Intra-particle Diffusion Modeling of Isothermal Dehydration of Locally Made Brown Sugar

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Abstract:- **Locally made brown sugar samples were purchased at five different locations (Z_1,Z_2,Z_3, Z_4, and Z_5) in Zaria Kaduna, Northern part of Nigeria have been subjected to dehydration with an objective of modeling the intra –particle diffusion pattern of the intrinsic water molecules at a constant process temperature of 102^{o}C.The model considered the sugar samples as a sorbent layer which controls the movement of the water molecules in relationship with the square root of the time taken ($\sqrt{t}$) at a different specified rate of 5,10,20,30,40,50 to 60 minutes and an extension of determination of reaction(dehydration) rate with the process mechanism.Experimental and the theoretical models were established via the linear plot of equivalent weights of the lost moisture against the square root of the elapsed time at a constant temperature of 120^{o}C. Experimental plots of sample Z_1, Z_2, Z_3, Z_4 &, Z_5 generated regression factors (R^2_E) of 0.9168, 0.9615, 0.9716, 0.8976, & 0.9869; Slope (K) of 1.1982, 1.2686, 1.3082, 0.6379 & 0.3851; Intercept (C) of 0.9598, -0.4738, 0.5957, 0.5957 & 0.0809 respectively.**

Theoretical modeling was achieved by direct substitution of the slope and the intercept from the experimental model which generally produced a regression (R^2_T) of 1 (unity) as an ideal and perfect model. However, the disparity between the experimental and the theoretical models was ascribed to experimental error or systematic error. Coefficient of non determination was adopted to calculate the percentage error encounter, which with Z_1, Z_2, Z_3, Z_4, & Z_5 is 8.32%, 3.85%, 2.84%, 10.24%, & 1.31% respectively.Parameters such as temperature, moisture, and rate with respect to molasses as a second component are very germane to the preservation, control and pilot production of brown sugar.

***Keywords*: Local, brown sugar, isothermal, intraparticle diffusion, Regression.**

I. INTRODUCTION

Sugar was traditionally known to be brown in appearance without any artificial modification [1]. The expulsion of moisture from the raw sugar cane juice concentrate the molasses; a viscous brown liquid containing some mineral and vitamins. In the 20th century, further steps were considered in the production of sugar, in which the molasses was extracted with centrifugation and chemically converting the second fraction into sugar crystals [2]. Meanwhile, sugar manufacturers in the time past believed brown sugar to harbor microorganism therefore not hygienic and suitable for man use [3]. Conversely, this was far from the truth because brown sugar retains more minerals, vitamins and of higher nutritional benefits than the white processed conventional sugar [4]. Health wisely, taking brown sugar can help prevent obesity, menstrual cramp, and prevention of cold [5].The uniqueness and activity of brown sugar are strongly related to its moisture contents, however at certain percentages which serve as an inhibiting agent against microbial attack and longer shelf live[6]. Also, the kinetics of moisture removal is expected to explain the relationship of the sugar samples under a constant temperature of 120^{o}C [7]. Intra-particle diffusion is the mobilization of matter from one stationary point to another through the thermal movement of atoms or molecules. This is active and faster in a gaseous state, slow in liquids, and very retarded in solids [8]. The concept of intra particle diffusion is clearly evidenced in more than a few molecular processes such as osmosis, evaporation, and mobilization of neutrons in a thermal state in a nuclear power reactor [9]. The speed at which chemical processes occur is typically controlled by the rate at which diffusion can enhance the activities of the reactants or transport them to the site of reaction with catalysts or enzymes as the case may be. Diffusion processes are relevant for the kinetics of many microstructural changes that occur during preparation, processing, and heat treatment of materials[10]. Appreciable diffusion in solids mostly takes place at temperatures well above room temperature [10]. Knowledge and understanding of diffusion mechanisms are therefore of high importance particularly for scientists who establish the conditions and principles for materials at elevated temperatures and for engineers who build equipment for process operation at such temperatures.

