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Determination of Moisture Diffusivity during Drying of Rectangular Cassava Pellets: Experimental and Modeling Study

Onyemazuwa Andrew Azaka[1], Samuel Ogbonna Enibe[2], Chinonso Hubert Achebe[3]
[1,2,3]Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria.
[*]Corresponding Author's E-mail: oa.azaka@unizik.edu.ng

Abstract
The aim of this study is to experimentally determine the drying dynamics of cassava pellets during convective drying. TMS 30572 specie of Cassava tubers were hand peeled and cut into slabs with a rectangular mold (40 mm×20 mm×10 mm) designed for the purpose. The drying tests were conducted using a hot air-convective dryer that can dry samples weighing from 0 to 100g. The response of the drying curve or the drying kinetic depends on the applied drying conditions. The dryer was set at different heater temperatures of 150°C, 140°C, 130°C, 120°C and 110°C which gave corresponding hot air temperatures of 81°C, 78°C,75°C,70°C, and 66°C respectively. The hot air velocity was kept constant at 4m/s. The drying dynamics dictated by Fick's second law for a 2-dimensional element as influenced by both initial condition and Neumann Boundary condition was used to define the mass transfer process, by assuming isotropic behavior of the samples. The comparison between the experimental results and the proposed analytical solutions of the equation of diffusion represented by Fick's law, applied to 2–dimensional analysis for a finite shape, allows determination of the values of the diffusion coefficient. The diffusivity of the rectangular samples was determined to be in range of 2.3304 x 10^9 – 1.4260 x 10^9 m^2s-[1] and described using a 3[rd] order polynomial equation ($y = -9E - 05x^3 - 0.0343x^2 - 4.4281x + 189.6$) with the value of R^2 = 0.8989. The diffusivity plots clearly explainthat the moisture diffusivity of cassava pellets can be expressed as a function of temperature using a 3[rd] order polynomial equation.The study could provide theoretical bases for equipment design and process optimization for hot air drying of Cassava pellets.

Keywords: Thermal Energy, Convective Drying, Moisture Diffusivity, Cassava Pellets.

Nomenclature

Ta - Hot air Temperature
Th - Heater Temperature
M - Moisture Ratio
Meq - Equilibrium Moisture content
Deff - Effective Diffusivity
r - correlation coefficient.
H - Thickness
T - Temperature (^oC)
t - Time (seconds)
FE - Finite Element
RSME - Roor Mean Square Error
R - Coefficient of Regression

1. Introduction

Conventional air-drying is the most frequently used drying method in the food industry. During drying mass and heat transfer play an important role. Understanding and formulation of well-verified mathematical drying models will make it possible to control the process to produce stable products of high quality. During the drying process, the samples shrink and change color has a high effect on the quality of the product.

The goal is to retain the actual nutrients, tastes and color. In vegetables and fruits, the amount of shrinkage is very closely related to the amount of water lost by dehydration or evaporation. However, the effect of shrinkage during drying has often been ignored due to its complexity. In the cases where it was considered though, different authors developed different equations to describe the shrinkage during drying (Mayor et al 2004). Even the shrinkage itself is not only defined by thickness, area or volume shrinkage, it can also experience other geometric changes during drying such as bending, twisting, and irregular size reduction, producing an evident shape change or deformation (Campos-Mendiola et al. 2007) . As drying is a complex process, it is good to use numerical modeling to represent the process of a system in a set of mathematical equations, which can effectively characterize the overall process of the system. Those sets of equations developed should predict the coupled heat and mass transfer of the overall process. Therefore, modeling and simulation give the opportunity to have an insight on the process at each specified time.

The main goal of this study is to experimentally determine and simulate the drying process of rectangular cassava pellets under convective hot-air drying. The work also tried to evaluate the effect of the shrinkage on moisture diffusivity with the help of simulation using MATLAB version 7.7.0 (R2008b). The results from simulation were compared and validated with experimental data obtained by comparing the experimental and simulation plots to see if they follow the same trend.

2.0 Material and methods

2.1 Dryer Set up

The experiments were conducted using a laboratory scale conventional double layer convective hot air dryer. The air is provided by a fan. The air flow speed was kept constant at 4m/s. Throughout the experimental run, the sample weights were continuously recorded at predetermined time (20mins) intervals until no noticeable differences between subsequent readings were observed.

