THERMAL CONVECTION AND MOISTURE-DIFFUSION IN THIN-LAYER FIXED-BED SOLAR DRYING

*A. Ayensu**

ABSTRACT

A mathematical model, developed for macroscopic and microscopic heat- and mass-transfer for thin-layer fixed-bed natural convective solar drying, has been used to predict the drying time, drying rates and coefficient of moisture-diffusion. The parameters considered in the analysis were: (i) the initial conditions of the sample to be dried and (ii) the psychrometry of the ambient and heated air, for the low temperature drying (32 °C <T< 57 °C)

The drying processes involve movement of moisture, within the food sample, to the surface and removal of moisture from the surface. Moisture-movement within the sample is controlled by moisture concentration-gradient, while the driving force for the moisture-evaporation is the difference between partial pressure of the water-vapour at the surface, and that in the drying air-stream. It is, therefore, shown that Fick's law holds for the moisture-loss, involving non-steady state diffusion.

During the convective drying, heat-transfer between the sample and the surroundings is controlled by the humidity-ratio of the saturated air at the surface and the drying air, the temperature of the plenum and temperature of the sample surface.

INTRODUCTION

Solar drying refers to the removal of free and bound moisture from a sample, by using solar energy in a specially designed dryer. Recent requirement for quality farm-produce, devoid of moulds and aflatoxins, has generated renewed interest in solar drying, for post-harvest processing and storage. In convective solar drying, the airflow is generated by natural convection, while the drying process involves the passage of solar-heated air, unlike open-air sun-drying, where the sample is exposed directly to solar radiation. During drying, there is simultaneous transfer of heat, to evaporate and transfer moisture to the surface and as vapour from the surface into the hot carrier-air, within an optimal period of time, to preserve integrity of the product.

Movement of moisture through the sample is in the form of water-vapour within the cell-cavities and bound water that is hydrogen-bonded to the hydroxyl groups of the polysaccharides. Therefore, the driving force responsible for moisture-transport is a combination of diffusion, along the moisture concentration-gradient and difference of vapour-pressure due to temperature-gradient. As shown in Figure-1, the transfer of liquid inside a sample may occur by various mechanisms; including diffusion in the continuous homogeneous solids, capillary-flow in the granular and porous solids, flow caused by shrinkage and pressure-gradients, and flow caused by sequence of vapourization and condensation. In this paper we present and discuss the factors governing the heat and transfer of mass in determining the drying rates as well as the analytical equations and numerical parameters for designing convective solar dryers.

Ayensu and Bondzie [1] tested a low-cost, non-mechanical, fixed-bed convective solar dryer, which uses a flat-plate solar collector and energy-storage system, to dry agricultural produce, such as cassava-chips and vegetables. The experimental trials have spanned a period of ten years and the technology has been transferred to community-based food-processors and exporters of non-traditional crops. For instance, cassava-chips were dried from initial moisture-content of about 70%, to final moisture-content of 14% on wet basis in 80h, and the dried samples were stored for one year without deterioration [2]. The dryer was designed to operate efficiently on solar radiation of intensity ranging from 550 - 1075 Wm^{-2} and total incident-energy of 15 - 30 MJm^{-2} per day [3]. The tilt-angle of south-facing collector was set at 15 Ú (i.e. latitude + 7Ú), to offer the highest solar-irradiation for drying, throughout the year [4]. The design also incorporates a rock energy-storage system that enhances drying during the night and cloudy weather.

Figures 2 (a), (b) and (c) illustrate the moisture-loss profiles of cassava-chips, exhibiting constant-rate and falling-rate drying periods. The constant-rate period (IC) of drying involves removal of free or unbound water, while in the falling-rate period (CF), there is removal

* Industry, Natural and Social Sciences Sector, Council for Scientific and Industrial Research (CSIR), P.O.BoxM32, Accra, Ghana.

of bound water in the cell-walls of the product. The falling- rate period is described by two stages, namely, the first falling-rate period (CE), and the second falling-rate period (EF). The regime CE consists of a period of evaporation from a saturated surface of gradually decreasing area, while the regime EF consists of a period when the water evaporates in the interior of the solid.

During the drying process, heated air at the plenum temperature, T_P, is passed over the layer of food-crop of initial moisture-content, M_I %, at time t = 0, to reach a critical moisture-content, M_C %, at the end of the constant-rate period ($t = t_C$); to be followed by the falling-rate period, upto the attainment of equilibrium moisture-content, M_E % ($t = t_E$); for the air to exit at the chimney temperature (T_C) into the atmosphere.

The attainment of critical moisture-content depends on the drying conditions (humidity and temperature) and the characteristics of the samples (shape, size, density, area and specific heat-capacity). Moisture in excess of free moisture-content, in equilibrium with the air, can only be removed upon prolonged contact of the sample with hot drying air. The drying parameters of selected food-samples are shown in Table-1.

CONVECTIVE SOLAR-DRYING PROCESS

Natural convective drying is reliant on thermally induced density-gradients for the flow of air through the dryer. Figure-3 is a schematic diagram of a thin-layer fixed-bed drying-system, in which the drying air is moving from the plenum through the food-bed, in the drying chamber, to the chimney. Ambient air at temperature T_A is heated by solar energy, via the collector, to plenum temperature T_P before being used in dehydrating food-samples, in the drying chamber. Exchange of moisture takes place in a finite depth or layer in the drying zone, as the heated air takes up the moisture by convection and is cooled by evaporation.

Samples located below the drying zone have attained moisture-content (M_E), and are in equilibrium-conditions with the in-coming hot air, while those above the zone have not begun to dry and still have the initial moisture-content (M_I), which is assumed to be constant or uniform. Two gradients, therefore, exist across the drying zone: (i) a moisture concentration-gradient from M_I to M_E, and (ii) a temperature-gradient from T_P to T_C. For a shallow food-bed of depth H” 0.3 m, with convective airflow of velocity of 4.4 m/min, the drying zone will extend completely through the bed [2].