It is as well the phenomenon that is responsible for the transport of physical species inherent in a solution through a solid medium. In a well-stirred batch adsorption system, the model has been engaged to illustrate the adsorption process taking place on a permeable adsorbent[11]. The model reveals the association connecting the amount of adsorbate adsorbed or desorbed onto or from the adsorbent surface with respect to time. In addition, the model is also a method in the rate-determining mechanism of sorption processes and reaction.[12].

Therefore, a systematic understanding of diffusion in materials is fundamental for materials development and engineering. Hence, theoretical and experimental basis for moisture removal (dehydration) which directly evaluates the diffusion mechanism of water molecules by dehydration (desorption) at constant temperature has been explored. This is also to enlighten the technocrats and the entire sugar sector on the fundamental basis, factors, theories, and conditions that will practically favor the production of standard brown sugar. It is also to disclose to the technologists and engineers who build and fabricate equipment for operation at a certain temperature which aims in the control of parameters such as moisture.

II. EXPERIMENTAL

Brown Sugar dehydration

Five forms of unrefined brown sugar were sourced from five different locations Z_1, Z_2, Z_3, Z_4 and Z_5 in Zaria Kaduna State, Northern Nigeria. The samples were crushed nearly into powder with 10g of each of the sample into a clean, dried and labeled porcelain crucible and collectively placed in an oven drier (MINO/75/F/DIG) set at 120^{o}C for 5, 10, 20,30,40,50 and 60 minutes of time. Resultants weights were taken after cooling with a desiccator [13]

Intra-Particle diffusion Theory

This is an established concept in material science and sorption studies which study the behavior of the adsorbate molecules against the active sites of the adsorbent with respect to the square root of the time spent. It explains and models the rate-determining steps of the sorption processes by allowing the transportation of the adsorbate through the layer of the adsorbent particles and the diffusion of the solute molecules through the interior of the available pores. It is usually a slow process in solid materials and it is expressed as;

$$\mathbf{M_{wt} = K_3\sqrt{t} + C}$$

Where K is the intra-particle diffusion rate constant, that can be defined from the slope of the linear plot of Mw_t (lost moisture weight at time t) against the square root of the time ($\sqrt{t}$) and C the intercept

[Nwadiogbu et al .2014]. The intercept of the plot reflects the boundary layer effects during sorption.

In other words, the larger the intercept, the greater the contribution of the surface sorption in the rate-controlling step. Linear regression with the plot touching the origin portray the diffusion to be the sole rate-limiting step and if otherwise, it means the diffusion model is not the only mechanism involved in the sorption process because of the boundary layer activity and control [14].

III. RESULTS AND DISCUSSION

Table I. Moisture desorption (Experimental) and theoretical intra Particle modeling of Sample Z_1

Sample Z_1									
Initial.W(g)	**Final.W(g)**	**Mw_E(g)**	**Time (min)**	**Time$^{1/2}$ (min.$^{1/2}$)**	**Mw_t(g)**	**K_3**	**C**	**R^2_E**	**R^2_T**
10.0	10	0	0	0	0.9598	1.1982	0.9598	0.9168	1
10.0	5.9	4.1	5	2.2361	3.6391	1.1982	0.9598		
10.0	5.6	4.4	10	3.1622	4.7488	1.1982	0.9598		
10.0	2.7	7.3	20	4.4721	6.3183	1.1982	0.9598		
10.0	1.1	8.9	30	5.4772	7.5226	1.1982	0.9598		
10.0	1.1	8.9	40	6.3246	8.5379	1.1982	0.9598		
10.0	1.1	8.9	50	7.0711	9.4324	1.1982	0.9598		
10.0	1.1	8.9	60	7.7460	10.2410	1.1982	0.9598		

