Evaluation of Thermal and Mass Transfer Process in Poriferous Material through Forced Convective Drying

Bakri A.J.[1], Ajayi T.B.[2], Ogunmola O.Y.[3], Ogunleye T. O.[4]
[1]*Department of Mechanical Engineering, Yaba College of Technology, Lagos, Nigeria*
[2]*Department of Industrial Maintenance Engineering, Yaba College of Technology, Lagos, Nigeria*
[3]*Department of Mechanical Engineering, University of Lagos, Nigeria*
[4]*Department of Mechanical Engineering, Yaba College of Technology, Lagos, Nigeria*

***Abstract*-In the world today, any physical activities carried out by man is caused as a result of energy being converted from one form to another and this has played a vital role to meet human being daily activities. This study focused on the analytical investigation of the samples used and a simplified mathematical model was generated for effective forced convection with the aim of achieving a perfect amount of temperature and dampness level within the multi-layered poriferous material. An integral transform method in compliance with the initial and specified boundary conditions was introduced to analyse numerically using MatLab software. The analytical model developed was justified with an existing experimental set up designed to look into the analysis and the effect of uncoupled heat and mass movement in the wet substance. The temperature and the moisture level of the plantain samples were juxtaposed with the experimental values transcribe during the dehydrating process, there was 72% careful scrutiny collating the experimental and the simulated out-turn. Overall, it may be said that the radiant heat diffusion coefficient has a vital influence on the temperature spread and the mass dispersal coefficient in the system and the result obtained described a closed-form relationship between the experimental and the simulated process.**

***Key Words*- Convective drying; poriferous material; thermal energy; dampness level; analytical model.**

I. INTRODUCTION

The demand for energy has increased due to the consistent increase in the population around the world and, therefore, the consumption of conventional fuels has equally moved up on the scale. The reductions in the sources of hydrocarbon fuels have drawn researchers' consciousness to the need for the improvement on the usage of renewable energies in this present day and time, knowing fully well that the solar energy being absorbed by the atmosphere, oceans and land is quite enormous which of course can be transformed into vital use in replacement for conventional fuel.

The amount of solar energy being radiated to the atmosphere is so much, especially, in some tropical countries such as Nigeria where a vast amount of thermal energy is recorded throughout the year which is about twice as much that could ever be realised from Earth's non-renewable resources of energy combined together. Renewable energy which has been thoroughly investigated is a safe, clean source of green energy and of course in abundance [6]. Globally, there is a fast-growing attention towards the need to increase and facilitate the rise for the use of renewable energy, which is quite essential by extending the technology to the farmers in developing countries targeted at increasing their productivity.

Drying of food products for the purpose of preservation is one the methods usually used to keep products for longer periods putting into consideration the quality of the item. It is a basic principle of reducing the moisture content from a product aiming at achieving the desired dampness level which would definitely undergo a thermal energy-intensive process.

The actual aim of drying a product are basically for purpose of retaining the quality, extending the storage life, making the handling easier and furthermore sanitation. Drying is one of the oldest methods of food preservation being practised which involves the use of heat to dispel the water content from the food products. This is, therefore, a combination and concurrent effect of heat and mass movement behaviour subjected to adequate thermal energy[8].In the earlier days, the process of drying was done with so much dependence on the solar energy but in these present days and time, a whole lot of ultra-modern equipment and facilities has emerged for dehydrating purposes.

Drying is one of the oldest procedures used in agricultural product storage and preservation majorly aiming at maintaining its quality[10], [11]. The most widely accepted form of drying from years past has always been open-air sun drying but then; it has a long run negative effect disadvantage which is the nutritional contamination and quality depreciation[4].

In time past, measurable attempt was made to analyse and investigate some of the chemical and biochemical changes that could manifest throughout the drying process and, as well as, evolving methodologies that could at least reduce the level of materials degradation. With regards to this, thermal dehydration using the forced convective drying technique seems to be the most predominant, that is the drying method involving the blowing of heated air which circulates through or over the product and then resulting to evaporation of the solvent.

