantity of water lost by evaporation during initial stage drying of wet Nsu (Nigeria) clay at a temperature range; 80-95^0C. The clay is designated for production of the ceramic component of a spark plug.

2. Model formulation

Experimental data obtained from research work (Nwoye,2007) carried out at SynchroWell Research Laboratory, Enugu were used for this work. Results of the experiment used for the model formulation are as shown in Table1.Computational analysis of the experimental data (Nwoye, 2007) shown in Table 1, gave rise to Table 2 which indicate that;

$$N \text{ Log}\beta = \text{Log}\left(\frac{A}{T}\right) \text{ approximately)} \qquad (7)$$

$$\text{Log } \beta = \text{Log}\left(\frac{\left(\frac{A}{T}\right)}{N}\right) \qquad (8)$$

Introducing the values of A and N into equation (8)

$$\text{Log } \beta = \text{Log}\left(\frac{\left(\frac{833}{T}\right)}{1.05}\right) \qquad (9)$$

$$\text{Log } \beta = \left(0.9524 \text{ Log}\left(\frac{833}{T}\right)\right) \qquad (10)$$

$$\beta = \text{Antilog}\left(0.9524 \text{ Log}\left(\frac{833}{T}\right)\right) \qquad (11)$$

Where

(β) = Weight of water evaporated during the drying process (g)

A = Area of evaporating surface (mm^2)

N = 1.05(Collapsibility coefficient of binder-clay particle boundary at the drying temperature range ;80-95^{0}C) determined in the experiment (Nwoye, 2007).

(T) = Drying temperature (^{0}C).

Table 1: Variation of quantity of evaporated water with drying temperature. (Nwoye, 2007)

(T)	A	(β)
80	833	9.60
85	833	8.80
88	833	8.35
90	833	8.01
95	833	7.98

3. Boundary and Initial Conditions

Consider a rectangular shaped clay product of length 49mm, width 17mm, and breadth 9mm exposed to drying in the furnace while it was in wet condition. Initially, atmospheric levels of oxygen are assumed. Atmospheric pressure was assumed to be acting on the clay samples during the drying process (since the furnace is not air-tight). The grain size of clay particles used is 425µm, weight of clay and binder (bentonite) used (for each rectangular product); 100g and 10g respectively, quantity of water used for mixing; 2% (of total weight), range of drying temperature used; 80-95^{0}C, area of evaporating surface;833mm^2 and drying time used; 130 minutes.

The boundary conditions are: atmospheric levels of oxygen at the top and bottom of the clay samples since they are dried under the atmospheric condition. No external force due to compression or tension was applied to the drying clays. The sides of the particles and the rectangular shaped clay products are taken to be symmetries.

4. Model Validation

The formulated model was validated by direct analysis and comparison of the model-predicted β values and those from the experiment for equality or near equality.

Analysis and comparison between these β values reveal deviations of model-predicted β from those of the experimental values. This is believed to be due to the fact that the surface properties of the clay and the physiochemical interactions between the clay and binder, which were found to have played vital role during the evaporation process (Nwoye, 2007) were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted β value to that of the corresponding experimental value.

Deviation (Dv) (%) of model-predicted β values from the experimental β values is given by

$$Dv = \left(\frac{Pw - Ew}{Ew} \right) x\ 100 \qquad (12)$$

Where

Pw = Quantity of water evaporated as predicted by model (g)

Ew = Quantity of water evaporated as obtained from experiment (g) (Nwoye,2007)

Correction factor (Cf) is the negative of the deviation i.e

$$Cf = -Dv \qquad (13)$$

Therefore

$$Cf = -100 \left(\frac{Pw - Ew}{Ew} \right) \qquad (14)$$

Introduction of the value of Cf from equation (14) into the model gives exactly the corresponding experimental value of β (Nwoye, 2007).

5. Results and Discussion

The derived model is equation (11). Computational analysis of the experimental data (Nwoye, 2007) shown in Table 1, gave rise to Table 2

Table 2: Variation of NLogE with Log (A/T)

NLogE	Log (A/T)
1.0314	1.0176
0.9917	0.9912
0.9678	0.9762
0.9488	0.9664
0.9471	0.9429

5.1 Evaporation per unit rise in drying temperature

Water evaporated per unit rise in temperature resulting from drying of the clay at a temperature range 80-95^{0}C was determined following comparison of the evaporation per unit rise in temperature obtained by calculations involving experimental results, and model-predicted results obtained directly from the model.

