Thermal Stimulated Moisture Desorption and Drying Characteristics of Tropical Hardwood

H. Lawluvi & A. Ayensu

Dept. of Physics, UCC, Cape Coast

Industrial & Natural Resources Sector, CSIR, Accra

Abstract

The processes of thermal stimulated moisture de-sorption and drying characteristics of selected species of tropical hardwoods have been investigated. Empirical equations representing the desorption by sun drying and oven drying were established. The sun-drying occurred in two phases, the constant rate period and falling rate period. For each phase the drying constants were evaluated and the values range from 0.74 to $1.39 hr^{-1}$ for the constant rate period and from 0.0 to 0.191^{-1} for the falling rate period. The moisture diffusion coefficients for sun-drying were determined and the values ranged from 5.0×10^{-10} to 1.6×10^{-8} $m^{-1}s^{-1}$. During the oven-drying process, three stages of desorption with different amount of shrinkage levels were identified the values of shrinkage factor calculated range between 0.43 to 2.17. Obeche was found to possess the highest value of shrinkage in confirmation with the high void fraction.

Introduction

Timber is seasoned or partially dried to attain equilibrium moisture content with the surrounding ambient conditions. Unfortunately, large quantities of timber species are used immediately after conversion form logs, leading to insect infestation and attack by fungi, shrinkage and warping in drying out. This practice has perhaps been responsible for the poor reputation of timber as building material. To utilise the full potential of different wood species, the response to thermal stimulated environment and the accompanying moisture flow rates, moisture gradient and temperature gradients existing in wood during drying must be known.

For the selection and use of wood as building material, the general physical process governing desorption of moisture must be investigated thoroughly since desorption is one of the major processes which control durability. Studies on water movement, moisture diffusional flow experimental and numerical solution of non-steady state flow in local wood species has been reported. It is generally accepted that the two basic phenomena involved in drying processes are evaporation of moisture from the surface and migration of moisture from the interior. The present study is intended to investigate thermal stimulated moisture desorption by imposed temperature ramps from sinusoidal variation of solar radiation and step-wise change of oven temperature and the associated drying characteristics.

Desorption Process

In drying, diffusivities are often activated by thermal fields and consequently become strong functions of temperature and time. When a solid of initial moisture concentration M_1 is subjected to thermal fields at selected temperatures and timbers for desorption to occur the kinetics of the desorption process can be described as essentially the decay of the adsorbed moisture concentration, M(t). Such a process yields insight into the forces binding water molecules to the wood structure as the dehydration takes place by removal of free and chemically bound water. These phenomena involved in the drying can be described as evaporation of moisture from the surface and migration of moisture from the interior to the surface, and each of these phenomena is affected by external factors which control the drying process.

The rate equation of the desorption process can be described by:

$$\frac{dM}{dt} = -kM^v \tag{1}$$

with $M(0) = M_1$, where k and v are the rate constants and order of the desorption reaction respectively. The desorption equation (1) is separable so long as k does not depend on concentration, and if k is also time independent, the solutions become:

$$kt = \ln\left(\frac{M_I}{M}\right) \text{ if } v = 1 \tag{2}$$

$$kt = (v - 1)^{-1}[M^{(1-v)} - M_I^{(1-v)}] \text{ if } v \neq 1 \tag{3}$$

If k is also any function of temperature T, and if the temperature is programmed to change linearly at a ramp rate α such that

$$T(t) = T_I = \alpha t \tag{4}$$

Then the left hand side of kinetic equations (2) and (3) can be expressed as

$$\int_0^t K[T(t)]dt$$

Thermally Stimulated Desorption

In thermally stimulated processes of drying, the ramp rate, α is considered positive. The two competing forces are such that the temperature ramp tends to increase k and with it the rate of desorption and the natural isothermal tendency of dM/dt to decrease with time according to equation (1). Therefore the desorption rate must exhibit a transition which can be analysed to provide information on adsorbed and structurally bound water in wood.

For thermal stimulated desorption of moisture in wood, the usual source of irradiation. F(t), which may be used to induce phase change or structural modification is either solar flux or heat flux form a radiator. Thermal stimulation offers the means to study the interactions between external sources of heat and wood, on the assumption that the wood is semi-infinite and bounded by a planar surface. Assuming that the thermal flux, $F_0(t)(W/m^2)$, is of infinite lateral extent with arbitrary time dependence, and that not all impinging power is effective, and if R is the reflection coefficient of wood, then a fraction RF_0 is reflected and the remainder $(1-R)F_0$ is transmitted into the wood where it is dissipated such that at a depth x, the change in dissipated power, P(%) can be expressed as:

$$P(x) = P_0\, e^{-\lambda x} \tag{5}$$

where P_0 is the power dissipated at the surface (x = 0) or $P_0 = (1-R)F_0$ as power input, and λ is the decay constant.