In present times, many investigators[5],[12],[17]have put in a lot of effort into investigating the numerical drying model of joining the movement of dampness content and heat flux across the permeable medium. They also analysed a two-dimensional model of diffusion which describes the momentum, mass and the thermal movement to project the dehydration level of the banana products.

They eventually concluded that the hypothetical outcomes realised conforms to the anticipated solution[2] equally established a short term template to assess the product convective drying curve and temperature thereby initiating shrinkage. Furthermore, the diffusion coefficient and drying curves of cowpea grain were analysed which was actually based on numerous numerical models[9].In the process of heat and mass transfer Computational Fluid Dynamics(CFD) framework was introduced, throughout the period of spraying dehydrating activities[13].

A large volume of research work has been prepared and issued relating to heat and dampness transfer model using various proportions and majorly the numerical study of the drying value, water level distribution, thermal reading across different materials, cortex effect [18],evaporation and the diffusion transport properties [16].

With respect to the referencing of the outcome of the thermo physical resources on the convective drying energy and also taking into consideration the adjoining of heat and mass transfer reaction, it is rather unfortunate that a little literature is available in this area of study[5],[16]. A passionate model with the introduction of a third boundary constraints for illustrating the unstable thermal and mass diffusion process inside the wet permeable medium amidst, forced hot air drying was recommended. This research work aims at developing a closed form solution and carry out parametric studies of the drying process using integral transforms regarding the uncoupled heat and mass transfer model during forced convective drying.

II. MATHEMATICAL MODEL

The principle involving the combination of heat and mass movement operation is consequentially a very complex model; therefore, simplification of the technique is assumed as listed below:

- The levelled permeable piece are polyunsaturated,
- Materials are correlative and isotropic.
- The permeable bodies are of a sustained piece throughout the dehydration phase while the effect of squeeze-abilityis insignificant.
- At time (t) = 0; the materials are at constant temperature.
- The facet of the material comprising of the sides and base was encased. Subsequently, dimensions of the opposite positions of the product is wide enough to allow the movement of heat and moisture spread in one dimensional flow only through the x-axis.

In actualising the above mentioned, a model was developed which displays the sliced permeable material to natural hot air in order to propagate a drying process as shown in the figure1. The techniques incorporated for analysing and investigating of flow movement relating to heat and mass required for convective drying of the product are as stated below:

- The flow of heat from a region of high-temperature to a low-temperature region.
- The application of forced convective drying between the outward surface of the permeable medium and its surrounding.
- A one-dimensional process of mass movement of the material is applied which occurs primarily at the outermost surface level of the sliced permeable product.
- The temperature slope and correlative dampness level of the product are regarded as the propelling force for mass diffusion of the material

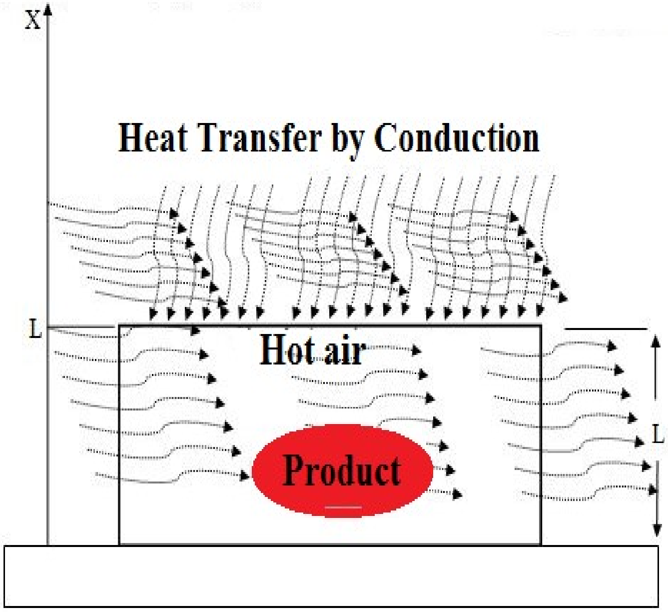

Fig. 1: A model design of the permeable productundergoinga drying process

III. DEVELOPMENT AND ANALYTICAL SOLUTION OF UNCOUPLED ENERGY AND MASS TRANSFER

The governing equations of uncoupled energy and the mass movement spread of the damped medium under going drying in one-dimensional flow process is given as follows;[4]

