Kinetics of Gelatinized White Yam (*Dioscorea Rotundata*, Poir) During Convective Drying

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Abstract — Gelatinized white yam cubes, having a moisture content of 196% dry basis were dried in a convective dryer under different conditions of air temperature (40, 50, 60 and 70°C) and relative humidity (20 - 50%). There was no constant rate period throughout the entire drying period as drying took place entirely during a falling rate period. The effect of temperature was more pronounced than that of relative humidity. The drying data were fitted to five thin-layer drying models. The goodness of fit of the models were evaluated by comparing the percent mean relative deviation modulus (E%), RMSE, χ² and R² between their observed and predicted moisture ratio. The Binomial approximation of Fick's diffusion equation gave the best fit to the drying data as the highest values of R² and the lowest values of χ² and RMSE were consistently obtained with the Binomial model equation.

Keywords — Gelatinized white yam, thin-layer drying, modelling, moisture diffusion coefficient.

1 INTRODUCTION

Yams are an important staple food and cash crop in many countries of West Africa and Southeast Asia. However, they are highly perishable and have to be processed into stable products. Currently convective heated air drying is the most widely used method in post-harvest technology of agricultural products. Using this method, a more uniform, hygienic and attractive dried product can be produced rapidly (Doymaz, 2004). Therefore, drying is a very important unit operation in the processing of yam into flour. However, there are certain inherent problems associated with the operation.

Firstly, most thermal processes such as food drying are high energy consuming having low energy efficiency. According to Patil (1987), the energy used in the drying of grains accounts for 20 to 30 % of the total energy used in the production of grains in the USA. In Hungary, drying consumes about 15 % of the total energy input in crop production (Lang et al., 1985); and according to Mujumdar and Devahastin (2000), drying consumes 10 to 25 % of national industrial energy consumed in the industrialized economies of the world. Yam drying is particularly high-energy demanding because yam, especially when gelatinized, has a very dense structure and as a result dries very slowly at an enormous energy cost. Besides, as much as 25 % of the energy consumed in the drying process may be lost through ineffective practice and dryer designs (Patil, 1987).

Secondly, during the drying of yam, transformation of its chemical, physical, biological and other characteristics do occur leading to deleterious changes in its colour and nutritive qualities. Many of these changes which are internal include changes in shape, structure, shrinkage, cracks, casehardening, and denaturation of unstable components (Fortes and Okos, 1980). These changes are influenced both by the external process conditions such as air temperature, humidity and air velocity, and by the mechanisms of internal moisture movement.

Thus, if the drying of yam is to be done in such a manner that guarantees minimal energy consumption and maximum retention of the yam’s desirable quality, there must be a procedure for selecting appropriate process conditions. Such a procedure requires accurate knowledge of temperature and moisture movement within the yam during the drying process. As at the moment, reports on such knowledge on yam drying are scanty. Accordingly, the objectives of this paper are to determine the drying characteristics of gelatinized white yam under various process conditions and to determine an accurate model that describes the drying kinetics of the product in a convective dryer.

2 MATERIALS AND METHOD

2.1 MATERIALS

White yams (*Dioscorea rotundata, Poir*) from Benue State of Nigeria were used for the study. The yams were peeled, washed and diced into 10 millimetre cubes by means of a dicing machine (Hobart Manufacturing Company Ltd, Toronto, Canada). The cubes were immediately immersed in a bath of 1 % solution of sodium meta-bisulphite for 10 minutes. This was to prevent non-enzymatic browning, which would occur due to Maillard reaction and phenolic oxidation during drying which darkens the colour of the product. The yam pieces were blanched in a steam blancher at atmospheric pressure until they were completely gelatinised. This generally took about five minutes.