Equation (5) is a source term of the diffusion equation:

$$\frac{dM(x,t)}{dt} = D\frac{d^2 M(x,t)}{dx^2} \tag{6}$$

and for cases of constant coefficient, the equation (6) can be written as:

$$\frac{dM(x,t)}{dt} = D\frac{d^2 M(x,t)}{dx^2} + (1 - R)F_0(t)e^{-\lambda x} \tag{7}$$

Equation (7) shows that a change in moisture content with time is controlled by the moisture gradient and the imposed thermal field.

If it is assumed that the solid was initially at a constant temperature, $T_\alpha = 30°C$, which is maintained constant far from the surface, and the ambient surface temperature change prior to experimentation is also considered small enough so that radiation into the surrounding medium is negligible compared to stimulation effect of the imposed thermal flux, the boundary conditions then become:

$$T(x, 0) = T_\alpha$$
$$T(0, t) = T_\alpha, \ dT/dx\ ]_{x=0} = 0$$

Experiments

In desorption studies, the moisture content of the sample at any time is defined on dry basis (db) by:

$$M(t) = \frac{W_m(t) - W_D}{W_D} \qquad (8)$$

where $W_m(t)$ is the weight of moist sample at t and W_D is the weight of dry sample. The bulk desorption was investigated for sun-drying and oven drying and hence anisotropic characteristics were neglected. The wood species were cut into rectangular blocks of 5 x 2 x 20cm. The species of hardwoods selected for the experimental investigation are shown in Table 1. Diurnal variation of ambient relative humidity and temperature for drying has been reported.

Table 1: Timber species selected for experimental investigation

Species	Local name	Bulk density ρ_b(kg/m^3)	*Void fraction V_f
Afrormosia (*Afrormosia elata*)	Kokrodua	720	0.54
Iroko (*Terminalia ivorensis*)	Odum	690	0.56
Utile (*Entandrophragma utile*)	Utile	660	0.58
Sapele (*Entandrophragma cylindricum*)	Sapele	630	0.60
Obeche (*Triplochiton scleroxylon*)	Wawa	380	0.76

* The density of wood cellulose material, $\rho_w = 1.56 \times 10^3$ kg/m^3. $V_f = 1 - (\rho_b/\rho_w)$

During sun drying, the specimens were exposed to ambient atmospheric conditions and the results obtained for variation of moisture content (db) with time for constant exposure time of one hour at an initial ambient temperature of 30^{0}C and relative humidity of 81% are shown in Figure 1. At an hourly interval, the samples were recovered and weighed until a constant weight was obtained. The hourly variation of solar radiation provided different energy input for the drying and hence different temperature ranges for the thermal stimulation.

The oven-drying method was used to investigate the variation of moisture content (db) with temperature. The samples were placed in an oven for one hour at a temperature of 30^{0}C and the weight at the end of each period was recorded. The temperature was increased in steps of 10^{0}C up to 150^{0}C to obtain a series of data as shown in Figure 2; whereby the temperature ramp rate was 10t. The samples showed signs of thermal cracking and deterioration at 150^{0}C due to decomposition of organic matter.