$$\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial X^2} \qquad (1)$$

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial X^2} \qquad (2)$$

The initial conditions:

$$t = 0, \quad M = M_0, \quad T = T_0$$

$$0 \le x \le L \qquad (3)$$

Boundary conditions

$$X = 0, \quad -K\frac{\partial T}{\partial X} = h(T - T_\infty), \quad D\frac{\partial M}{\partial X} = h_m(M - M_0)$$

$$X = L, \quad -K\frac{\partial T}{\partial X} = h(T - T_\infty), \quad D\frac{\partial M}{\partial X} = h_m(M - M_0) \qquad (4)$$

thenon-flow dimensional parameters was used to evaluate

$$X = \frac{x}{L}, \quad \theta = \frac{T - T_\infty}{T_0 - T_\infty}, \quad Sh = \frac{h_m L}{D}, \quad Bi = \frac{hL}{K}, \quad \tau = \frac{\alpha t}{L^2}, \text{ and } M = \frac{M - M_0}{M_0 - M_a} \qquad (5)$$

Substituting the evaluated parameters into equations (1) and (2) we have:

$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial x^2} \qquad (6)$$

$$\frac{\partial M}{\partial\tau} = \frac{\partial^2 M}{\partial x^2} \qquad (7)$$

From the initial conditions;

$$\tau = 0, \theta = 1, M = 1 \qquad 0 \le x \le L$$

Boundary conditions;

$$\tau > 0, \ \frac{\partial\theta}{\partial\tau} = -Bi\theta, \ \tau > 0, \ \frac{\partial M}{\partial\tau} = -Sh\theta \quad \text{at } X = 0$$

$$\tau > 0, \ \frac{\partial\theta}{\partial\tau} = -Bi\theta, \ \tau > 0, \ \frac{\partial M}{\partial\tau} = -Sh\theta \text{ at } X = 1 \qquad (8)$$

$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial X^2}$$

Applying the Integral of Laplace transform into equation (6)

$$\frac{\partial^2\bar{\theta}}{\partial X^2} - S\bar{\theta} = -1 \qquad \text{as } (\theta = 1) \qquad (9)$$

$$\bar{\theta} = A\,Cosh\sqrt{S}X + B\,Sinh\sqrt{S}X + \frac{\theta}{S} \qquad (10)$$

$$\frac{\partial\bar{\theta}}{\partial X} = \sqrt{S}\left[ASinh\sqrt{S}X + BCosh\sqrt{S}X\right] \qquad (10a)$$

$$\frac{\partial\theta}{\partial X}I_{x=0} = \sqrt{S}[0 + B] = 0$$

Substituting (x =0), then, B=0 and when (x = 1) we get;

$$\frac{\partial\bar{\theta}}{\partial X}I_{x=1} =$$
$$\sqrt{S}\left[A\,Sinh\sqrt{S}(1) + 0\,Cosh\sqrt{S}(1)\right] = Bi + 0\,Sinh\sqrt{s} + \frac{1}{s} \qquad (11a)$$

$$\frac{\partial\bar{\theta}}{\partial X}I_{x=1} = \sqrt{S}\,ASinh\sqrt{S} = -Bi\left[ACosh\sqrt{S} + \frac{1}{S}\right] \qquad (11b)$$

$$A = \left[\sqrt{S}\,Sinh\sqrt{S} + Bi\,Cosh\sqrt{S}\right] = -\frac{Bi\theta s}{S} \qquad (11c)$$

$$A = \frac{Bi\theta_S}{S\left[\sqrt{S}\,Sinh\sqrt{S} + Bi\,Cosh\sqrt{S}\right]} \qquad (11d)$$

Fill in the value of 'A' and 'B' into equation (10)

$$\bar{\theta} = \frac{1}{S}\left[1 - \frac{BiCosh\sqrt{S}X}{\sqrt{SSinh\sqrt{S}} + Bi \quad h\sqrt{S}}\right] \qquad (12a)$$