Evaporation per unit rise in the drying temperature, E_d (g /^{0}C) was calculated from the equation;

$$E_d = E/T \qquad (15)$$

Therefore, a plot of mass of water evaporated E against drying temperature T, as in Fig. 1 using experimental results in Table 1, gives a slope, S at points (9.60, 80) and (8.01, 90) following their substitution into the mathematical expression;

$$S = \Delta E/\Delta T \qquad (16)$$

Equation (16) is detailed as

$$S = E_2 - E_1/ T_2 - T_1 \qquad (17)$$

Where

ΔE = Change in the quantities of water evaporated E_2, E_1 at two drying temperature values T_2, T_1. Considering the points (9.60, 80) and (8.01, 90) for (E_1, T_1) and (E_2, T_2) respectively, and substituting them into equation (17), gives a negative slope: - 0.16 g/^{0}C which is the quantity of water evaporated per unit rise in the drying temperature during the actual experimental drying process. Also similar plot (as in Figure 2) using model-predicted results gives a slope. Considering points (9.3146, 80) and (8.3253, 90) for (E_1, T_1) and (E_2, T_2) respectively and substituting them into equation (17) also gives a negative slope, S as - 0.10 g/^{0}C. This is the model-predicted quantity of water evaporated per unit rise in the drying temperature during the drying of the clay. A comparison of these two quantities of water evaporated per unit rise in the drying temperature shows proximate agreement. This indicates a very high degree of validity for the model as a reliable tool for computational analysis of the quantity of water evaporated as well as the evaporation per unit rise in the drying temperature during drying of Nsu clay at a temperature range 80-95^{0}C.

An ideal comparison of the quantities of water evaporated per unit rise in the drying temperature as obtained from experiment and as predicted by the model for the purpose of testing the validity of the model is achieved by considering the R^2 values. The values of the correlation coefficient, R calculated from the equation;

$$R = \sqrt{R^2} \qquad (18)$$

using the r-squared values (coefficient of determination) from Figures.1 and 2 show a better correlation (0.9984) with model-predicted quantity of water evaporated per unit rise in the drying temperature than that obtained from experiment (0.9419). This suggests that the model predicts more accurate, reliable and ideal quantity of evaporated water than the actual experiment despite its deviations from the experimental values.

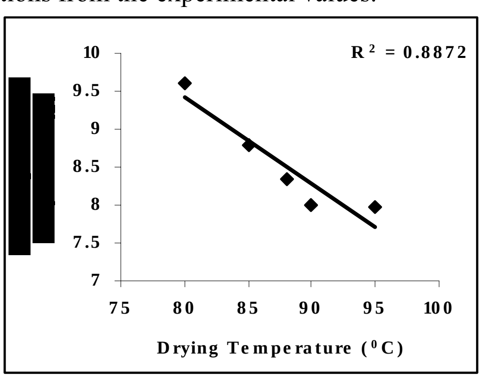

Figure 1. Effect of drying temperature on the quantity of water evaporated (as obtained from the experiment (Nwoye,2007))

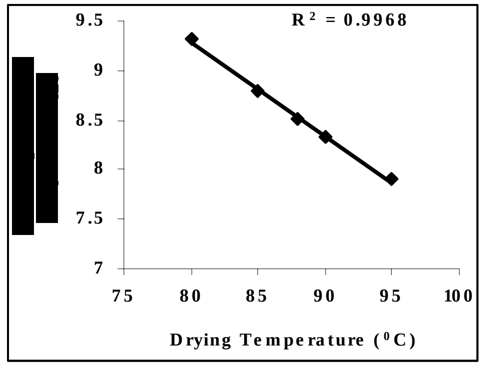

Figure 2. Effect of drying temperature on the quantity of water evaporated (as predicted by model)

Figure 3 shows that the quantities of water evaporated per unit rise in the drying temperature as obtained from the experiment (Nwoye, 2007), designated by the line ExD and as predicted by the model (line MoD) are in very good agreement within the drying temperature range used. Figure 3 shows that above 80^{0}C, both quantities of evaporated water as obtained from experiment (Nwoye,2007) and derived model show proximate agreement; both decreasing with increase in the drying temperature.