Results

Sun-drying processes

During drying, water evaporated slowly from the wood until equilibrium was reached with the surrounding air, at an equilibrium moisture content of about 2% of dry weight. The drying curve in Figure 1 shows the variation of moisture content with drying time. The data for Obeche and Sapele are re-plotted in Fig.3 as a log-linear graph of moisture loss with time, which illustrates that drying takes place by two sequential mechanisms over the periods AC and CE. This confirms the existence of transition in the drying process. From an initial moisture content M(1) the transition in desorption occurs at the critical moisture M_C and thereafter the desorption continues until the equilibrium moisture content M_E is reached.
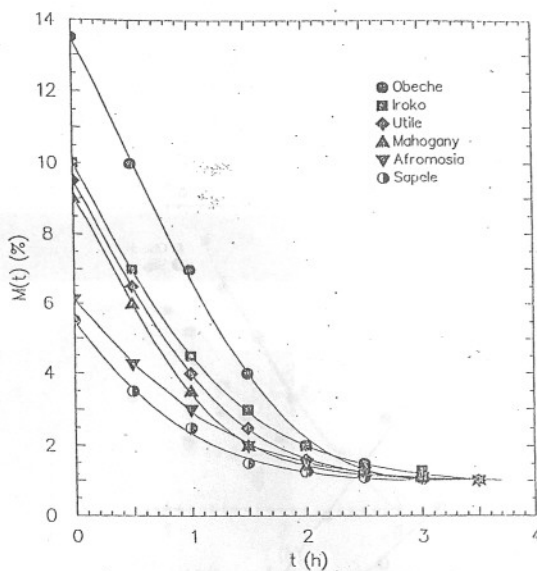
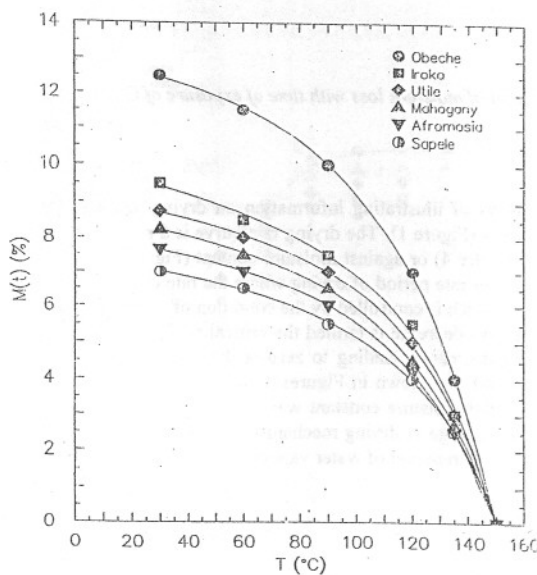*Figure 1. Moisture content change with time of exposure to atmosphere*

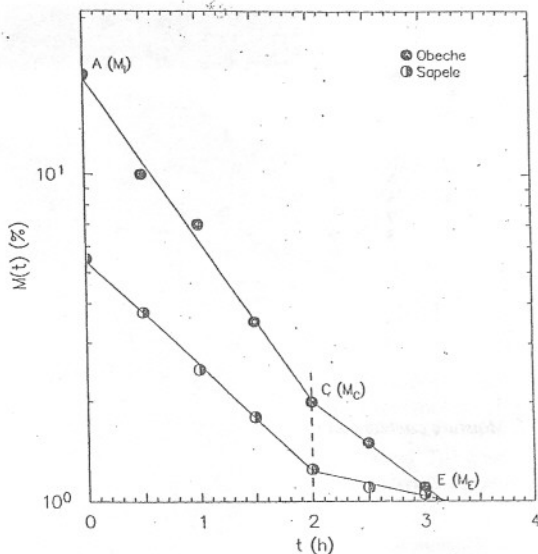*Figure 2. Moisture content change with temperature*

Figure 3. Log-linear plot of moisture loss with time of exposure of Obeche and Sapele to atmosphere.