Applying Inverse Laplace to equation gives

$$\theta(X, T) = 1 - \left[1 - 2Bi\sum\frac{cos\beta_n Xe^{-\beta_n{}^2\tau}}{\beta_n{}^2\left[\frac{Sin\,\beta_n(1+Bi)}{\beta_n} + Cos\beta_n\right]}\right] =$$
$$2Bi\sum_{n=1}^{\infty}\frac{\cos(\beta_n X)e^{-\beta_n{}^2\tau}}{\beta_n(1+Bi)Sin\beta_n + \beta_n Cos\beta_n}$$

Or

$$\theta(X, T) = 2\sum_{n=1}^{\infty}\frac{Sin\beta_n Cos\beta_n\,Xe^{-\beta_n{}^2\tau}}{\beta_n + Sin\beta_n\,Cos\beta_n} \qquad (13)$$

Similarly,

$$M(X, T) = 2\sum_{n=1}^{\infty}\frac{Sin\text{ʎ}_n\,Cos\,\text{ʎ}_n \times e^{-\text{ʎ}_n{}^2\tau}}{\text{ʎ}_n + Sin\,\text{ʎ}_n\,Cos\,\text{ʎ}_n} \qquad (14)$$

Where; $\boldsymbol{\beta_n}$= roots of equation $\beta_n \tan\beta_n = Bi$ $\quad$ $\boldsymbol{\text{ʎ}_n}$ = roots of equations $\text{ʎ}_n \tan \text{ʎ}_n = Sh$

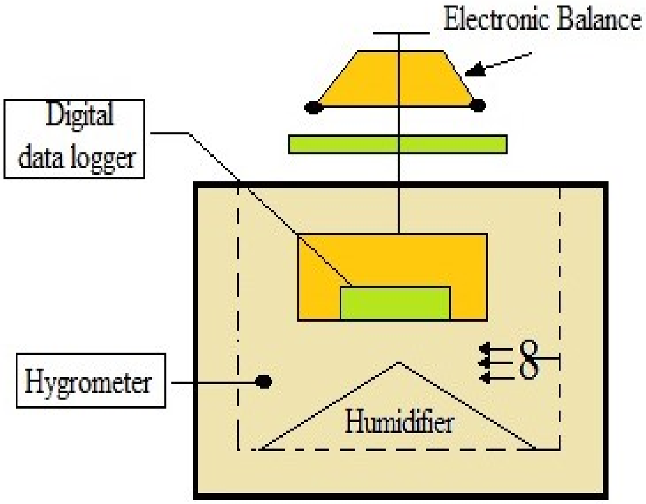

Fig.2: Schematic diagram of the equipment[15]

The Fig. 2 shows the illustration of different thickness of the plantain samples that was measured using an instrument called a thermocouple to ascertain the local temperatures, which was then stored in a digital data logger for a duration of 2minutesat intervals. In addition, the outcome perceived from the research was collected in developing the table which was used to classify it. Fig.2 also identifies the electronic balance scale handed-down to obtain the actual drying amount and as well as the weight differential of the plantain samples used for the experiment.

In the process of realising an accurate dehydration rate, as shown in figure 2 above the plantain samples were positioned into an oven at about 100^0 C for a period of7-8 hours. With regards to the convective drying procedures, streams of drying experimental analyses were performed to further validate the arguments. The plantain sample was, therefore, placed under different conditions as illustrated in Table1.

Table 1: Extended principles of the content drying evaluation[15]

Temp $^0\mathrm{C}$	Relative humidity %	Velocity m/s	$\frac{dT}{dt}$ $1\times10^4\ m/s$	$\frac{dM}{dt}$ $\left(x10^{4\%/E}\right)$	$\left.\frac{dT}{dx}\right\|_{x=1}$ $\left(^0\mathrm{C}/s\right)$	$\left.\frac{dT}{dx}\right\|_{x=L}$ $\left(\%/s\right)$
60	45	$0\cdot294$	$6\cdot75$	$-3\cdot421$	$176\cdot4$	-291
65	45	$0\cdot294$	$8\cdot25$	$-4\cdot522$	$219\cdot5$	-149
65	63	$0\cdot294$	$4\cdot23$	$-2\cdot153$	$104\cdot7$	-189
60	63	$0\cdot521$	$5\cdot51$	$-2\cdot553$	$147\cdot2$	-225

The inverse method was used to obtain the unknown parameters as described by the thermo-physical properties where the heat and mass transfer coefficients are prescribed as $\alpha_q = 254\times10^7\ m^2/s$, $\beta_q = 6\cdot95\times10^8\ m^2/s$ $\delta = 0.0124\ \mathrm{K}^{-1}$ and $E = 0.0185K$ [1], [14].