2.2 Methods

TMS 30572 specie of Cassava tubers were harvested from a farm in NnamdiAzikiwe University, Awka, Anambra State. They were peeled, chipped and dried at varying temperatures and constant air velocity to obtain dried cassava chips. The test trials done were triplicates to obtain accurate drying process data. In carrying out the experiment, the Cassava tubers were hand peeled and cut into slabs with a rectangular mold (40 mm×20 mm×10 mm) designed for the purpose. The initial moisture content of the cassava sample was determined by drying 10 g of the fresh samples at 103 °C until constant weight is attained. Prior to each experiment, the samples were left at room temperature for 2 h to reach thermal equilibrium with the environment. Two trays were placed in the drying chamber. During the drying experiments, one of the trays was used to monitor dehydration behavior (weighting tray) and the other was used to determine shrinkage kinetic (sampling trays) of the samples.

For each drying experiment, 8 pieces of the cut sample were placed in small wire gauze with a known weight inside the drying tray. The remaining samples were spread in the drying tray inside the drying chamber. The airspeed of the fan was kept constant at 4 m/s throughout the experiment while the temperature of the heater was set at 110^{o}C. The samples were left to dry to a constant weight. The loss in weight of the sample in the wire gauze was taken at interval of 10 minutes, and the shrinkage rates were determined at the same time by inserting a piece of the sample taken from the drying tray into a 100 mL measuring cylinder containing toluene at a known level. The volume of toluene displaced was measured. The experiments were replicated twice. The sample mass was measured by a digital mass measuring scale, accuracy of 0.001g.

2.3 Dryer Calibration

The dryer was calibrated to ascertain the accurate hot air temperature for every heater temperature been set to be used for the drying process. A linear relationship between heater temperature Th and hot air temperature Ta (eqn.1) with R^2 value of 0.9685 was developed using regression analysis. With the aid of equation 3.1, heater temperatures of 110°C, 120°C, 130°C, 140°C, and 150°C gave corresponding hot air temperatures of 81°C, 78°C,75°C,70°C, and 66°C respectively.

$$T_a = 24.7230 + 0.3757T_h \quad (1)$$

2.4 Governing Equations

2.4.1 Effective Moisture Diffusivity

The convective heat transfer from the air to the sample interface was assumed to be an external convection process whereas heat transfer from the surface of the product to the body of the product occurred mainly by conduction. In the meantime, moisture was transported within the product via convection and diffusion processes and moved from the inside of the product to its surface.

The decrease in moisture concentration during drying leads to an unsteady state condition, i.e. the concentration(d_c/d_x) or the equivalent moisture content gradient (d_w/d_x) changes over time (falling-rate period). For such conditions Fick's second law of diffusion as given in equation 2 is often applied to analyze moisture transport mechanisms within the sample during the falling-rate period (Okos et al 2003, Sablani et al 2000, Saravacos et al 2001).

The effective moisture diffusivity was determined experimentally using Fick's second law of diffusion for rectangular geometries as shown in eqns. 2.

$$\frac{\partial M}{\partial t} = \mathrm{Div}\left[D_{eff}(T)\mathrm{grad}(M)\right] = D_{eff}(T)\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) \tag{2}$$

The Crank's series solution for variation with time of moisture ratio for an infinite slab is

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}\,t}{4H^2}\right) \tag{3}$$

where$H$ is half thickness of the sample and moisture ratio MR is given as

$$MR = \frac{M - M_{eq}}{M_0 - M_{eq}} \tag{4}$$

The first term of the series can give acceptable results for long drying periods

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}\,t}{4H^2}\right) \tag{5}$$

In logarithmic form, Equation (5) becomes

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff}}{4H^2}t \tag{6}$$

Eq. 2 expresses how the concentration changes with time t at different positions in the food (Lewis 1987). This differential equation is solved analytically for certain sample geometries under the following assumptions:

- The food sample is two-dimensional
- Moisture diffusivity in the sample is constant
- Free-water content at the surface is essentially zero and moisture is initially distributed uniformly throughout the sample
- The shape and size of the sample remains constant during drying (i.e. there is negligible shrinkage)
- Heat transfer proceeds very quickly (negligible internal and external heat-transfer effect)
- Resistance to mass transfer at the surface is negligible compared to the internal resistance of the sample. That is, internal moisture movement is the main resistance to drying (there is no external moisture movement resistance)

Once the shape of the food product has been determined, eq. 2 is simplified and solved to obtain the effective moisture diffusivity (D_{eff}).