Table-1: Drying Parameters for Selected Food-Samples

Samples dried	Drying time (h)			Moisture Content (%)					Moisture diffusion coefficient (cm/s^2)			Drying constant (h^{-1})	
(thickness, δ)	t_{IC}	t_{CF}	t_D	M_I	M_C	M_E	M_f	M_b	Constant Rate, D_{IC}	Falling Rate, D_{CE}	Overall DIE	Constant Rate, k_C	Falling Rate, k_E
Cassava Leaves (δ ~ 2 mm)	10	26	36	72	45	13	27	32	3.83×10^{-2}	1.11×10^{-2}	1.00×10^{-2}	0.025	0.018
Pepper (δ ~ 1 cm)	10	56	66	68	52	13	16	39	3.30×10^{-2}	6.37×10^{-3}	5.99×10^{-3}	0.047	0.027
Groundnuts (δ ~ 1 cm)	11	57	68	70	47	13	23	34	3.30×10^{-2}	5.97×10^{-3}	5.81×10^{-3}	0.028	0.016
Cassava chips (δ ~ 3 cm)	12	68	80	75	55	13	20	42	2.94×10^{-2}	5.35×10^{-3}	5.08×10^{-3}	0.031	0.012
Fish (δ ~ 5 cm)	20	110	130	80	61	13	19	48	1.74×10^{-2}	3.39×10^{-3}	3.17×10^{-3}	0.014	0.009

Note: (M_C = critical moisture content; M_E = equilibrium moisture content; M_f = free moisture content; M_b = bound moisture content; t_{IC} = time to attain M_C; t_{CF} = time to attain near zero moisture content; t_D = total drying time; D = moisture diffusion coefficient; k = drying constant)

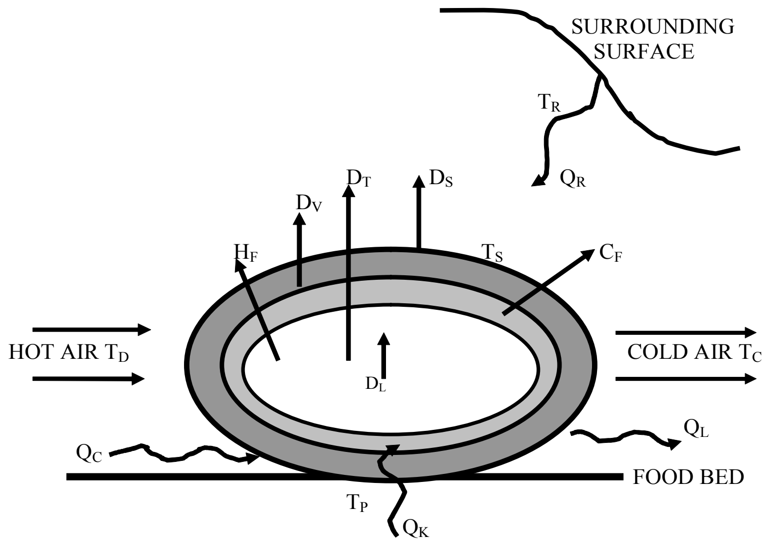

Figure - 1: A schematic diagram of heat and moisture flow between food-sample and surroundings in the drying chamber, illustrating thermal conduction (Q_K), latent heat (Q_L), thermal radiation (Q_R), thermal convection (Q_C), plenum temperature (T_P), drying-zone temperature (T_D), surface temperature (T_S), chimney temperature (T_C), temperature of radiating surface (T_R), capillary flow (C_F), hydro-dynamic flow (H_F), vapour-diffusion flow (D_V), thermal diffusion (D_T), surface diffusion (D_S) and liquid diffusion (D_L).

