Analysis of Moisture Transport in the Solar Drying of Food Items.

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ABSTRACT

In this study, the principle of moisture transport in porous materials was used to analyze the rate of moisture removal from food items during the solar drying process. A cabinet solar dryer was designed, fabricated, and tested to evaluate moisture flux from samples of food items. The dryer exhibited sufficient ability to dry the samples reasonably to a safe moisture level. The results obtained show that at lower liquid concentrations the moisture flux increases with increase in the concentration, while the moisture flux was constant at liquid concentrations above 70 kg m^{-3} for shelled corn and above 150 kg m^{-3} for yam chips. The drying temperature and the intensity of solar radiation were the main factors that influenced the rate of moisture removal from the food items.

(Keywords: food items, liquid concentration, moisture transport, solar dryer, food preservation)

INTRODUCTION

Food and energy are the essential factors of the human survival, so the efforts for greater food production and smaller energy dissipation can undoubtedly provide more peaceful and secure future for mankind. Farmers in developing countries are confronted with the problem of preserving their harvested crops to prevent spoilage during storage. Farmers suffer heavy losses of food in the post harvest period during which the harvested crops pass through a series of well defined steps, like threshing (or shelling), drying, and final processing. Therefore, there must be a great interest in any device or process, which can contribute to the economic and industrial growth of developing countries.

Drying is a process by which water is removed from a substance. Two types of water are present in food items [1], the chemically bound water and the physically held water. In drying, only the physically held water is removed. The main reason for drying food items is to reduce its water content to a level where it can be safely stored for future use.

Many researchers have worked on the process of moisture transport in porous materials. Among them are Nowicki et al. [2]. Their study was based on the microscopic determination of transport parameters in drying porous media. Blumberg and Schluender [3] used a diffusion model to study the simultaneous vapor and liquid diffusion in partially wetted porous media. The diffusion approach was also used by Chen and Whitaker [4] to study moisture distribution during constant rate drying period for unconsolidated porous media.

Van der Zanden and Schoenmakers [5] presented a model for the influence of sorption isotherms on the drying of porous materials. The model described the evaporation inside a porous material with a mass transfer coefficient and a specific evaporating surface.

The various studies reviewed above were carried out in the area of moisture transport in drying of clay and earthen materials. Therefore, it is necessary to consider moisture transport in the drying of food items since the process involves the removal of moisture from the items to prevent the development of a favorable environment for the growth of moulds, bacterial, and insects that normally cause spoilage.

In this study, the mechanisms involved in the transport of moisture from food items during solar drying are analyzed. Also a cabinet solar dryer for food preservation is designed, constructed, and the performance is evaluated using the concept of moisture transport in porous materials.

MATERIAL AND METHODS

Moisture Transport in Drying of Food Items

A sample of food item is considered which has a volume (V). This sample can contain an amount of liquid water having a volume (V_L). The volume fraction of water is then V_L/V. The concentration of liquid water, E_L in kg per m^3 sample is:

$$E_L = \rho \frac{V_L}{V} \text{, therefore, } \frac{V_L}{V} = \frac{E_L}{\rho} \qquad \textbf{(1)}$$

where, ρ = density of water (kgm^{-3}).

The volume fraction of the vapor phase is (Blumberg and Schluender 1993):

$$\varepsilon - \frac{V_L}{V} \quad \text{or} \quad \varepsilon - \frac{E_L}{\rho} \qquad \textbf{(2)}$$

where, ε = the porosity.

The differential equations for the liquid and vapor transport can be derived by considering the liquid flux (n_L) and vapor flux (n_v) in the pores. For the liquid flux:

$$n_L = D_L \frac{\partial E_L}{\partial x} \qquad \textbf{(3)}$$

For vapor flux:

$$n_v = D_v \frac{\partial E_v}{\partial x} \qquad \textbf{(4)}$$

where E_v is the vapor concentration, and D_L and D_v are the liquid and vapor diffusion coefficient, respectively.