3.0 Results and Discussions

3.1 Effective Moisture Diffusivity

By plotting $\ln(MR)$ against t, a straight line is obtained with the slope $S = -\frac{\pi^2 D_{eff}}{4H^2}$ such that $D_{eff} = -\frac{4H^2}{\pi^2} S$. The plots are shown in Figures 1a & b to 3a for the experimental drying of the rectangular samples as discussed under the experimental procedure. The plots for the five considered heater temperatures exhibited expected trends; lines with negative slopes. The slopes are seen on the inserted linear equations which are lines of best fit from linear regression. The calculated D_{eff} are given in Table 1. Also, based on the experimental measurements, the equilibrium moisture content at different times of the days the experiments were conducted are tabulated in Table 1 alongside the heater temperatures employed for experiments.

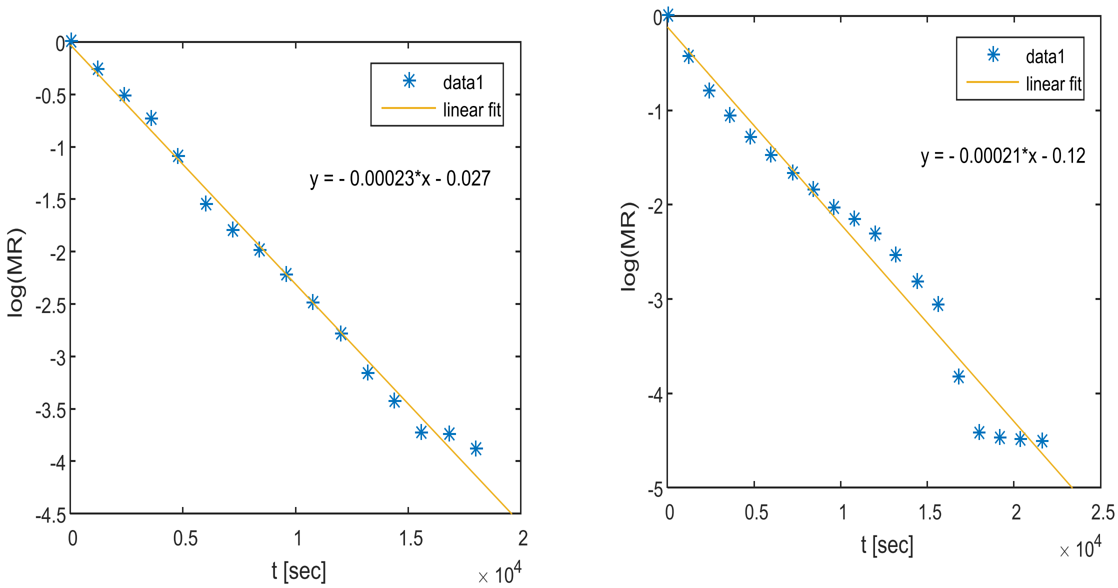

Figure 1a & b. The plots of $\ln(MR)$ against t for the Experiment at Heater Temperature of 150°C (81°C air temperature) and 140°C (78°C air temperature) respectively for the rectangular samples