The blanched yam cubes were tested for complete gelatinization by means of a differential scanning calorimeter (Du Pont Instruments DSC, Model 910). The Interactive Differential Scanning Calorimeter Version 3.0 Programme (Du Pont Thermal Analyzer, Model 1090) was then used to determine the heat and temperatures of transition of the samples. Gelatinization was generally initiated at 71.3 °C, peaked at 73.8 °C and terminated at 76.4 °C. Samples that deviated from the regular 10 mm cubes were discarded; and the rest were sealed in plastic bags and kept in refrigerated storage at 3 °C until they were required for drying tests.
2.2 Experimental Set-up
The drying apparatus used for this study is illustrated in Fig. 1. A description of the dryer and data acquisition system used for the drying tests are presented in detail in Satimehin (2014).

2.3 Experimental Procedure
The initial moisture content of the gelatinized yam was determined by air oven method at 103 °C for 72 hours, after which convective air drying experiments were conducted at 40, 50 and 60 °C air temperatures, and 10 - 50% relative humidity at a constant air velocity of 0.8 m/s. The air velocity was measured by means of an airflow meter (Airflow Developments Canada Ltd., Model TA6000). In each experiment, 215 g of gelatinized yam cubes were accurately weighed by means of a precision electronic balance (Mettler PJ3000) and uniformly spread on a sample tray. To begin a drying test, the dryer was run empty for two hours to enable it stabilize at constant temperature and relative humidity. The samples on the sample tray were then dried until the difference between two successive mass of the sample was consistently within 0.1 gram during a four-hour period. The mass of sample was measured continuously during drying by means of a 1.0 kg load cell connected via an amplifier to a data logger and a computer. At the end of a drying test the samples were transferred to a desiccator and allowed to cool down at room temperature for 15 minutes. They were then oven-dried at 103 °C for 72 hours in order to obtain the total solids content of the sample.

2.4 Analysis of Drying Data
Various equations have been reported to predict the evolution of moisture content during the drying of a moist material in a thin layer. Five of such model drying equations commonly used in the literature were selected to fit the experimental drying data in this study. The thin-layer drying models are given in Table 1. The moisture ratios (MR) of the yam samples were calculated as follows.

\[ MR = \frac{M_t - M_e}{M_0 - M_e} \]  (1)

where MR is the dimensionless moisture ratio. The symbols \( M_0 \), \( M_t \), and \( M_e \) denote the initial, instantaneous and equilibrium moisture contents of the drying substance in percent dry basis, respectively. The drying rate constants and coefficients of the models were evaluated using the nonlinear regression procedure (PROC NLIN) of Statistical Analysis System (SAS, 2012). The goodness of fit of the models were evaluated and compared by means of the coefficient of determination (R²), percent mean relative deviation modulus (E%), root mean square error (RMSE) and reduced chi-square (χ²) between their observed and predicted moisture ratio. The parameters for evaluating the goodness of fit of the models were calculated using equations 2-5.

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Fig. 1. Diagrammatic illustration of the drying apparatus.

(1) - A centrifugal fan; (2) - Air pre-heater; (3) - Column of gravel; (4) - Humidification tower; (5) - Water sprinkler; (6) - transparent plastic jar; (7) - Constant-head water tank; (8) - A centrifugal water pump; (9) - water pre-heater; (10) - Thermostatically controlled heater; (11) - Bank of resistance heaters; (12) and (13) - Water temperature controller; (14) - surge tank; (15) - Air diversion flap; (16) - aluminum honeycomb; (17) - Sample holder; (18) - Thermistor; (19), (20) and (21) - copper-constantan thermocouples; (22) - data logger; (23) - microcomputer; (24) - load cell.
\[ R^2 = \left( \frac{\sum_{i=1}^{N}(\text{MR}_{\exp,i} - \text{MR}_{\text{pred},i})^2}{\sum_{i=1}^{N}(\text{MR}_{\exp,i} - \overline{\text{MR}})^2} \right)^2 \]  
\[ E\% = \frac{100}{N} \sum_{i=1}^{N} \left( \frac{\text{MR}_{\exp,i} - \text{MR}_{\text{pred},i}}{\text{MR}_{\exp,i}} \right) \]  
\[ \text{RMSE} = \left( \frac{1}{N} \sum_{i=1}^{N} (\text{MR}_{\exp,i} - \text{MR}_{\text{pred},i})^2 \right)^{1/2} \]  
\[ \chi^2 = \frac{\sum_{i=1}^{N}(\text{MR}_{\exp,i} - \text{MR}_{\text{pred},i})^2}{N-z} \]  