The most appropriate means of illustrating information on drying mechanisms is by drying rate curves rather than the drying curves (Figure 1). The drying rate curve is a plot of change in moisture content with time against either time (Figure 4) or against moisture content (Figure 5). With reference to Figures 4 and 5, the regime BC is a constant rate period of drying where the rate controlling mechanism is evaporation of moisture from the surface, which is controlled by the condition of air adjacent to the surface. The point C at which the drying rate starts to decrease is termed the critical moisture content. Below the critical moisture content the rate of drying decreases, leading to zero at the equilibrium moisture content. This period is termed the falling rate period. As shown in Figures 4 and 5, some of the species did not exhibit constant rate period because the initial moisture constant was less than the critical moisture content as a result of previous conditioning. The change in drying mechanism illustrated at the point E is attributed to diffusion controlled drying, whereby the removal of water vapour is largely the rate controlling process.
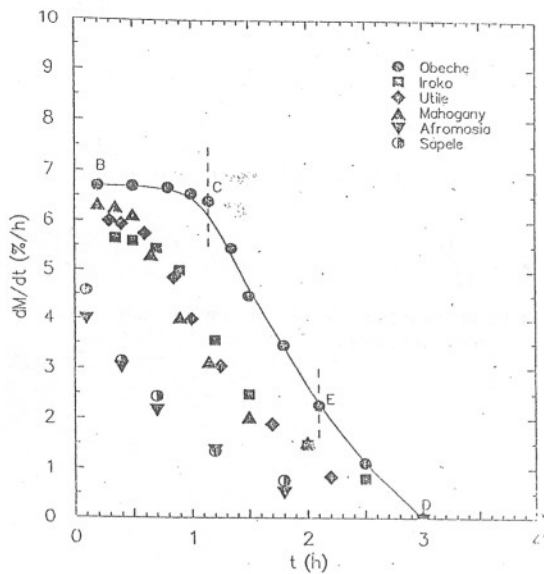
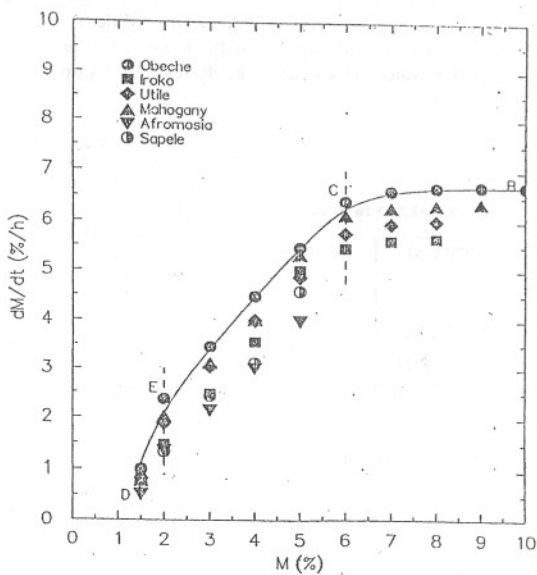*Figure 4. Plot of time rate of change of moisture content versus time.*

Figure 5. Plot of time rate of moisture content versus residual moisture content.

For each drying regime the moisture loss can be described by the expression $M = M_{exp}(-kt)$ or $dM/dt = -kM$, where k is a drying parameter.

$$\frac{dM}{dt} = \frac{\pi^2 D}{4L^2}(M - M_E) \qquad (9)$$

and therefore k is related to the moisture diffusion coefficient D, of the appropriate regime by an equation of the form:

$$k = \frac{\pi^2 D}{4L^2} \qquad (10)$$

For the constant rate period, the drying is proportional to the free moisture content, or $dM/dt = -k(M-M_C)$ and the empirical drying equation can be written as:

$$\frac{M(t) - M_C}{M_I - M_C} = \exp(-k_1 t_C) \qquad (11)$$

Similarly, the drying equation for the falling rate period can be expressed as:

$$\frac{M(t) - M_E}{M_C - M_E} = \exp(-k_2 t_E) \qquad (12)$$

The drying constants, k_1 and k_2 were evaluated to determine the corresponding diffusion coefficients D_1 and D_2 as shown in Table 2. The diffusion coefficient ranges from 5.0×10^{-10} m²/s to 1.6×10^{-8} m²/s, and the specimens with high drying rates possess high k values.

The drying characteristics were also examined by plotting the drying rate against residual moisture content. A plot of drying rate (dM/dt) against residual moisture content, M, shown in Figure 5 for two wood species confirms that drying takes place in phases with the transition at about 2% moisture content. That is, above 2% moisture content, drying process involves the removal of free water, while below 2% moisture content, the drying process involves the removal of bound water. In addition, the transition shows that much of the water in wood species consists of free water, which can be easily removed by application of low thermal fluxes.

Table 2: Drying parameters and shrinkage factors for timber species

Species	Moisture content (%)			Drying constant (h⁻¹)		Bulk diffusion coefficient x 10⁻⁸ m²/s		*Shrinkage factor S x 10⁻³% (°C)²		
	M_I	M_C	M_E	k_1	k_2	D_1	D_2	PS	SS	TS
Obeche	10.0	2.0	0.25	1.39	0.19	1.56	0.21	0.63	1.57	2.17
Utile	11.5	1.7	0.20	1.29	0.14	1.29	0.15	0.57	0.70	1.57
Afrormosia	5.5	1.0	0.11	0.74	0.04	0.83	0.06	0.47	0.43	1.30
Iroko	7.0	1.4	0.14	0.87	0.05	0.98	0.05	-	-	-

* PS = Primary stage, SS = Secondary stage, TS = Tertiary stage.