Considering the volume fraction of the vapor phase, Equation (2), the effective vapor flux in the sample is then:

$$n_v = \left(\varepsilon - \frac{E_L}{\rho} \right) D_v \frac{\partial E_v}{\partial x} \qquad \textbf{(5)}$$

At the drying surface a flux, N_{out}, occurs out of the drying sample which is the sum of the vapor flux, Equation (5) and liquid flux, Equation (3). Therefore,

$$N_{out} = D_v \left(\varepsilon - \frac{E_L}{\rho} \right) \frac{\partial E_v}{\partial x} + D_L \frac{\partial E_L}{\partial x} \qquad \textbf{(6)}$$

If the drying surface is very wet, the liquid flux dominates over the vapor flux. However, if the drying surface is very dry, the vapor flux dominates over the liquid flux. During the drying process the vapor flux becomes more significant and the liquid flux becomes less significant. If the vapor concentration, E_v, is in equilibrium with the liquid concentration, E_L, the moisture profiles inside the food item are not so much influenced by whether the flux at the surface is formed by a vapor flux or by a liquid flux.

The mathematical problem can be solved by introducing the boundary conditions. The boundary conditions are at the drying surface when x = 0 and at the isolated surface when x = H. At an isolated surface no flux occurs, therefore,

$$\frac{\partial E_v}{\partial x} = 0 \text{ and } \frac{\partial E_L}{\partial x} = 0 \text{ at } x = H \qquad \textbf{(7)}$$

Also, at the drying surface, the flux is formed by a vapor flux. Therefore,

$$N_{out} = D_v \left(\varepsilon - \frac{E_L}{\rho} \right) \frac{\partial E_v}{\partial x} \text{ at } x = 0 \qquad \textbf{(8)}$$

In the porous material there exists an equilibrium between E_L and the water activity in the vapor phase, a_w. The water vapor concentration in air when the air is saturated is denoted by $E_{v,sat}$. The vapor concentration in the vapor phase in equilibrium with E_L is $a_w E_{v,sat}$. Therefore, the water vapor flux, N_{out}, from the surface to the bulk is:

$$N_{out} = k_m \left(a_w E_{v,sat} - E_v \right) \qquad \textbf{(9)}$$

where, k_m = the mass transfer coefficient.

Substitution of Equation (9) in Equation (8) gives:

$$D_v \left(\varepsilon - \frac{E_L}{\rho} \right) \frac{\partial E_v}{\partial x} - k_m \left(a_w E_{v,sat} - E_v \right) = 0 \qquad \textbf{(10)}$$

Equation (10) is solved numerically by the Crank Nicolson method [5] using the simplification that the process of vapor diffusion is quasi-steady.

Design of Solar Dryer

The heat gained by the dryer per unit time, Q_g is given by [6]:

$$Q_d = A[I\tau\alpha - U_L(T_i - T_a)]. \quad \textbf{(11)}$$

where, A = area of transparent cover (m^2)
I = incident insolation (Wm^{-2})
U_L = overall heat loss for the collector ($W\,^0C^{-1}$)
α = solar absorbance
τ = transmittance
T_i = temperature of incoming air
T_a = temperature of ambient air

Since the dryer draws the ambient air directly, the last term on the right-hand side vanishes and the rate of energy collection is simply:

$$Q_d = AI\tau\alpha \quad \textbf{(12)}$$

If the mass of air leaving the dryer per unit time is $\dot{m}_a$, the heat gained by the air Q_u is [7]:

$$Q_a = \dot{m}_a C(T_o - T_i). \quad \textbf{(13)}$$

where, C = specific heat capacity of air ($kJkg^{-1}\,^0C^{-1}$)
T_o = temperature of out-going air

A simplified energy equation for the dryer is $Q_g = Q_u$, i.e.,

$$AI\tau\alpha = \dot{m}_a C(T_o - T_i). \quad \textbf{(14)}$$

Therefore, the required surface area of the transparent cover, which determines the size and dimensions of the dryer, is obtained from:

$$A = \frac{\dot{m}_a C(T_o - T_i)}{I\tau\alpha} \quad \textbf{(15)}$$

The total energy required for drying a given quantity of food items can be estimated using the basic energy balance equation for the evaporation of water [8]:

$$\dot{m}_w L_v = \dot{m}_a C(T_o - T_i). \quad \textbf{(16)}$$

where, L_v = specific latent heat of vaporization of water from the food surface (kJ/kg)
$\dot{m}_w$ = mass of water evaporated from the food item ($kg\,s^{-1}$).