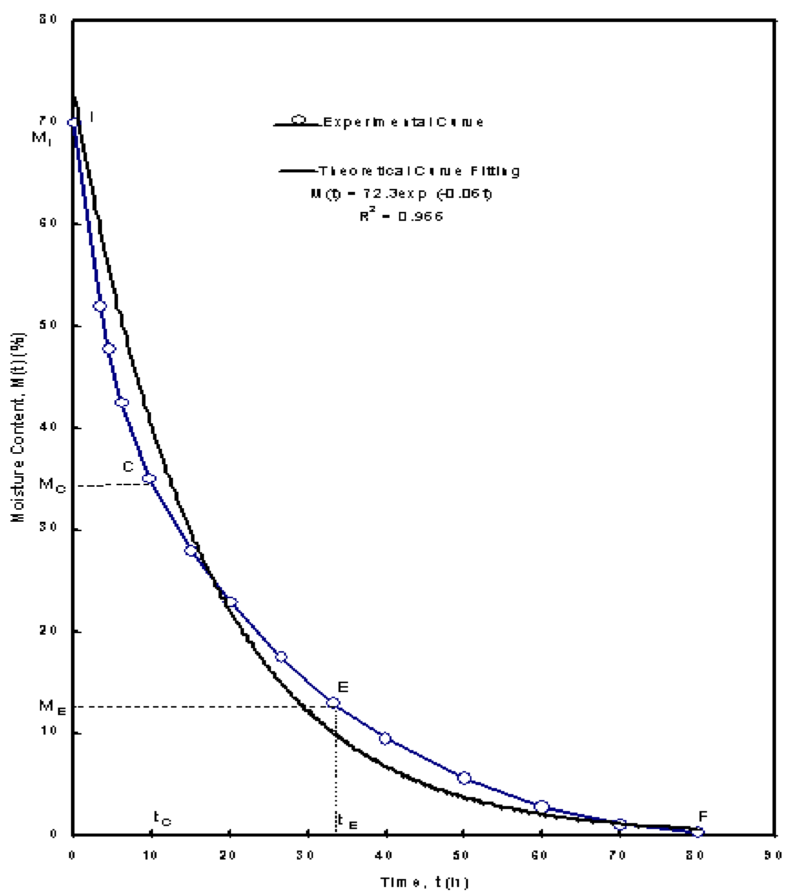

Figure - 2(a): Drying curves for cassava-chips of sizes 3 cm

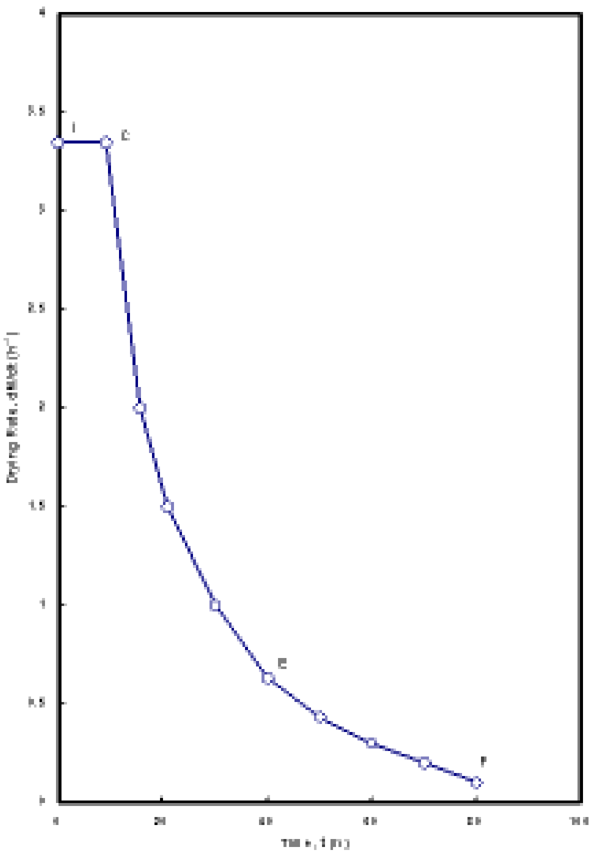

Figure - 2(b): Drying-Rate versus Time

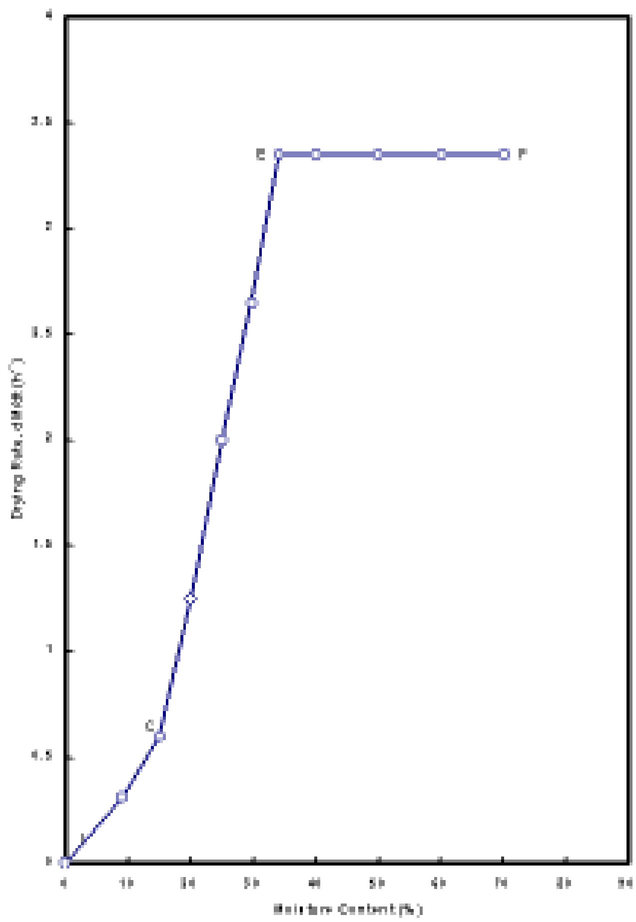

Figure - 2(c): Drying-Rate versus Moisture-Content

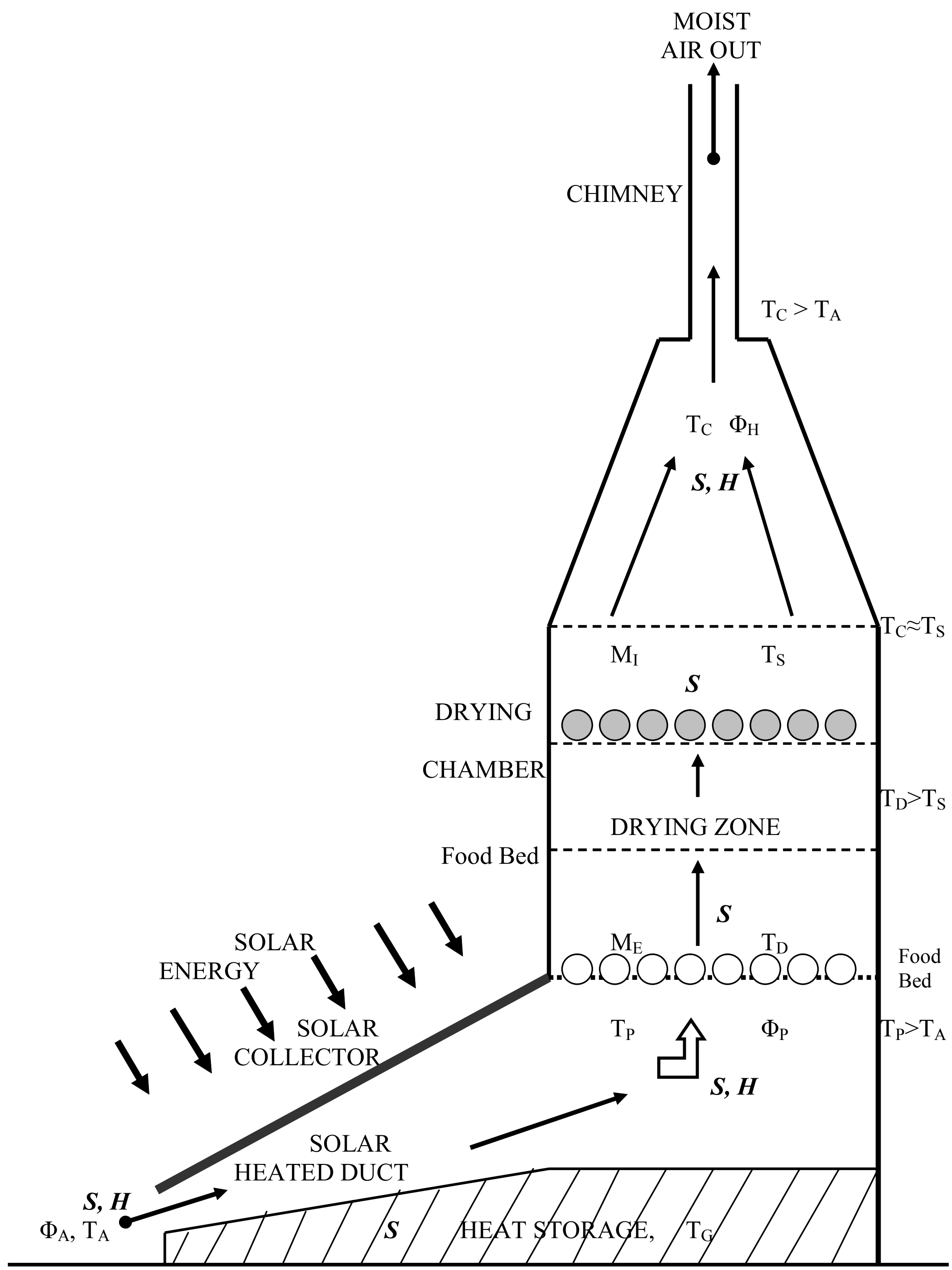

Figure - 3: A Fixed-Bed Thin-Layer Solar Dryer with Temperature and Humidity Sensors Located at Points S and H, Respectively

PSYCHROMETRY AND PRINCIPLES OF DRYING

During the initial stage of drying the rate of moisture-loss can be considered as a function of three external parameters; namely, air-velocity, drying air-temperature and relative humidity in the plenum chamber. The principles of drying can, therefore, be examined on a standard ASHRAE Psychrometric Chart Number-1 for normal temperature range [5].