Oven-drying Method

The oven-drying method was used to investigate the moisture loss with imposed temperature ramp as shown I Figure 3. The temperature rate of change of moisture content. [dM/dT] is plotted against T in Figure 6, and it is observed that loss of moisture takes place in three stages. The low thermal activated rate occurs between 30°C to 90°C, the intermediate rate occurs between 90°C and the high activated phase

occurs between 130°C to 150°C. The level of thermal activation is significant, as the primary stage consists of free water removal, which requires minimum thermal activation while the intermediate stage involves bound water removal and with significant level of thermal activation. The tertiary stage is the result of structural disintegration, which is of no significance to seasoning mechanisms.
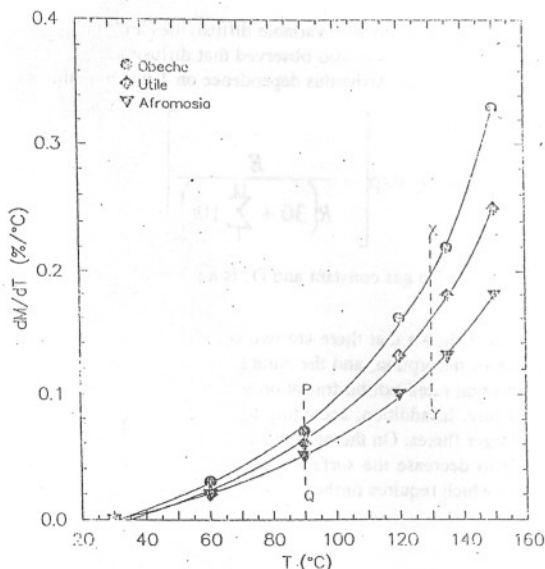

Figure 6. Plot of temperature rate of change of moisture content versus temperature.

The variation of moisture desorption with temperature resulted in dimensional changes which were evaluated by the shrinkage factor, S. From Figure 6, an empirical relation [dM/dT] = ST was deduced to describe the stages of desorption which has a general solution of the form:

$$M(t) - M_I = 0.5S[T_I^2 - T^2] \qquad (13)$$

where M_I and T_I represent the initial conditions of desorption.

The shrinkage factors determined are shown in Table 2 and Obeche has the highest rate of moisture movement and shrinkage level as a result of the high void fraction. Shrinkage usually occurs when combined water absorbed to the cell walls diffuse to the surrounding air with subsequent collapse of the voids. A 1% change of absorbed water corresponds to about 0.5% change in dimension lateral to the grain such that a maximum strain of over 10% is possible.

Discussion

The oven drying temperature was programmed to vary linearly at a temperature ramp of 10°C such that

$$T(t) = 30 + \sum_{0}^{12} 10t \tag{14}$$

While for sun drying, the imposed thermal field results from the sinusoidal variation of diurnal solar radiation expressed as:

$$I(t) = I_{max} \sin\left(\frac{\pi t}{N}\right) \tag{15}$$

where $I(t)$ is the radiation intensity at t hours after sunrise, I_{max} is the maximum value at solar noon and n is the day length in hours.

The linear desorption problems considered involve variable diffusivities and the programmed temperature changes induce additional driving forces. It was also observed that diffusivities were activated and for the oven drying, the diffusion coefficient has an Arrhenius dependence on T given by the expression:

$$D(T) = D_{\infty} \exp\left[-\frac{E}{R\left(30 + \sum_{1}^{12} 10t\right)}\right] \tag{16}$$

where E is the activation energy, R is the gas constant and D_{∞} is a pre-exponential term which represents D at infinite temperature.

Since the temperature results have shown that there are two competing forces, a temperature ramp which tends to increase k and the rate of desorption, and the natural isothermal tendency of [dM/dt] to decrease with time. Therefore, the desorption rates exhibit transition which has confirmed the existence of free and bound water in the wood structure. In addition, according to equation (16), the diffusion coefficient rises with temperature and causes larger fluxes. On the other hand, the amount of diffusant in any finite sample decreases with time and tends to decrease the surface flux. From the above analysis, the mechanism of drying is a complicated process which requires further investigation to develop the mathematical relations.

Conclusion

Species of tropical wood of commercial values have been subjected to two modes of thermal stimulated desorption to investigate the drying characteristics.

1. The sun-drying process could be described by a general empirical relation of the form M M_1exp(-kt), for which the k values and diffusion coefficient were evaluated for the constant and falling rate periods of desorption.

2. The oven-drying method confirmed that drying takes place in stages with different diffusivities and shrinkage levels. The shrinkage factor ranges from 0.63 to $1.3 \times 10^{-3}\%(°C)^{-2}$.

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