The mass of water $\dot{m}_w$ is estimated from the initial moisture content M_i and the final desired moisture content M_f as follows:

$$\dot{m}_w = \dot{m}_{wc}\left(\frac{M_i - M_f}{100 - M_f}\right) \quad \textbf{(17)}$$

where $\dot{m}_{wc}$ is the mass of the wet crop or food item ($kg\,s^{-1}$).

During drying, water at the surface of the substance evaporates and water in the inner part migrates to the surface to get evaporated. The ease of this migration depends on the porosity of the substance and the surface area available. Other factors that may enhance quick drying of food items are: high temperature, high wind speed and low relative humidity.

Construction of the Solar Dryer

The solar cabinet dryer is shown schematically in Figures 1 and 2. The transparent top cover is 4 mm thick clear glass with a total surface area of 1.22 m by 0.90 m. The dryer cabinet is made of 25 mm plywood. The front is higher than the rear giving the top cover an inclination of about 17.5^0. This is approximately 10^0 more than the local geographical latitude (Ado-Ekiti Nigeria, 7.5^0N), which is the best recommended orientation for stationary absorber [9]. This inclination is also to allow easy run off of water and to enhance air circulation.

Vents were made at the low end of the front of the cabinet and at the upper end of the back of the cabinet to facilitate and control the convectional flow of air through the dryer. A drying tray was constructed with wire mesh, which fitted snugly and covered the entire floor of the dryer. Access door was also provided at the back of the cabinet to allow the loading of the drying tray with food items.

The dryer is a passive system in the sense that it has no moving parts. It is energized by the sun's rays entering through the transparent top. The trapping of the rays is enhanced by the inside surfaces that were painted black and the trapped energy heats the air inside the dryer. The green house effect achieved within the dryer drives the air current necessary for faster drying. The hot air rises and escapes through the upper vent while cooler air at ambient temperature enters through the lower vent.

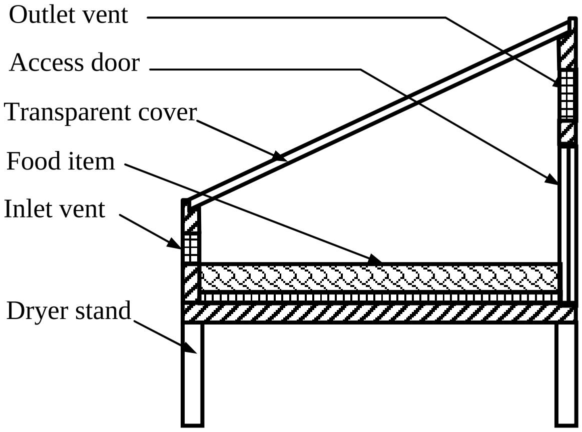

Figure 1: Solar Cabinet Dryer.

RESULTS AND DISCUSSION

The solar cabinet dryer was tested to evaluate the moisture transport in food items during drying. The temperature profile of the dryer was determined by measuring the hourly temperatures inside the drying cabinet and the ambient air between 08.00 and 18.00 hours (local time). The results obtained are shown in Figure 3.

The incident solar radiation intensity was measured using a portable Kipps Solarimeter and the result is also shown in Figure 3. During test periods, the dryer was used to dry yam chips and shelled corn. Known weights of these items were dried until no further weight loss was attained and the time taken measured. Moisture removed from the item was measured hourly during the day. The results are shown in Figures 4 and 5.

Figure 3 shows the hourly variations of the dryer and ambient air temperatures along with the corresponding variation of solar radiation intensity.