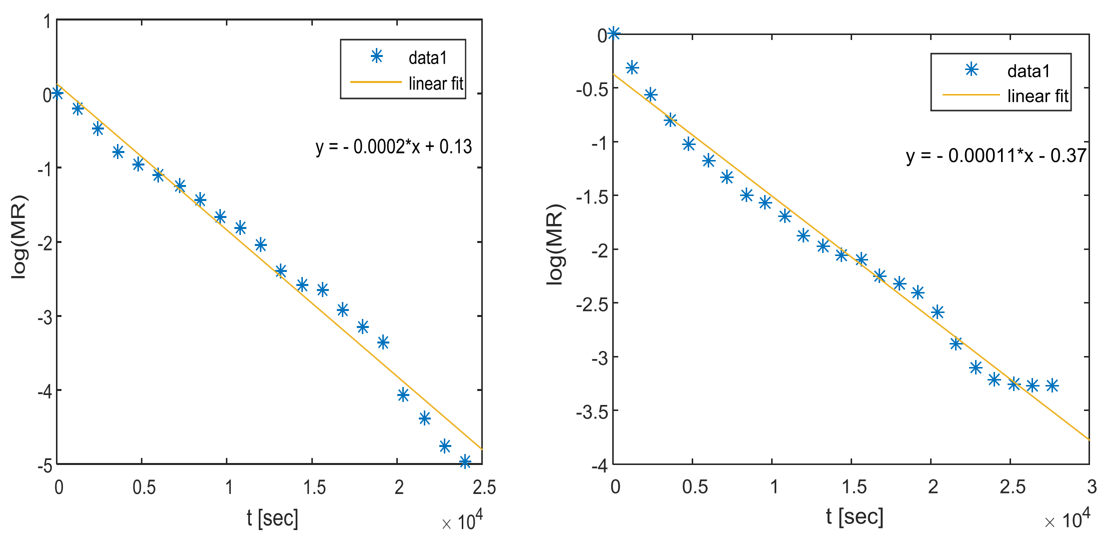

Figure 2a & b. The plots of $\ln(MR)$ against t for the Experiment at Heater Temperatures of 130°C and 120°C (70°C air temperature) (75°C air temperature) respectivelyfor the rectangular samples

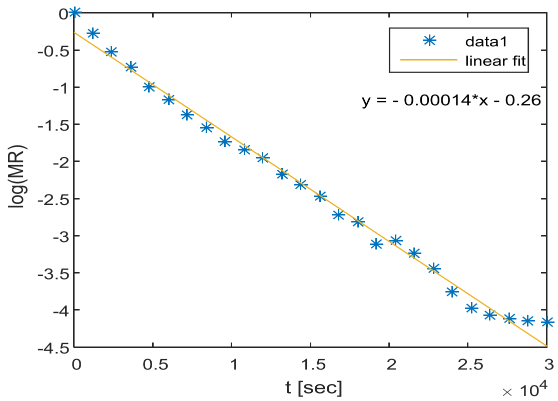

Figure 3. The plot of $\ln(MR)$ against t for the Experiment at Heater Temperature of 110°C (66°C air temperature) for the rectangular samples

Table 1. The effective diffusivity at various heater temperatures for the rectangular samples

Rectangular Samples		
Heater Temperature [°C]	M_{eq}	$D_{eff} \times 10^9$
150	0.5400	2.3304
140	0.8380	2.1277
130	0.7375	2.0004
120	0.9410	1.1498
110	1.2376	1.4260

As tabulated in Table 1, the diffusivity of the rectangular samples was determined to be in range of 2.3304×10^9 - 1.4260×10^9 m^{2}s^{-1}, and described using a 3rd order polynomial equation ($y = -9E - 05x^3 - 0.0343x^2 - 4.4281x + 189.6$) with the value of R^2 = 0.8989. The effect of drying air temperature on the moisture diffusivity can be discussed using figure 6. The plot clearly explains that the moisture diffusivity of cassava pellets can be expressed as a function of temperature using a 3rd order polynomial equation.

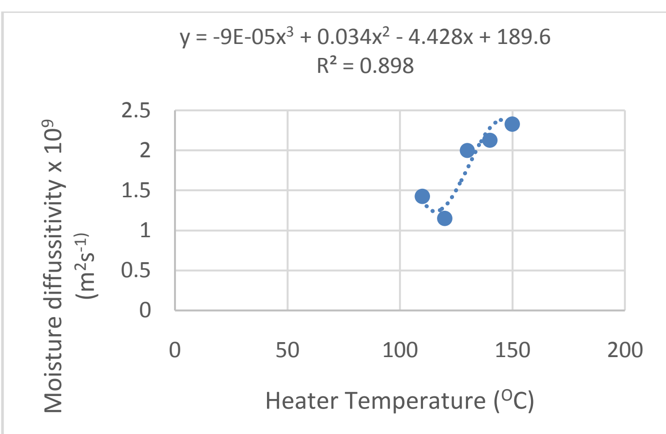

Fig. 6: Air temperature effect on effective moisture diffusivity for the Rectangular shape cassava pellets.