where MR_{\exp,i} and MR_{\text{pred},i} are the i\textsuperscript{th} experimental and predicted dimensionless moisture ratios, respectively; N is the number of observations; and z is the number of constants in the model. The values of \( R^2 \) were used as the primary criterion of comparing model accuracy to fit the models to the experimental data. A model is also considered to fit better than another if it has a higher value of \( R^2 \) and lower values of E%, RMSE, \( \chi^2 \).

| Thin-layer model equations | Model No | Model name | References |
|---------------------------|----------|------------|-------------|
| MR = \exp(-kt)\textsuperscript{I} | I        | Newton     | Kajuna et al. (2001) |
| MR = a.\exp(-kt)\textsuperscript{II} | II       | Henderson and Pabis | Hamdami et al. (2006) |
| MR = \exp(kt)\textsuperscript{III} | III      | Page       | Mihindu-kulasuriya and Jayasuriya (2013) |
| MR = a.\exp(-kt) + (1-a).\exp(-kt)\textsuperscript{IV} | IV       | Two-term Diffusion model | Hamdami et al. (2006) |
| MR = a.\exp(-kt) + b.\exp(kt)\textsuperscript{V} | V        | Binomial   | Sharaf-Eldeen et al. (1980) |

Table 1. Thin-layer Drying Models Evaluated

\( MR \) is the dimensionless moisture ratio of the material at time, t, of drying, the parameters a, b, k, k1, k2 and n are the drying rate constants of the model equations.

### 3 RESULTS AND DISCUSSION

#### 3.1 EFFECT OF TEMPERATURE ON MOISTURE CONTENT AND DRYING RATES OF GELATINIZED WHITE YAM

Fig 2 and Fig. 3 show the drying curves of gelatinized white yam under various process conditions. From the figures, there were no straight line segments in any of the lines. Rather, the figures show that the moisture content of the material decreases continuously, exhibiting a decaying exponential trend with time which asymptotically approached the equilibrium moisture content of the gelatinized yam at the thermodynamic state of the drying air. The two figures also show that gelatinized yam dries faster at the higher air temperatures hence its instantaneous moisture content is lower at a higher temperature that it is at the lower temperatures. This implies that the temperature of the drying air has a significant influence on the product’s moisture content.

Torres et al. (2012) reported that higher drying temperatures resulted in steeper curves and shorter drying times. They also observed that the time required to reduce the moisture content to any given level was dependent on the drying temperature. This trend was similarly reported by Doymaz (2005) who also observed that moisture content decreased rapidly with increased drying air temperature.

![Drying curves of gelatinized yam at 20% relative humidity and different temperatures](image1)

![Typical drying curves at two drying conditions of 20% RH, 70 °C (○) and 30% RH, 50 °C (×)](image2)

Fig 4 is a typical plot of the drying rates against moisture content at various temperatures. The figure shows that there was no constant drying rate period throughout the drying of gelatinized white yam. Rather, drying took place entirely during two falling rate periods; showing a change of slope at about 80 % dry basis. The absence of a constant drying rate period shows that the product contained no free (or unbound) moisture. Therefore, the rate of evaporation of moisture from the surface of the material was limited by the rate at which moisture was able to diffuse from the interior to the surface of the material. The mechanism for moisture movement in the gelatinized white yam was, therefore, predominantly by diffusion. This phenomenon is generally characteristic of hygroscopic food substances.
tended to attain equilibrium moisture content more quickly at the higher temperature than they did at the lower temperature. This is because at higher temperatures molecular linkages become weakened due to increases in the cycles of excitation of water molecules, leading to increases in the distance between the molecules and hence a faster weakening of the forces of attraction between them.