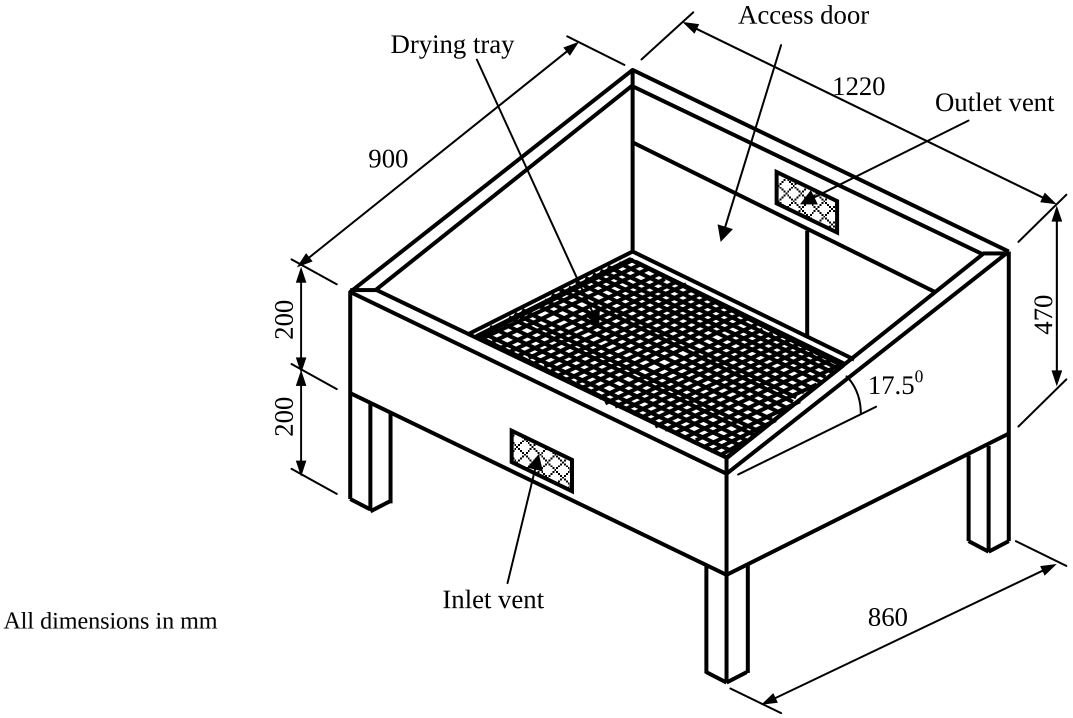

Figure 3: Isometric Drawing of Solar Cabinet Dryer.

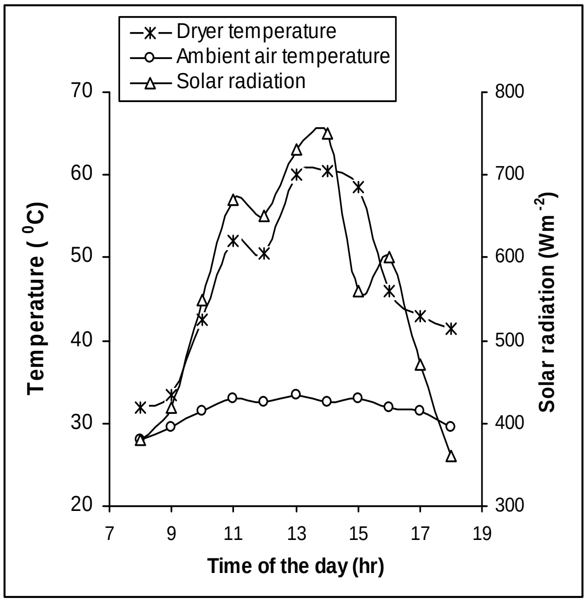

Figure 3: Hourly Variation of Dryer Temperature, Ambient Temperature, and Solar Radiation.

As the solar intensity increases, the dryer temperature also increases. The heating temperature inside the dryer was higher than the ambient air temperature throughout the greater part of the daylight. This indicates prospect for higher rate of moisture transport in solar dryer than open-air sun drying.

Figure 4 shows the curves of moisture flux as a function of liquid concentration in the food items. It was observed that at lower liquid concentration, the moisture flux increases with increases in the liquid concentration, but the moisture flux was constant at liquid concentration above 70 kg m^{-3} for shelled corn and above 150 kg m^{-3} for yam chips. This shows that yam chips are more hygroscopic than shelled corn.