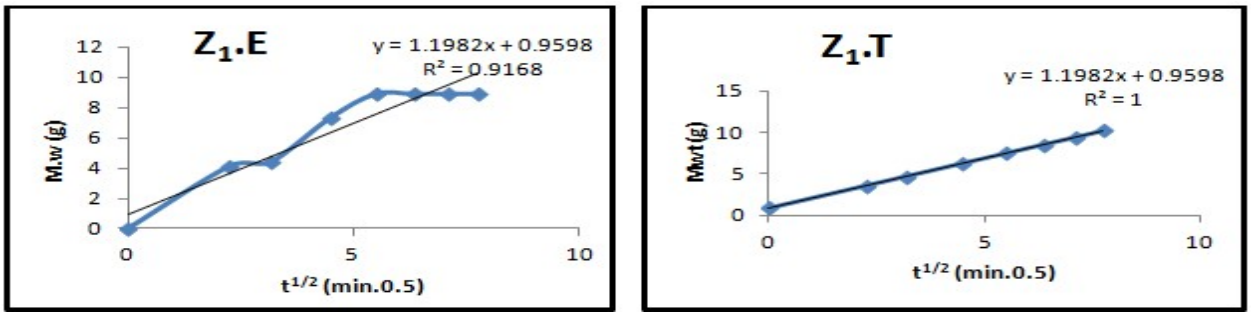

Figure I. Experimental (E) and theoretical (T) plots of intra-particle models of sample Z_1

Table II. Moisture desorption (Experimental) and Theoretical Intra-Particle modeling of Sample Z_2

Sample Z_2									
Initial Wgt.(g)	Final Wgt.(g)	Moisture Wgt (g)	Time (min)	Time$^{1/2}$ (min.$^{1/2}$)	Mw_t	K_3	C	R^2_E	R^2_T
10.0	10.0	0	0	0	-0.4738	1.2686	-0.4738	0.9615	1
10.0	7.8	2.2	5	2.2361	2.3629	1.2686	-0.4738		
10.0	7.4	2.6	10	3.1622	3.5379	1.2686	-0.4738		
10.0	5.3	4.7	20	4.4721	5.1996	1.2686	-0.4738		
10.0	2.6	7.4	30	5.4772	6.4746	1.2686	-0.4738		
10.0	1.8	8.2	40	6.3246	7.5495	1.2686	-0.4738		
10.0	1.3	8.7	50	7.0711	8.4966	1.2686	-0.4738		
10.0	1.3	8.7	60	7.7460	9.3527	1.2686	-0.4738		

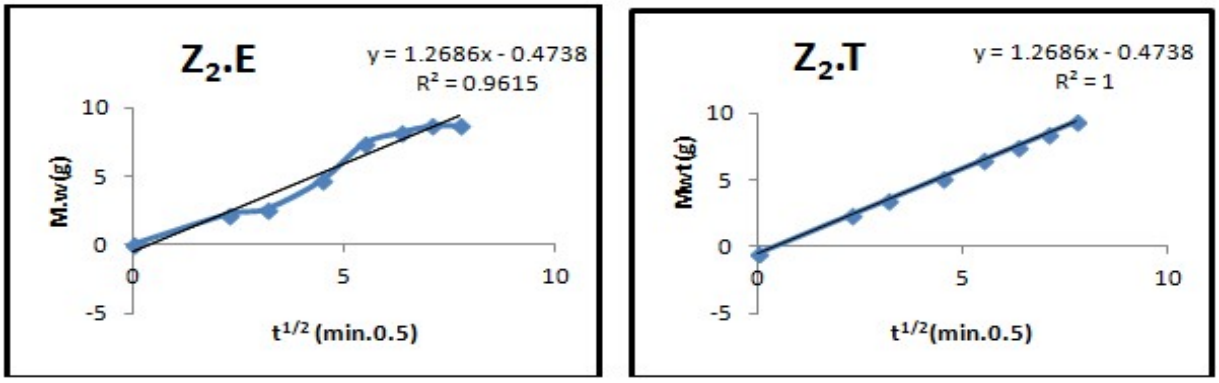

Figure II. Experimental (E) and theoretical (T) plots of intra-particle models of sample Z_2