In finite elements analysis, solutions can be improved by mesh refinement. That is why predictions are generated for a 99-element model, a 367-element model, a 1395-element model and a 5447-element model. The FE analysis show that the solutions progressively fell within the experimental range of moisture content as number of elements increased. The FE predictions at the experimental intervals are compared with the measured values in Figure 7. The R^2, RMSE and *r* for the predictions in Figure 7 (a) are respectively 0.9340, 0.1924 and0.9912 for the 1395-element model while the prediction accuracy improved to 0.9958, 0.0483 and0.9984 for the 5447-element model. Marked improvement in accuracy is recorded on mesh refinement. Using the 5447-element model, FE predictions at the experimental intervals are compared with the measured values in Figures 8a & b to 9a & b and the corresponding statistical goodness of fit values are presented in Table 2. All the R^2 values in the tables are above 90% where majority were up to 99% indicating high accuracy of FE prediction of cassava drying.

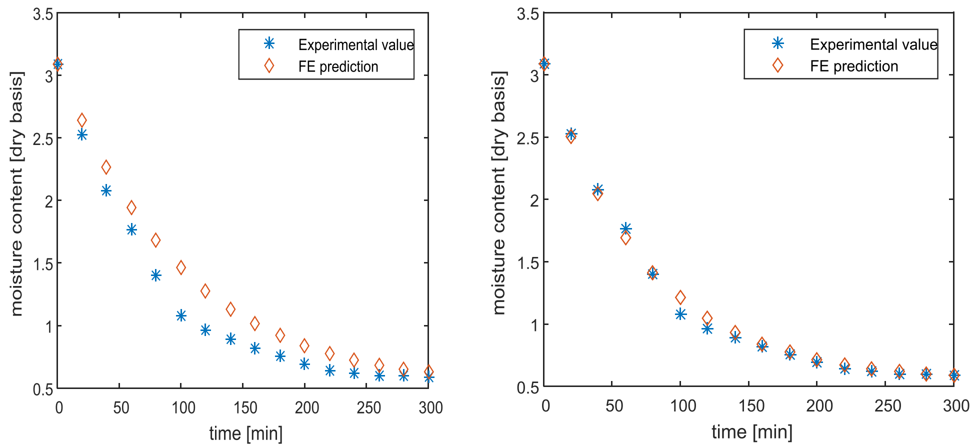

Figure 7.Measured moisture content and the FE predicted moisture content at heater temperature of 150°C for the Rectangular cassava sample (a) results for a (b) results for a 5447-elements model

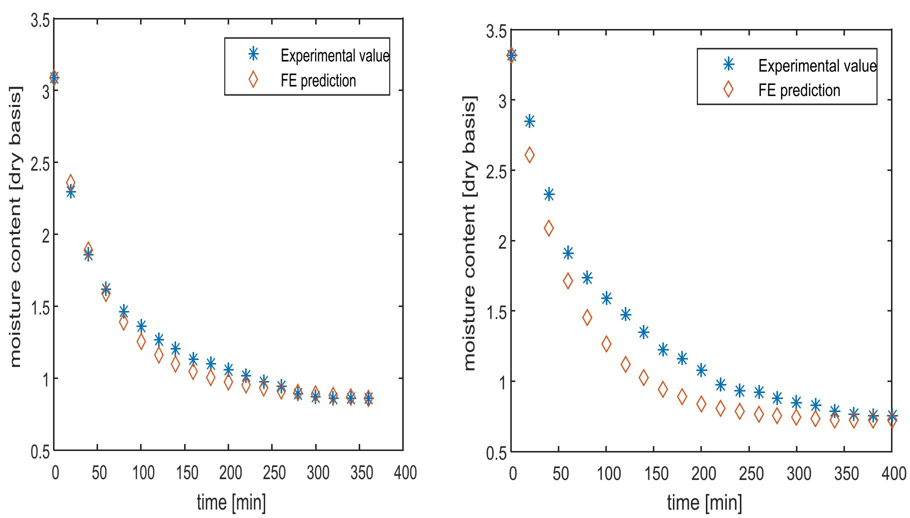

Figure 8a & b.Measured moisture content and the FE predicted moisture content at heater temperatures of 140°C and 130°Cfor the Rectangular cassava sample