Furthermore, Fig. 4 shows that drying took place more rapidly at higher temperatures even for yam pieces that had the same initial moisture content. Satimehin et al. (2010) posited that the reason for this is that as the material becomes drier, movement of moisture from the interior occurs more slowly thereby requiring more energy to detach water molecules from the solid matrix. As a result, the time to reach the product’s final moisture content decreases as the air temperature increases. Similar observations were reported by Akpinar et al. (2003), Sacilik (2007), Satimehin et al. (2010), and Mihindukulasuriya et al. (2013). It is also considered that the temperature influence on the rate of drying is due to the higher moisture diffusivity associated with higher temperatures. Therefore, final stages of drying were characteristically slower than the initial stages because the moisture binding forces had become stronger towards the end of drying. Thus, as moisture contents reduced to levels below 20% dry basis, rates of drying became nearly the same for all drying conditions. This phenomenon can be explained using the concept of free moisture content. Free moisture content is the difference between the product’s instantaneous moisture content and its equilibrium moisture content at the temperature and relative humidity of the drying air. As the free moisture content approached zero, drying rates at the various temperatures also gradually dropped to zero, signifying the end of a drying process.

The rate of moisture loss during drying was plotted against drying time at 40 and 70 °C (Fig. 5). The figure shows that drying took place faster at 70 °C than it did at 40 °C temperatures. Generally, during a period of decreasing drying rate, the rate of drying is continually proportional to the difference in temperature between the bulk of the drying air and that of the surface of the material that is being dried. The rate of drying is also proportional to the difference in water vapour pressure between the surface of the material and the drying air. These differences are higher at the higher temperatures and are therefore responsible for the faster drying at 70 °C than at 40 °C. Figure 5 further shows that yam pieces
| Air Temperature | Model No | R² | E% | RMSE | χ² | R² | E% | RMSE | χ² | R² | E% | RMSE | χ² | R² | E% | RMSE | χ² |
|----------------|----------|----|----|------|----|----|----|------|----|----|----|------|----|----|----|------|----|
| 40°C           | I        | 0.966 | 21.14 | 0.0403 | 0.001650 | 0.983 | 41.66 | 0.0354 | 0.001258 | 0.994 | 23.29 | 0.0227 | 0.000518 | 0.994 | 15.13 | 0.0202 | 0.000413 |
|                | II       | 0.998 | 10.41 | 0.0217 | 0.000483 | 0.994 | 43.97 | 0.0287 | 0.000831 | 0.999 | 16.64 | 0.0182 | 0.000333 | 0.995 | 12.56 | 0.0196 | 0.000390 |
|                | III      | 0.990 | 4.37  | 0.0092 | 0.000087 | 0.989 | 63.92 | 0.0204 | 0.000419 | 0.996 | 9.50  | 0.0088 | 0.000078 | 0.994 | 5.26  | 0.0177 | 0.000319 |
|                | IV       | 0.999 | 5.26  | 0.0068 | 0.000049 | 0.995 | 62.81 | 0.0196 | 0.000390 | 1.000 | 9.64  | 0.0056 | 0.000032 | 0.996 | 7.96  | 0.0170 | 0.000296 |
|                | V        | 0.999 | 5.35  | 0.0067 | 0.000047 | 0.995 | 62.17 | 0.0196 | 0.000389 | 1.000 | 8.30  | 0.0042 | 0.000018 | 0.996 | 7.14  | 0.0164 | 0.000280 |
| 50°C           | I        | 0.978 | 22.49 | 0.0344 | 0.001202 | 0.988 | 20.34 | 0.0253 | 0.000643 | 0.998 | 28.12 | 0.0132 | 0.000175 | 0.994 | 39.38 | 0.0205 | 0.000425 |
|                | II       | 0.999 | 12.35 | 0.0184 | 0.000350 | 0.998 | 17.41 | 0.0158 | 0.000255 | 0.999 | 28.33 | 0.0124 | 0.000156 | 0.994 | 33.74 | 0.0205 | 0.000427 |
|                | III      | 0.994 | 3.88  | 0.0073 | 0.000055 | 0.995 | 33.52 | 0.0111 | 0.000125 | 0.998 | 29.49 | 0.0105 | 0.000111 | 0.994 | 35.74 | 0.0204 | 0.000426 |
|                | IV       | 1.000 | 3.96  | 0.0044 | 0.000021 | 0.999 | 24.48 | 0.0088 | 0.000079 | 0.999 | 29.79 | 0.0099 | 0.000100 | 0.994 | 37.66 | 0.0203 | 0.000425 |
|                | V        | 1.000 | 4.11  | 0.0037 | 0.000015 | 0.999 | 23.40 | 0.0075 | 0.000059 | 0.999 | 29.75 | 0.0091 | 0.000085 | 0.994 | 38.05 | 0.0195 | 0.000394 |
| 60°C           | I        | 0.989 | 35.20 | 0.0162 | 0.000267 | 0.993 | 27.09 | 0.0185 | 0.000345 | 0.997 | 12.46 | 0.0125 | 0.000159 | 0.997 | 31.27 | 0.0123 | 0.000152 |
|                | II       | 0.995 | 26.46 | 0.0135 | 0.000189 | 0.996 | 27.33 | 0.0159 | 0.000259 | 0.998 | 11.94 | 0.0122 | 0.000151 | 0.998 | 30.68 | 0.0123 | 0.000151 |
|                | III      | 0.995 | 27.41 | 0.0123 | 0.000155 | 0.995 | 29.49 | 0.0152 | 0.000236 | 0.997 | 15.24 | 0.0107 | 0.000115 | 0.997 | 31.52 | 0.0116 | 0.000136 |
|                | IV       | 0.996 | 23.06 | 0.0124 | 0.000160 | 0.996 | 28.15 | 0.0151 | 0.000234 | 0.998 | 16.83 | 0.0101 | 0.000102 | 0.999 | 84.62 | 0.0090 | 0.000081 |
|                | V        | 0.996 | 23.28 | 0.0123 | 0.000160 | 0.996 | 28.01 | 0.0151 | 0.000235 | 0.999 | 16.40 | 0.0082 | 0.000069 | 0.999 | 82.50 | 0.0088 | 0.000078 |
4 CONCLUSION
The results of this study revealed as follows.