As illustrated in Figure-4, if air at ambient temperature T_A = 32° C and relative humidity ϕ_A = 80 % is heated by solar-energy to plenum-temperature T_P = 45° C, the relative humidity is reduced to ϕ_P = 40 %. If the heated air (T_P = 45° C, ϕ_P = 40 %) is used to remove moisture from a bed of cassava-chips of M_I ~ 70 % (wet basis) and the equilibrium ϕ_C = 90 % is reached, the temperature of the drying air is reduced to T_C = 33.3° C, and the humidity ratio, W, changes from 0.0248 to 0.0296; i.e. $\Delta W = W_C - W_P = 0.0048$. On the contrary, if ambient air at T_A = 32° C and ϕ_A = 80 % is used directly in a sun-drying process and equilibrium humidity is reached, the temperature will be reduced to T'_A = 30.6° C and the humidity ratio changes from 0.0248 to 0.0254, or ΔW = 0.0006. The above analysis indicates that the drying capability of the solar-heated air is eight times greater than it would have been if the air had not been pre-heated (as in ordinary sun-drying). The two distinct drying paths APC and AD, representing solar drying and sun drying, respectively, are shown in Figure-4.

To predict the drying rate, it is not only the extent of macroscopic convective heat- and mass-transfer, associated with the sample and the surroundings in the drying chamber that have to be considered, but also the mechanisms of microscopic heat- and mass-diffusion within the sample must be included in the analysis, as illustrated in Figure-1. The rate of heat or mass-transfer is determined by multiplying the respective transfer-coefficient and the driving force.

The mathematical equations developed for heat and mass-transfer were used to simulate the drying processes to obtain drying parameters (Table-1) for the design and optimization of the drying. The data obtained for the drying time and drying constant represent both the macroscopic and microscopic phenomena of the drying.

MEASUREMENT OF TEMPERATURE AND RELATIVE HUMIDITY

The temperature profile in the solar-dryer determines the performance of the drying-system. Copper-constantan thermocouples were used to measure the temperature, since the thermocouple-generates a linear response over the operating temperature range (0–100ºC) and gives a large output for a given temperature-difference. Copper-constantan is also resistant to corrosion in moist atmosphere and is available in a relatively homogenous state and in thick wires of convenient sizes (~1mm diameter).

The temperature-profile was measured at hourly intervals, using the thermocouples inserted at various locations (S) as indicated in Figure-3. Figure-5 shows the diurnal variation of temperature with time as monitored during the drying process for ambient (T_A), plenum (T_P), drying zone (T_D), chimney (T_C) and the energy storage-medium (T_G). The values of temperature within the dryer were greater than the ambient air-temperature, such that $T_A < T_C < T_D < T_P < T_G$. The peak values of temperature recorded in the dryer occurred at about 1400 H, as against 1300 H for ambient when the solar intensity is expected to be greatest in the locality. The time-lag is due to large thermal inertia of the collector, dryer-superstructure and storage system, since the materials used for the collector, dryer and absorber have large heat-capacity. On continuous operation, the time-lag is reduced by about 30 min, due to the smoothing effect of the energy storage-system.

A thermo-hydrograph (type 110) and a hair-hygrometer, were used to measure the relative humidity at locations (H) as indicated in Figure-3. A micro-anemometer was used to measure the rate of airflow into the plenum-chamber. Figure 6 shows the diurnal variation of relative humidity during the drying process for ambient (ϕ_P), plenum (ϕ_P) and chimney (ϕ_C), respectively.

MACROSCOPIC HEAT- AND MASS-TRANSFER

The heat-transfer between a food-sample and surroundings involves latent heat by virtue of moisture-evaporation, and sensible heat due to convective, radiative and conductive heat-transfer. If the heat is supplied by convection, conduction and radiation, the surface-temperature (T_S) of the food-sample will be higher than the wet bulb-temperature (T_W), and hence the rate of drying can be expressed as [6]:

$$-\frac{dM}{dt} = \frac{h_C A(T_P - T_S) + \dot{Q}_C + \dot{Q}_R}{\Delta H} \quad (1)$$

where h_C is convective heat-transfer coefficient, A is surface-area for heat-transfer, T_P is temperature of the drying air in the plenum (temperature of dry-bulb), T_S is temperature of sample-surface in the drying chamber, $\dot{Q}_C$ is heat transferred by conduction, $\dot{Q}_R$ is the heat transferred by radiation and ÄH is the enthalpy.

The effect of radiation and conduction are negligible in convective solar-drying; and with the assumption that T_S varies with the drying-front (constant value cannot be accurately measured), the surface-temperature can be approximated to the chimney-temperature, T_S H≈T_C, such that eqn. (1) reduces to

$$-\frac{dM}{dt} = \frac{h_C A(T_P - T_S)}{\Delta H} \approx \frac{h_C A(T_P - T_C)}{\Delta H} \quad (2)$$

For macroscopic mass-transfer, the drying-rate could be written as:

$$-\frac{dM}{dt} = g_m A(P_S - P_P) \quad (3)$$

where g_m is the coefficient of mass-transfer, A is the surface area and $P_S - P_P$ (partial pressure driving force) is the difference between the partial pressure of the water-vapour at the surface and the hot-air stream in the plenum.