IV. RESULTS AND DISCUSSIONS

Matlab software was used in writing the codes for the developed models in the equations (13) and (14). The Figures 3a and 3b relates the results of the simulated and experimental process of drying temperature. It also shows the level of dampness with respect to drying time of the plantain during the forced convective drying procedure. Figure 3a outlines that as the temperature of each layer of plantain amplifies the dehydration period equally appreciates. Therefore, the differential in the temperature connecting the apex and the base surface of the samples reduces with the dehydration time.

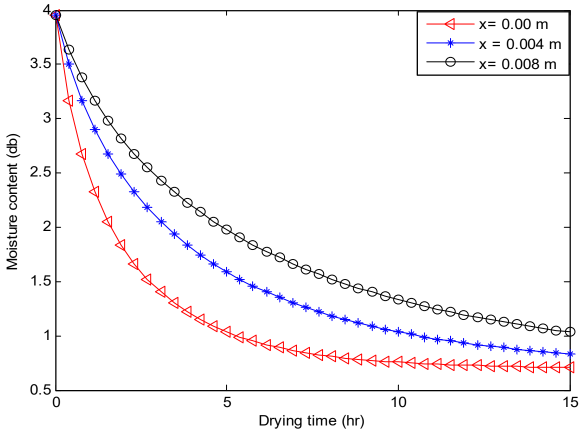

Figure 3a (Simulated)

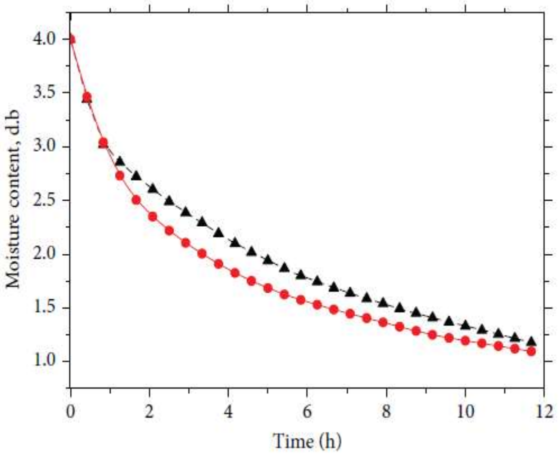

Figure 3b (Experimental)