1) The moisture content of gelatinized yam decreases with increasing temperature and lower levels of moisture content would be obtained when the temperature of the drying air is increased.

2) Drying also takes place faster at the higher air temperatures which implies that the temperature of the drying air has a significant influence on the product’s moisture content.

3) Drying of gelatinized white yam takes place entirely during falling rate period and hence is a moisture diffusion controlled process.

4) The drying kinetics of the gelatinized white yam can accurately be predicted by a Binomial model thereby making a drying process amenable to automation through the application of microcontrollers.

Table 3. Parameters of the Binomial drying model equation at various levels of temperature and relative humidity

| RH | T(°C) | a     | b     | k1    | k2    | R²   | RMSE | χ²   |
|----|-------|-------|-------|-------|-------|------|------|------|
| 40 | 0.7286| 0.2904| 0.0057| 0.0356| 0.999 | 0.0067| 0.000047|
| 20%| 50    | 0.7627| 0.2710| 0.0072| 0.0475| 1.000 | 0.0037| 0.000015|
| 30%| 60    | 0.8647| 0.1976| 0.0105| 0.0930| 0.996 | 0.0123| 0.000160|
| 40%| 40    | 0.6880| 0.3222| 0.0054| 0.0251| 0.995 | 0.0196| 0.000389|
| 60%| 50    | 0.8211| 0.2618| 0.0082| 0.0606| 0.999 | 0.0075| 0.000059|
| 50%| 60    | 0.9115| 0.1153| 0.0109| 0.0686| 0.996 | 0.0151| 0.000235|

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