By combining eqns. (2) and (3), the general expression for convective drying can be expressed as

$$-\frac{dM}{dt} = \frac{h_C A(T_P - T_S)}{\Delta H} = g_m A(P_S - P_P) \quad (4)$$

MICROSCOPIC MOISTURE AND THERMAL DIFFUSION

As illustrated in Figure-1, the mechanisms for moisture-transfer in a capillary-porous food-sample are capillary flow (liquid movement due to surface-forces), liquid diffusion, (liquid movement due to moisture-concentration differences), surface-diffusion (liquid movement due to diffusion of moisture to the pore-surface), vapour-diffusion (vapour movement due to moisture-concentration differences), thermal diffusion (vapour movement due to temperature-differences), and hydrostatic flow (water and vapour movement due to total pressure differences).

The moisture-transfer from the sample interior to the surface is predominantly due to thermal-stimulated diffusion, resulting from vapour-movement due to moisture-concentration gradient. The net flux, J(x, t), of water molecules diffusing per second across a unit area is proportional to the moisture-concentration gradient, (∂M(x, t)/∂x), or,

$$J(x,t) = -D\frac{\partial M(x,t)}{\partial x} \quad (5)$$

where D is the moisture-diffusion coefficient, x is the distance from the centre of mass to the surface of sample, being dried and t is drying time. Since the diffusion-process causes the concentration of water-molecules to change with time, the flux changes from J_1 to J_2 over a distance äx, such that $J_2 = J_1 - (\partial J_1/\partial x)\delta x$. Therefore, at the microscopic level, the amount of material depleting in a volume per second, $\delta J = J_2 - J_1$, can be expressed as,

$$\delta J = \frac{\partial J}{\partial x}\delta x = \frac{\partial}{\partial x}\left(-D\frac{\partial M}{\partial x}\right)\delta x \text{ or } \frac{\partial J}{\partial x} = -\frac{\partial}{\partial x}\left(D\frac{\partial M}{\partial x}\right) \quad (6)$$

Continuity relation requires flux-change over distance to be equal to the rate at which the moisture-concentration in the volume is decreasing with time, ∂M/∂t = - ∂J/∂x, or

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial M}{\partial x}\right) \quad (7)$$

Equation (7) is the general form of Fick's second law for diffusion in one dimension that applies when the diffusion-coefficient (D) is a function of concentration. For cases where D is considered constant, eqn. (7) reduces to a simpler form,

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial x^2} \quad (8)$$

showing that Fick's law holds for microscopic moisture-loss involving non-steady state diffusion.

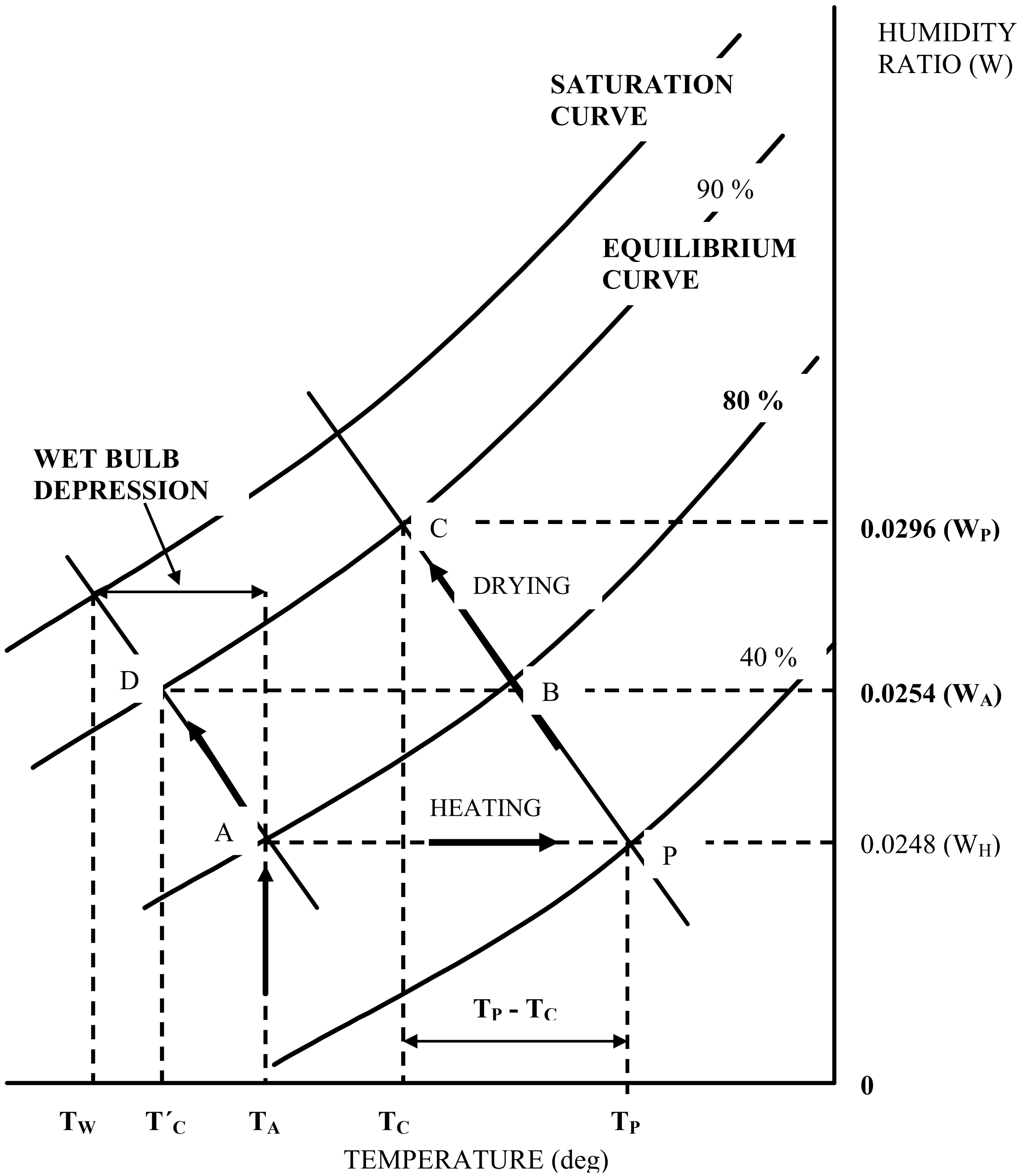

Figure - 4: A Schematic Psychrometric Chart, Illustrating Temperature-Changes of Heated and Unheated Air During Drying

At the surface of the sample, the rate of moisture-evaporation can be considered a function of moisture-difference between the drying air and the sample-surface through the surface-conductance, S (m/s), such that [8],

$$\left(\frac{\partial M}{\partial t}\right) = S(M_S - M_E) \qquad (9)$$

where M_S is the moisture-content at the surface and M_E is the equilibrium moisture-content. It is also assumed that equilibrium exists at the interface between liquid and drying air; that is, the resistance to mass-transfer across the interface is negligible. Solutions of eqns. (8) and (9) determine the relationship between variation of moisture-content with time and product geometry, respectively.