Table III. Moisture desorption (Experimental) and Theoretical Intra-Particle modeling of Sample Z_3

Sample Z_3									
Initial Wgt.(g)	Final Wgt.(g)	Moisture Wgt (g)	Time (min)	Time$^{1/2}$ (min.$^{1/2}$)	Mw_t	K_3	C	R^2_E	R^2_T
10.0	10.0	0	0	0	0.5957	1.3082	0.5957	0.9716	1
10.0	5.8	4.2	5	2.2361	3.5209	1.3082	0.5957		
10.0	5.5	4.5	10	3.1622	4.732592	1.3082	0.5957		
10.0	3.6	6.4	20	4.4721	6.4462	1.3082	0.5957		
10.0	1.7	8.3	30	5.4772	7.7610	1.3082	0.5957		
10.0	0.5	9.5	40	6.3246	8.8695	1.3082	0.5957		
10.0	0.2	9.8	50	7.0711	9.8461	1.3082	0.5957		
10.0	0.2	9.8	60	7.7460	10.7290	1.3082	0.5957		

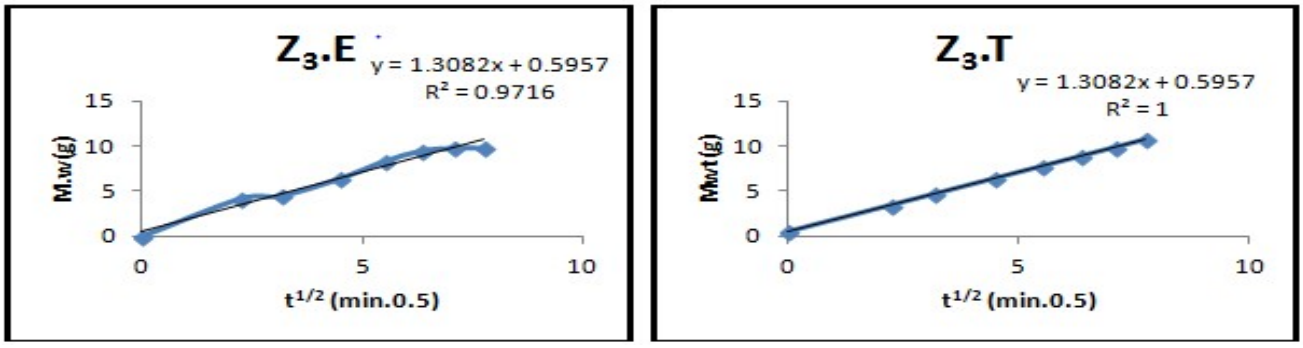

Figure III. Experimental (E) and theoretical (T) plots of intra-particle models of sample Z_3

Table IV. Moisture desorption (Experimental) and Theoretical Intra-Particle modeling of Sample Z_4

Sample Z_4									
Initial Wgt.(g)	**Final Wgt.(g)**	**Moisture Wgt (g)**	**Time (min)**	**Time$^{1/2}$ (min.$^{1/2}$)**	**Mw_t**	**K_3**	**C**	**R^2_E**	**R^2_T**
10.0	10.0	0	0	0	0.9904	0.6379	0.5957	0.8976	1
10.0	6.8	3.2	5	2.2361	2.4168	0.6379	0.5957		
10.0	6.5	3.5	10	3.1622	3.0076	0.6379	0.5957		
10.0	5.8	4.2	20	4.4721	3.8432	0.6379	0.5957		
10.0	5.5	4.5	30	5.4772	4.4843	0.6379	0.5957		
10.0	5.0	5.0	40	6.3246	5.0248	0.6379	0.5957		
10.0	5.4	5.4	50	7.0711	5.5010	0.6379	0.5957		
10.0	5.4	5.4	60	7.7460	5.9316	0.6379	0.5957		