The moisture content versus time plot (solar drying curves) for yam chips and shelled corn are shown in Figure 5. The drying rate was quite low during the first two hours as the drying chamber warmed up and the solar intensity was low. The maximum drying rate occurred between 100.00 hour to 14.00 hour, which correspond to the period of high temperature inside the dryer and high solar radiation intensity.

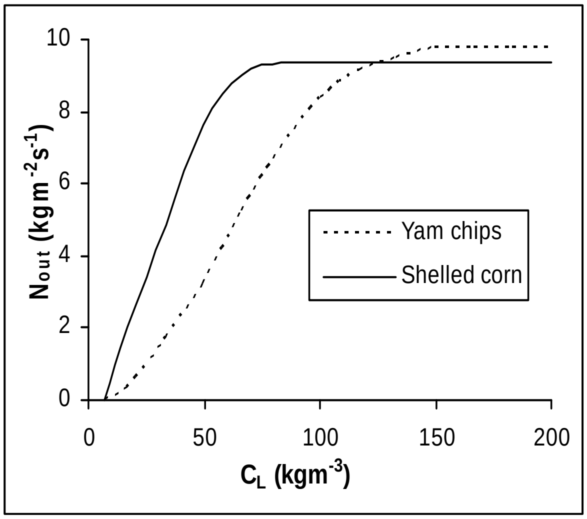

Figure 4: The Moisture Flux (N_{out}) as a Function of Liquid Concentration (C_L) in Solar Drying of Yam Chips and Shelled Corn.

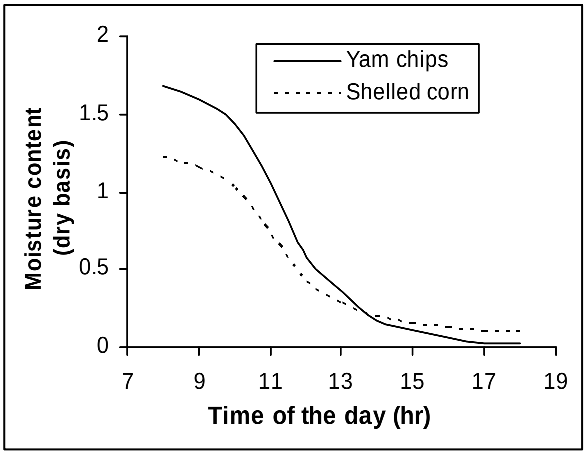

Figure 5: Drying Curves of Yam Chips and Shelled Corn in the Solar Dryer.

CONCLUSION

The principle of moisture transport in porous media has been used to analyze the rate of moisture removal from food items during solar drying. In order to evaluate the moisture flux, a solar cabinet dryer was designed, fabricated, and used to dry yam chips and shelled corn as samples of food items. The results obtained indicate prospect for higher rate of moisture removal in solar dryer than open-air sun drying.

The results also show that at lower liquid concentration in the food items, the moisture flux increases with increase in the liquid concentration and constant at higher liquid concentration. The rate of moisture removal from the food item is a function of both the temperature inside the dryer and intensity

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NOMENCLATURE

a_w - water activity defined under materials and methods
A_c - area of transparent cover (m^2)
C - specific heat capacity of air (kJ $kg^{-1}\ {}^0C^{-1}$)
D - diffusion coefficient
E - concentration in the porous material (kg m^{-3})
H - height of the sample (m)
I - incident solar radiation (W/m^2)
k_m - mass transfer coefficient
L_v - specific latent heat of vaporization of water from the food surface (kJ kg^{-1})
$\dot{m}$ - mass flow rate (kg s^{-1})
M - moisture content, decimal dry basis
n - flux in the pores mass (kg $m^{-2}s^{-1}$)
N - moisture flux (kg $m^{-2}s^{-1}$)
Q - heat gain per unit time (W)
t - time (s)
T - temperature (${}^0C$)
U_L - overall heat loss for the collector (W^0C^{-1})
V - volume (m^3)
x - position (m)

Greek symbols:

α - solar absorptance
ε - porosity
ρ - density of water (kg m^{-3})
τ - transmittance

Subscripts:

a - air
d - dryer
f - final
i - inlet, initial
L - liquid
out - leaving the sample
sat - saturation
v - vapor
w - water
wc - wet crop or food item

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