SOLUTIONS FOR DRYING EQUATIONS

As shown in Figure-2, the profile of convective drying exhibits a short period of constant drying (IC), whereby moisture is removed at a uniform rate, until the critical moisture is reached; beyond this is the falling-rate period (CE), where the moisture-removal decreases and is characterized by subsurface-evaporation throughout, until the equilibrium moisture-content is reached.

The rate of moisture-replenishment to the surface by diffusion from the interior depends on the nature of the sample and the moisture-content. If diffusion-rate is slow, it becomes the limiting factor in the drying process, but if it is sufficiently rapid, the controlling factor will be the rate of evaporation at the surface.

Constant-Rate Period

During the constant drying-rate period, the surface of the sample behaves as free-water and drying continues as long as water is supplied to the surface as evaporation takes place. If moisture-movement within the solid is sufficiently rapid to maintain a saturated condition at the surface, and if heat is supplied by convection from warmer air only, the surface temperature is the wet bulb-temperature.

For mass-transfer, the driving force for constant-rate drying is the difference between partial pressure of water-vapour at the surface and in the hot-air stream in the plenum, and eqn. (3) can be applied to express the free-surface evaporation of water or moisture-loss in the form:

$$\left(\frac{dM}{dt}\right)_{CR} = -g_m A(P_S - P_P) \qquad (10)$$

For heat-transfer, the driving force for constant-rate drying is the temperature-difference between the heated air and the exit-air, and the rate of drying given by eqn. (2), can be expressed as:

$$\left(\frac{dM}{dt}\right)_{CR} = -\frac{h_c A(T_P - T_C)}{\Delta H} \qquad (11)$$

If T_P - T_C = 0, the air is saturated and no drying takes place. In practice, eqn. (11) provides a more reliable estimate of the drying-rate than eqn. (10), because an error in estimating the surface-temperature affects the temperature driving force (T_P - T_C) less than the partial pressure driving force (P_S - P_P).

If the air-stream is constant, the time to attain critical moisture content at the end of the constant-rate period, $t_{IC,}$ can be determined by integrating eqn. (11) from M_I to M_C;

$$t_{IC} = \frac{\Delta H}{h_c A(T_P - T_C)} \int_{M_C}^{M_I} dM = \frac{\Delta H(M_I - M_C)}{h_c A(T_P - T_C)} \qquad (12)$$

Falling-Rate Period

Most of the drying takes place in the falling-rate period and involves the movement of moisture within the material to the surface and removal of moisture from the surface. As previously explained, the falling-rate period indicated by curve CF (in Figure-2) can be divided into the zone of unsaturated surface-drying (CE) and the zone where internal liquid-flow is controlling (EF).

During the falling-rate period, the driving force is determined by the moisture-concentration, hence, the drying-rate can be considered as a linear function of the available moisture, as shown by the straight line CE in Figure-2 (c), and eqn. (9) can be applied

$$\left(\frac{dM}{dt}\right)_{FR} = -k(M(t) - M_E) \qquad (13)$$

where M(t) is the moisture content in the zone of unsaturated surface-drying and the critical moisture-

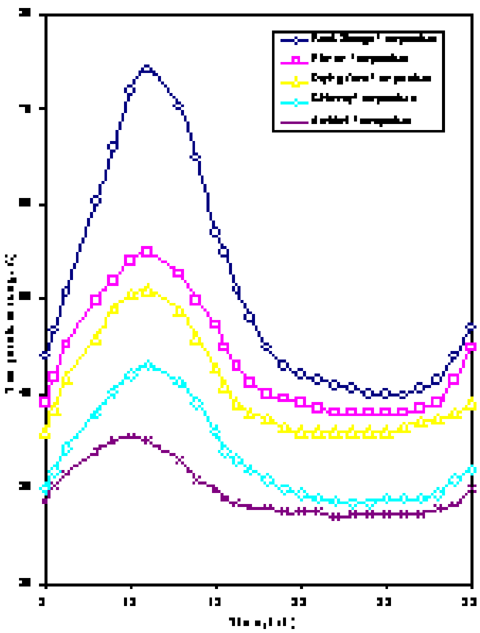

Figure - 5: Diurnal-Temperature Cycle for Drying Cassava-Chips

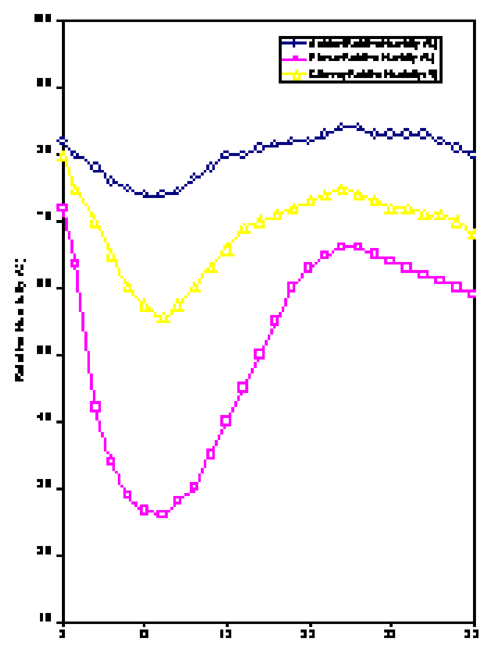

Figure - 6: Diurnal Humidity-Cycle during Dryng

content has been achieved. The drying constant, k, can be determined by applying the continuity relation $(dM/dt)_{CR} = (dM/dt)_{FR}$ to the process of desorption, such that:

$$h_C A(T_P - T_C)/\Delta/ = k(M_C - M_E) \text{ or } k = \frac{h_C A}{\Delta H}\frac{(T_P - T_C)}{(M_C - M_E)} \quad (14)$$

Combining eqns. (13) and (14) yields the expression:

$$\left(\frac{dM}{dt}\right)_{FR} = -\frac{h_C A(T_P - T_C)}{\Delta H}\frac{(M(t) - M_E)}{(M_C - M_E)} = k'\frac{(M(t) - M_E)}{(M_C - M_E)} \quad (15)$$

Integrating eqn. (15) from the critical moisture-content (M_C) to average moisture-content of the unsaturated zone ($\overline{M}$) gives the time to complete the first falling-rate as,

$$t_{CE} = \frac{\Delta H(M_C - M_E)}{h_C A(T_P - T_C)}\ln\left[\frac{M_C - M_E}{\overline{M} - M_E}\right] \quad (16)$$

where values of M_E obtained under conditions that simulate those in the dryer must be used, since M_E is a function of both the humidity and temperature of the air and of the surface-temperature of the solid.