Fig. 3: Result of product temperature on drying time

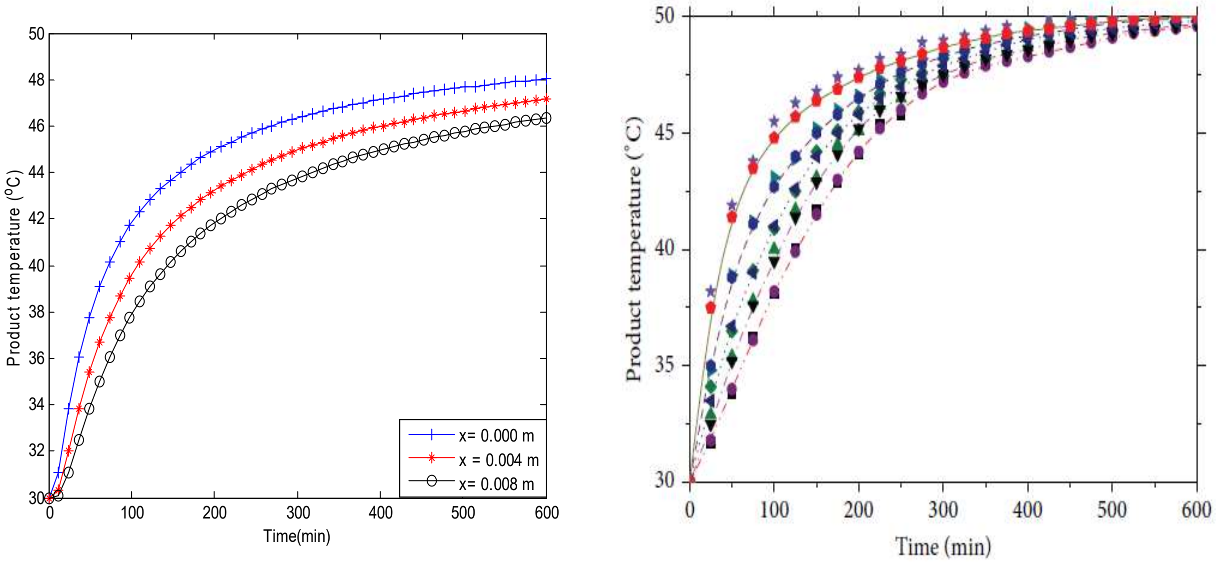

Figure 4a

Figure 4b

Fig. 4 Result of moisture content and dehydration time.

The result in the above figure 4a and 4b shows that the plantain dampness level decreases as the drying time increases, due to the fact that the rate of moisture content loss from the plantain becomes larger with the surrounding temperature air as the drying rate rises. The wetness content spans from 40% - 50% and the drying period falls at an interval of 0- 15 hours from the simulated result.

Table 2a: Moisture content comparison of the simulated and experimental result

Moisture Content (db)	Dehydration Time (hr)	
	Experimental	Simulated
1.2	9.3	8.4
1.5	7.6	6.1
2.0	3.9	4.0
2.5	2.1	2.1
3.0	1.4	1.4
3.5	0.9	0.7
4.0	0.0	0.0

Table 2b: Moisture content comparison of the simulated and experimental result

Moisture Content (db)	Dehydration Time (hr)	
	Experimental	Simulated
1.2	11.2	12.5
1.5	8.1	8.2
2.0	5.2	4.8
2.5	2.9	2.8
3.0	1.4	1.9
3.5	0.8	1.0
4.0	0.0	0.0

The tables 2a and 2b was obtained from figures 4a and 4b. The tables clearly shows that the experimental and simulated results are in close relations; it further shows that the moisture content of the plantain samples decreases as dehydration time increases.

Table 3a: Temperature comparison of the simulated and experimental result

Temperature ^{0}C	Dehydration Time (min)	
	Experimental	Simulated
30	0.0	0.0
33	23.0	22.0
36	37.0	36.0
39	58.0	59.0
42	101.0	102.0
45	126.0	132.0

Table 3b: Temperature comparison of the simulated and experimental result

Temperature ^{0}C	Dehydration Time (min)	
	Experimental	Simulated
30	0.0	0.0
33	45.0	48.0
36	72.0	77.0
39	125.5	120.0
42	210	180
45	380	240

The tables 3a and 3bdescribes the outcome of moisture content on the drying time in each instance. The similarity points of the experimental and simulated results are again closely related.

The result shows from the figures above that while the drying time increases the moisture content of the plantain decreases. This is as a result of the moisture loss from the plantain with the environmental temperature. However, the simulated model predicts the moisture content variations in close agreement with the experimental result.

V. CONCLUSION

The requirement for energy has increased by virtue of the consistency in the rise of population around the globe. This has set the pace for a steady rate of awareness, that drying has an important role to play in preserving food products without causing any depreciation in value. This research aims at developing heat and mass transport models for convective drying of plantain and equally validating the simulated model using a specific experimental data.

A mathematical model analysis was put forth with reference to the uncoupled heat and moisture movement was used in obtaining the result of temperature variations and dampness level inside the permeable materials at point when the convective drying was actualised. An analytical model interpreting the features of the convective drying principle was formulated and likewise to examine uncoupled heat and mass movement in the damped plantain using a closed form solution. Furthermore, a critical examination was put up investigating the consequence of using divergent properties of plantain specimens which lead to the consideration of the thermal diffusion and diffusion thermo effect on convective drying rate.

Finally, the result from the data shows that the product had a very great influence on the combined reaction of heat movement and moisture content on the sample when subjected to convective drying.

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