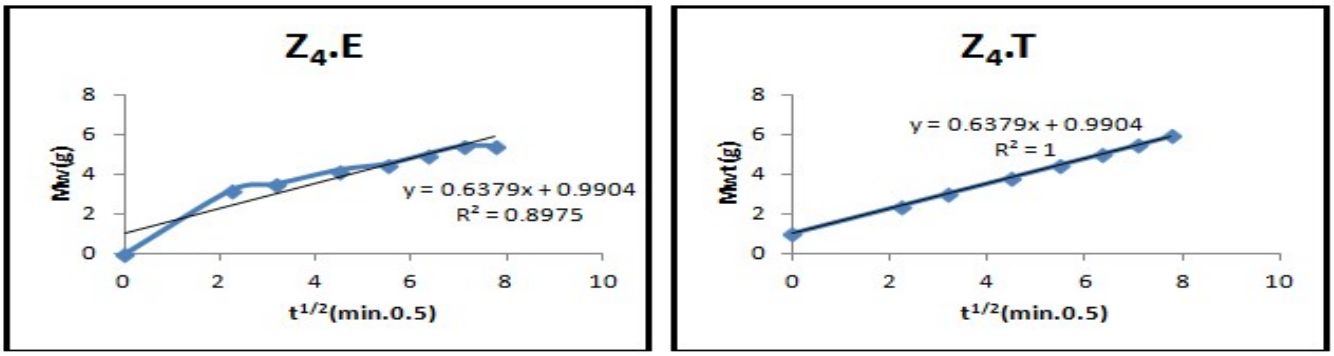

Figure IV. Experimental (E) and theoretical (T) plots of intra-particle models of sample Z_3

Table V. Moisture desorption (Experimental) and Theoretical Intra-Particle modeling of Sample Z_5

Sample Z_5									
Initial Wgt.(g)	**Final Wgt.(g)**	**Moisture Wgt (g)**	**Time (min)**	**Time$^{1/2}$ (min.$^{1/2}$)**	**Mw_t**	**K_3**	**C**	**R^2_E**	**R^2_T**
10.0	10.0	0	0	0	0.0809	0.3851	0.0809	0.9869	1
10.0	8.9	1.1	5	2.2361	0.9420	0.3851	0.0809		
10.0	8.7	1.3	10	3.1623	1.2987	0.3851	0.0809		
10.0	8.2	1.8	20	4.4721	1.8031	0.3851	0.0809		
10.0	7.9	2.1	30	5.4772	2.1902	0.3851	0.0809		
10.0	7.6	2.4	40	6.3246	2.5165	0.3851	0.0809		
10.0	7.0	3.0	50	7.0711	2.8040	0.3851	0.0809		
10.0	7.0	3.0	60	7.7460	3.0639	0.3851	0.0809		

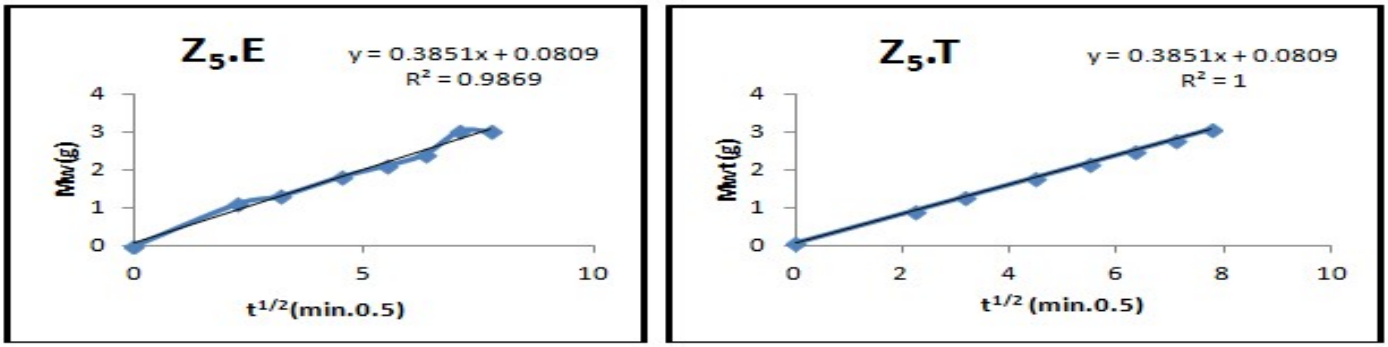

Figure V. Experimental (E) and theoretical (T) plots of intra-particle models of sample Z_5