In ideal situation of drying to near zero moisture-content ($M_E \approx 0$ %), covering both the first and second falling- rate periods, eqn. (16) can be approximated to by:

$$t_{CF} = \frac{\Delta H(M_C - M_E)}{h_C A(T_P - T_C)}\ln\left[\frac{M_C}{\overline{M}}\right] \quad (17)$$

Alternatively, based on difference in partial pressure, the diffusional processes lead to moisture-loss in the falling-rate period, expressed as [8],

$$\left(\frac{dM}{dt}\right)_{FR} = \left(\frac{dM}{dt}\right)_{CR}\frac{DP_T}{DP_T + \mu s g_m(P_T - P_M)} \quad (18)$$

where D is vapour-diffusion coefficient, ì is coefficient of resistance to diffusion, s is distance between liquid-level and surface, g_m is mass-transfer coefficient, P_T is total vapour pressure (~ atmospheric pressure), $P_M = (P_S + P_L)/2$ with P_S as partial pressure at surface of crop, and P_L as vapour-pressure at the liquid level.

ESTIMATING TIME TO ATTAIN AVERAGE MOISTURE-CONTENT ($\overline{M}$)

For most agricultural produce, drying must be slow at low-to-medium temperatures, to avoid degradation from over heating and cracking caused by too high moisture-gradients; i.e., the recommended range for low-temperature drying is $T_A < T_D < 50$ ºC. The differential equation (8) for microscopic outward moisture-diffusion can be applied along the entire drying-zone and an analytical solution for the non steady-state moisture diffusional flow with constant moisture-diffusivity (D) and constant temperature-gradient can be used [9]. Therefore, on the assumption that the initial moisture-concentration (M_I) is uniform, the average moisture-content, $\overline{M}$ (t), of the product, after a drying time t, can be given by an analytical solution of the form [10],

$$\frac{\overline{M}(t) - M_E}{M_I - M_E} = \frac{16}{\pi^2}\left(\Sigma_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\left(\frac{(2n+1)\pi}{2x}\right)^2 Dt\right]\right) \quad (19)$$

and for n = 0, 1, 2,

$$\frac{\overline{M}(t) - M_E}{M_I - M_E} = \frac{16}{\pi^2}\left\{\exp\left[-\left(\frac{\pi}{2x}\right)^2 Dt\right] + \frac{1}{3^2}\exp\left[\left(\frac{3\pi}{2x}\right)^2 Dt\right] + \right.$$
$$\left. + \frac{1}{5^2}\exp\left[-\left(\frac{5\pi}{2x}\right)^2 Dt\right] + \ldots\right\} \quad (20)$$

Equation (20) is derived on the assumption that D and M_E are constants, but in reality D varies with temperature and moisture-content, while M_E also varies with temperature. For long period of drying (t is sufficiently large), only the first-term in the series in eqn. (20) is significant (with $Dt/4x^2 > 0.02$, the error is less than 3 %) and hence,

$$\frac{\overline{M}(t) - M_E}{M_I - M_E} = \frac{16}{\pi^2}\left\{\exp\left[-\left(\frac{\pi}{2x}\right)^2 Dt\right]\right\} \quad (21)$$

such that the total time (t) required to attain an average moisture-content $\overline{M}$ is,

$$t = \frac{4x^2}{\pi^2 D}\ln\left(\frac{16}{\pi^2}\frac{M_I - M_E}{\overline{M} - M_E}\right) \quad (22)$$

Substituting values of the drying parameters for cassava-chips, $M_I = 75$ %, $M_E = 13$ %, and achieving $\overline{M}$ = 14 % after t = 80 h, the moisture diffusion-coefficient through the food-bed $D = 5.08 \times 10^{-3}$ cm^2/s; which is a reasonable estimate for dehydration to prevent deterioration of the sample. Table-1 gives the drying parameters for selected food samples, showing values of drying time and moisture diffusion-coefficient for the various stages of drying, i.e. constant rate, falling-rate and overall period of drying.

Equation (21) also represents the relative change in moisture-concentration, (- M_E)/(M_I - M_E), within the food-sample in the drying chamber, and can be re-written as:

$$\frac{\overline{M}(t)-M_E}{M_I-M_E}\approx\frac{16}{\pi^2}\left\{\exp\left[-\frac{t}{\tau}\right]\right\} \text{ or } \ln\frac{\overline{M}(t)-M_E}{M_I-M_E}=0.48-\frac{t}{\tau} \quad (23)$$

where ô = $4x^2$/Dð^2. The function expressed in eqn. (23) is represented graphically in Figure-7 for drying of cassava-chips, where D for the various stages of drying can be obtained from the gradient of the straight portions of the curve. The solution (eqn. 23) in the form of trigonometric series can also be obtained as a series of error-functions,

$$M = M_I \operatorname{erf}\left(\frac{x}{\sqrt{Dt}}\right) \quad (24)$$

For the finite-system considered here, the initial and boundary conditions are M = M_I for 0 < x < 0.3 m at t = 0; M = 0 for x = 0 and x = 0.3 m at t > 0.

For the stage of desorption-evaporation, the amount of water evaporated from the sample can be estimated by using the expression [9],

$$\frac{M_W(t)}{M_\infty}=1-\frac{64}{\pi^4}\left(\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp-\left(\frac{(2n+1)^2\pi^2Dt}{(2x)^2}\right)\right)^2 \quad (25)$$

where $M_W(t)$ is the amount of water evaporated up to time t, and M_∞ is potential amount to be desorbed after infinite time of drying (≈ M_I). As $t \to \infty$, the terms involving the exponentials varnish, leading to a linear concentration-distribution.

It should be noted that for various complex cases such as, when the initial moisture-content is not uniform, when the diffusivity is dependent on concentration, or when other more complex boundary conditions are observed, simple analytical solutions cannot be easily obtained.