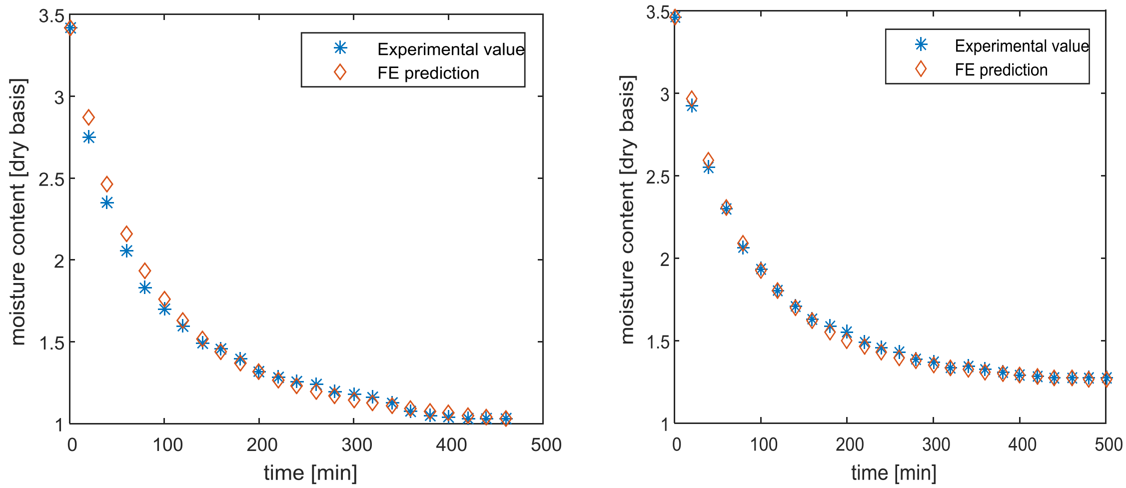

Figure 9a & b.Measured moisture content and the FE predicted moisture content at heater temperatures of 120^{o}C and 110^{o}Cfor the Rectangular cassava sample

Table 2. The statistical performance indices of the finite element prediction of cassava drying relative to the experimental measurements for the rectangular pellets

Rectangular pellets				
T [^{o}C]	M_{eq} M_0	R^2	*RMSE*	*r*
150	0.5400	0.9340	**0.1924**	0.9912
140	0.8380 3.0868	0.9877	0.0623	0.9963
130	0.7375 3.3151	**0.9126**	0.2077	0.9885
120	0.9410 3.4144	0.9924	0.0515	0.9978
110	1.2376 3.4577	0.9983	0.0224	0.9995

4.0. Conclusion

In this study, convective drying of Cassava Pellets was investigated experimentally and numerically. A two-dimensional finite element model was developed for the sample drying and programmed in MATLAB version 7.7.0 (R2008b) to simulate the process and predict the drying curves. Drying rate, moisture diffusivity and mass transfer coefficient of the samples were found to increase with the increment in drying air temperature. No constant rate period was seen and the entire drying process of the cassava occurred in the falling rate period at the applied air temperatures. The diffusivity of the samples was determined to be in range of 2.3304×10^{9} - 1.4260×10^{9} m^{2}s^{-1} forrectangular pellets and were perfectly described using a 3rd order polynomial as a function of air temperature. For each drying temperature, mass transfer coefficient of the samples were determined experimentally and found to be functions of the process time and moisture removal, respectively.

From the calculated D_{eff} given in Table 1. , it was observed that an increment in drying temperature increased the effective diffusivity value. Thus, an increase in temperature causes a decrement in water viscosity and increases the activity of water molecules. These phenomena facilitate diffusion of water molecules in object capillaries and consequently, increase the moisture diffusivity. The results showed that the moisture diffusivity of cassava pellets can be expressed as a function of temperature using a 3rd order polynomial

5.0 Recommendation

This study showed that Fick's second law describes satisfactorily the drying process performed through the model validation with the drying kinetics and the temperature of the cassava pellets. By this, it will be interesting to study this process after other mechanisms for the transport of water during drying, such as pressure driven and capillary flow, transport mechanisms of drying of porous media, Darcy's law, and evaporation condensation theory.

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