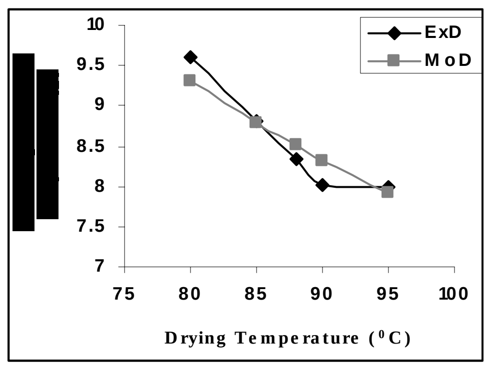

Figure 3 Comparison of the quantity of water evaporated as obtained from the experiment (Nwoye,2007) and as predicted by the model

5.2 Effect of drying temperature on the deviation and correction factor to model-predicted quantity of evaporated water

It was found that the validity of the model is rooted in the expression N Logβ = Log (A/T) where both sides of the expression are correspondingly approximately equal to 1. Table 2 also agrees with equation (7) following the values of N Logβ and Log (A/T) evaluated from Table 1 as a result of corresponding computational analysis.

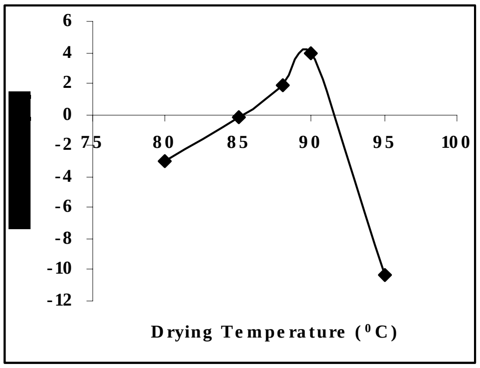

Figure 4. Variation of deviation (from experimental values) of model-predicted quantity of water evaporated with drying temperature

The maximum deviation of the model-predicted quantity of evaporated water from the corresponding experimental value is less than 11% which is quite within the acceptable deviation range of experimental results, hence depicting the usefulness of the model.
Figure 4 show that above 90^0C, the deviation (from experimental values) of the model-predicted quantity of evaporated water increases in magnitude with rise in the drying temperature.

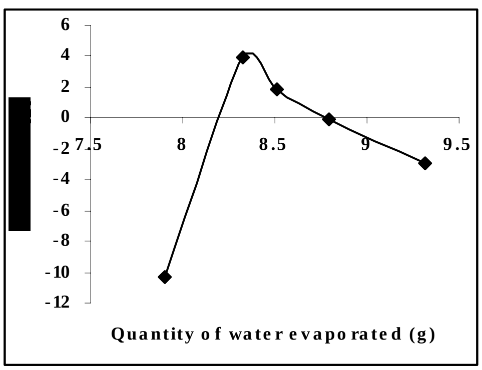

Figure 5. Variation of deviation (from experimental values) with model-predicted quantity of water evaporated

Figure 4 indicates that the highest and least deviations are -10.35 and -0.11% respectively corresponds to the drying temperatures: 95 and 85^0C respectively. Comparison of Figures 4 and 5 shows that these percent deviations also correspond to the model-predicted quantities of evaporated water: 7.9071 and 8.7906 g respectively. Figures 4-6 show that the orientation of the curve of the correction factor against the drying temperature is opposite that of the deviation against drying temperature.
This is attributed to the fact that correction factor is the negative of the deviation as shown in equations. (13) and (14). It is believed that the correction factor takes care of the effects of the surface properties of the clay and the physiochemical interaction between the clay and the binder which (affected experimental results) were not considered during the model formulation.

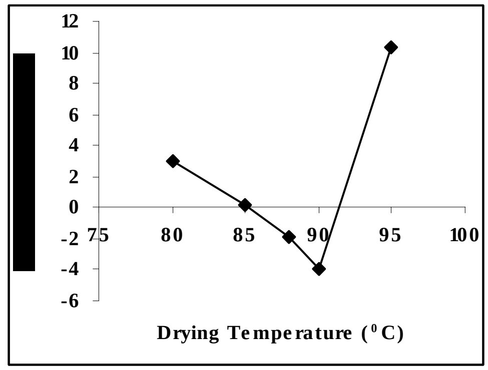

Figure 6. Variation of correction factor (to the model-predicted quantity of water evaporated) with drying temperature

6. Conclusion

The model computes the quantity of water evaporated during oven drying of Nsu (Nigeria) clay at a temperature range 80-95^0C. The validity of the model is rooted in the expression N Logβ = Log (A/T) where both sides of the expression are correspondingly approximately equal to 1. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value is less than 11% which is quite within the acceptable deviation range of experimental results. Water evaporation per unit rise in the drying temperature evaluated from experimental and model-predicted results are -0.16 and 0.10 g/^{0}C respectively, indicating proximate agreement.
Further works should incorporate more process parameters into the model with the aim of reducing the deviations of the model-predicted β values from those of the experimental.

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