Table VI. Coefficients of Nondetermination of experimental and theoretical regressions

Sample	R^2_E	R^2_T	R^2_T-R^2_E	% Error
Z_1	0.9168	1	0.0832	8.32
Z_2	0.9615	1	0.0385	3.85
Z_3	0.9716	1	0.0284	2.84
Z_4	0.8976	1	0.1024	10.24
Z_5	0.9869	1	0.0131	1.31

Table I, II, III, IV, and V present both the experimental and theoretical intra particle data on sample Z_1, Z_2, Z_3, Z_4, and Z_5 respectively. They are as well the function of the dehydration processes at a constant temperature of 120^{o}C for an intermittent period of 5, 10, 20,30,40,50 and 60minutes with each sample. The equivalent weight of expelled moisture (M_{we}) in each case was plotted against the square root of the time elapsed with the process. This is because the lost moisture is perceived to be the function of adsorbate area available for particulate movements. In other words, experimental plots were achieved form direct plot of loss moisture in term of weight against the square root ($t^{1/2}$) of the time and theoretical plots are from direct extrapolation and substitution for slope (K_3) and intercept(C) estimated from the experimental plots. Experimentally, sample A had a regression factor of 0.9168, slope of 1.1982 and intercept of 0.9598; B with a regression value of 0.9615, slope of 1.2686 and intercept of -0.4738; sample C with regression of 0.9716, slope of 1.3082 and intercept of 0.5957; sample D, a regression of 0.8976, slope of 0.6379 and intercept of 0.5957 and finally sample E with the regression of 0.9869, slope of 0.3851 and intercept of 0.0809.Theoretically and according to the nature of the model, regression value is always a unity which supports and satisfied the rate-determining step defines the nature of boundary layer of the adsorbate and as the mechanism for sorption process. Figure I, II, III, IV and V depicts both the experimental and theoretical plots of each of the brown sugar samples. However, to be completely certain of the validity of the model to be the only rate determinant, it is expected that the linear plot passes through the origin; otherwise, it will be perceived that it is entirely not the model that is responsible for the sorption mechanism. Rather, the boundary layer effect is another factor to be considered [13]. Hence, we can affirm that the model is ultimately the rate-controlling mechanism since the magnitudes of the intercepts are approximately 0 in all cases. In addition, the curves observed with the experimental plots reflect some degrees of experimental or systematic errors which were deduced by the coefficient of non-determination.These were estimated on table VI as 8.32, 3.85, 2.84, 10.24 and 1.31 percentage errors for sample Z_1, Z_2, Z_3, Z_4, and Z_5 respectively passes through the origin; otherwise, it will be perceived that it is entirely not the model that is responsible for the sorption mechanism. Hence, we can affirm that the model is ultimately responsible for the rate-controlling mechanism since the magnitudes of the intercepts are approximately zero in all cases.

IV. CONCLUSION

The diffusion model for the control of moisture and desorption from brown sugar samples has experimented. It is a model that explains the mechanism and determination of the rate of a chemical process at a particular constant temperature. Brown sugar-containing another natural and active component as molasses is not expected to be characterized in terms of sorption capacity for moisture and as well kinetics which defines the mechanism with respect to time with the refined and bleached conventional white ones.

Hence, technocrats in the Nations sugar sector should endeavor to understand the behaviors and the mechanism of both the brown and white sugars with respect to factors such as the level of moisture influence of various temperature gradients and the impacts of molasses in the case of brown sugar.

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