The problem of moisture-diffusion can also be solved by using a numerical method with finite difference. The foodbed of thickness 'x', can be divided into a number of N equal finite slices of thickness Δx, where each position is defined by integer i, such that:

x = iÄx;   0 ≤i≤ N;   x = NÄx   (26)

The moisture-balance during the time-increment Ät is evaluated within the small thickness Äx, centred at position i, by considering transverse diffusion on each face. The moisture-content after lapse of time Ät, at point i, M_N(i), can be expressed in terms of the previous concentration M(i), obtained at the same place and adjacent places for 1 ≤ i ≤ N as:

$$M_N(i) = M(i) + \frac{1}{M_X}[M(i+1) - 2M(i) + M(i-1)] \quad (27)$$

where $M_X = \frac{(\Delta x)^2}{D_X \Delta t}$ is a dimensionless number and D_X is diffusion-coefficient in X direction.

EMPIRICAL EQUATION FOR DRYING

The theoretical logarithmic curve-fitting to the experimental data, shown in Fig. 2 (a), confirms that the drying process can be represented by a general equation of the form, $M(t) = M_I \exp(-kt)$ or $\frac{dM}{dt} = -kM(t)$; where k is constant for the particular drying regime.

For the constant-rate period, $M_I < M(t) \le M_C$, the drying rate is proportional to the free moisture-content, i.e. $\left(dM/dt\right)_{CR} = -k_C(M(t) - M_C)$; and upon integration,

$\int_{M_I}^{M(t)} \frac{dM}{(M(t)-M_C)} = -\int_0^{t_{IC}} k_C dt$, and the drying equation for the constant-rate period becomes:

$$\frac{M(t)-M_C}{M_I-M_C} = \exp(-k_C t_{IC}) \quad (28)$$

where k_C is the drying-constant for that period.

Similarly, the drying equation for the falling-rate period ($M_C < M(t) \leq M_E$) is

$$\frac{M(t) - M_E}{M_C - M_E} = \exp(-k_F t_{CE}) \qquad (29)$$

where k_F is the drying-constant for that period.

Using the individual eqns. (28) and (29), respectively, the total drying time, $t_D = t_{IC} + t_{CE,}$ can be expressed by a two-term equation, in the form of moisture-ratio as:

$$\frac{M'(t)}{M} = \alpha\exp(-k_C t_{IC}) + \beta\exp(-k_F t_{CE}) \qquad (30)$$

where M´(t) is variable moisture-content, M is available moisture, á and â are dimension-less constants. From Table-1, it is evident that samples with high k and D values exhibit shorter duration of drying, and also, the rate of drying decreases with decrease in moisture-content, but increases with decrease in size of particle as previously reported [11].

DISCUSSION

The natural convective solar dryers have been adopted, by community-based organizations in Ghana, to dehydrate farm-produce so as to promote export of non-traditional products. The dryers were constructed from local materials and were less complicated to use. The initial cost for a given capacity of the convective solar dryer was found to be lower than other types of dryers, despite the general assumption that the initial investment costs of solar devices are higher, even though the running costs are lower. In addition, close regulation of the air-temperature, through baffles,

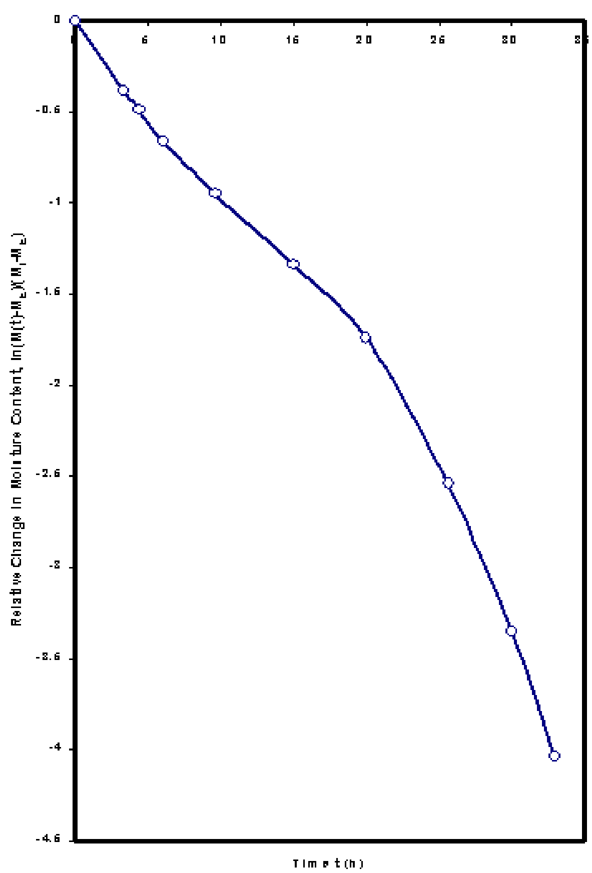

Figure - 7: Moisture-Diffusion out of Cassava Chips

ensures that samples were not subjected to objectionably high temperatures.

The thermal absorbtance of a sample is an important factor in solar-drying, since most agricultural produce exhibit relatively high absorbtance, ranging from 0.67 to 0.9 [12]. Therefore, the heat-transfer and evaporation-rates must be controlled closely for optimum combination of drying-rate and acceptable product-quality. The action of applying heat to dry a crop does not merely remove the moisture, but also can affect the quality of the final product, resulting from browning, migration of soluble constituents, case-hardening and loss of volatile constituents.

The analyses presented provide the theory (backed by experimental results) of principles of solar-drying, and, therefore, offer effective approach for the design and construction of low-cost solar dryer, especially, the mode of utilization of solar-heated air and arrangement for the major features of system. Even though the performance of natural convective solar dryers can be compromised by very high and wet-season ambient humidity, incorporating rock-energy storage-system, enhances drying-efficiency and reduces drying-time, thereby preventing deterioration of samples.

CONCLUSIONS

Analyses have been made of the processes of heat- and mass-transfer, in natural convective thin-layer fixed-bed solar-drying to predict the drying time, drying rates and moisture diffusion-coefficient; and obtain data for optimum operation to ensure integrity product.

The moisture-dehydration process obeys Fickian-diffusion, driven by moisture-concentration or vapour pressure, while the convective heat-transfer results from temperature-gradient. Classical analytical solution of non-steady state diffusion-equation can be used to describe the moisture-desorption when a food-sample is exposed to solar heated air, since the process is controlled by diffusion and evaporation.

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