Mathematical modeling of the natural solar drying process in lateritic mineral deposits

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Abstract:
The natural solar drying of lateritic mineral was modeled in order to obtain the moisture distribution and its movement mechanism in the section. In this work we give a physical model of the drying process, based on heat and moisture transport phenomena in porous media. The models that allow calculation of the heat fluxes by radiation, convection and conduction are determined; In addition the global solar radiation that affects the surface of minerals drying; the temperature and humidity distribution experienced by the material during the process; the rate of drying and the mineral moisture on the surface. Natural drying tests were performed and experimental values of material moisture were obtained. The experimental and theoretical results obtained were compared. The validation process was performed by comparing the moisture of the experimentally determined material with the theoretical humidity calculated with the models for the same physical conditions in which the experiment was developed. The mathematical models were obtained by solving, through the variable separation method, the differential equation of moisture exchange in a porous solid for the initial and boundary conditions specific to the natural drying. The results evidenced that during the process, significant changes in the moisture of the material occur until the layers that are separated about 29 and 87 cm from the surface of the east and west slopes of the pile respectively. In addition, it was confirmed that the moisture movement in the ore piles occurs through a mixed transport mechanism; combined effects of vapor diffusion, liquid diffusion and liquid movement.

Keywords: Mathematical modeling; simulation; natural solar drying; lateritic mineral deposit.

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I. INTRODUCTION

Solar drying of lateritic mineral in different countries has a positive influence on the material homogenization and the reduction of its moisture content. The material behavior during drying operations depends on heat and mass transfer mechanisms interesting the material under drying processes. The main problems associated with solar drying of the laterite mineral are as follows [1]:

- The rigorous evaluation of the heat and mass transfer processes that affect the solar drying is not consider, also the application of mathematical models adjusted to the conditions in which the process is developed in the nickel companies.
- Moisture variation experienced by the material during the natural drying process is not possible to predict, therefore, it is difficult to estimate the drying time required to reduce its moisture from a known initial value to another desired final value.
- The characterization of the cross- sectional geometry of the material is not consider, and therefore does not allow to accurately calculating the material exposure area, the material volume exposed to drying and the overall solar radiation incident on the drying surface.

The mathematical modeling allows the theoretical study of lateritic mineral solar drying and enables computational simulations of this process through the use of appropriate computer systems [2]. This is an alternative technologically viable to predict the behavior of the material moisture distribution when the independent variables and the parameters of the mathematical models take certain values [3]. The modeling is a necessary tool in the design and operation of the processes.

The mathematical modeling of natural solar drying has been used for various scientific and technical purposes [4]. Research has been carried out in the drying of grains, wood and pulp of bagasse [5]-[6]. In the last decades among the materials that have been studied in research on drying are coffee, seeds, medicinal plants, wood and miscellaneous products [7]-[8]-[9].

Free convective heat transfer in a differentially heated for the material porous has been investigated widely in the literature [10]-[11]. The thermodynamic analysis energy and exergy of a thermal system is very important to engineers in order to optimize the efficiency of the system, minimize losses, reduce the operational and capital investment costs, and improvement of productivity of the thermal system [12]. The drying of the product is affected by the drying air temperature and the product characteristics [13].

In solar drying of materials is fundamental to know the distribution of temperature and humidity in the system when it is required to design processes and equipment, as well as to control the quality and selection of handling and storage operations. For the physical process two fundamental phenomena are considered: The material moisture evaporates and successively diffuses, and the energy required for the evaporation of moisture flows in the opposite direction of diffusion and causes the wet mass to change from the liquid to the gaseous state. The resultant of these two processes thus provides the kinetic characteristics of the drying process; the two phenomena that occur are heat transfer and mass transport [14]. The analysis is carried out for a wide range of modified Rayleigh numbers for different heat source lengths and locations [15].

In materials solar drying is fundamental to know the temperature distribution and humidity in the system when it is required to design processes and equipment, as well as to control the quality and selection of handling and storage operations. For the physical process of the materials drying, or in general of granular elements, two fundamental phenomena are considered: The material moisture evaporates and then diffuses; the energy required for the moisture evaporation flows in the opposite direction of diffusion and causes the wet mass to change from the liquid to the gaseous state.

The resultant of these two processes thus provides the kinetic characteristics of the drying process; the two transport phenomena that occur are heat transfer and mass transport. Normally, in the drying process can be assumed that the material forms a capillary porous medium; the capillary potential is larger than the gravitational potential, gravitational forces can be neglected.

The bibliographic search revealed that the natural solar drying of the lateritic minerals is little treated in the scientific publications. The mathematical analysis and theoretical-experimental aspects of the process have not been studied. Considering the above, **the objective of the article** is to develop the mathematical modeling of the natural solar drying process of lateritic mineral.

II. METHOD DEVELOPMENT

To explain the moisture transfer in the porous materials, during the drying process, various mechanisms of moisture movement are referenced in the scientific literature [16]:

Liquid diffusion: due to the concentration gradients of moisture.

Steam diffusion: due to the partial vapor pressure gradients

Liquid movement: due to capillary forces

Flow of liquid or vapor: due to differences in the pressure inside the pores and the drying agent.

Effusion: occurs when the mean free path of the vapor molecules is the order of the pores diameter.

Surface diffusion: due to the gradients of moisture concentration and partial pressure of the steam that are generated in the drying surface.

The capillary flow mechanism is the one that predominates during the period of constant speed drying, whereas the mechanisms of condensation - evaporation and vapor flow correspond to the period of decreasing velocity. The study of these mechanisms, applied to the analysis of the drying process, has given rise to different theories of drying. The capillary theory states that during the drying the transport of the liquid occurs through the interfaces and on the solid surface due to the molecular attraction between the liquid and the solid, it has been demonstrated through experiments that the flow of moisture may be in the direction of the increase in concentration.

During the natural drying process of the lateritic mineral, as a result of the incident solar radiation, a film of water vapor is formed on the drying surface, the moisture of the material decreases and two gradients emerge in the interior: Humidity and temperature. In the presence of both gradients, the moisture is displaced from the inner layers to the drying surface of the material.

The lateritic mineral are subjected to solar drying in sections (with triangular cross sections) to achieve a better use of the horizontal surface available for drying and to facilitate the drainage of water in case of abundant rainfall. The sections are spaced to remove the material during drying and to enable its evacuation and transportation once the process is completed.

The material characteristics subjected to solar drying are as follows:

- Mass of material exposed to solar drying: 700 t;
- Length of side surface: 140 m;
- Width of base: 5,49 m;
- Tilting the drying surface of the east and west slopes: 61 degrees;
- Geometric shape of the cross-section: triangular

The process was studied considering the constant coefficients (k_u and δ), not dependent on the material moisture. Equation 1 is the general model that characterizes the rate of humidity change inside a porous solid at a point of coordinates (x; y; z) in function of the time, that is why it has been suggested and used by several researchers to study the drying process of porous materials.

$$\frac{\partial H}{\partial \tau} = k_u \cdot \left[\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} + \delta \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \right] \quad (1)$$

The simplified equation 1 determines the moisture distribution in the lateritic mineral exposed to natural drying (equation 2). For this, the same is solved using the initial and boundary conditions (characteristic boundary problems) of the process investigated.

$$\frac{\partial H}{\partial \tau} - k_u \cdot \frac{\partial^2 H}{\partial y^2} = f(y, \tau) \quad (2)$$

Where:

$$f(y, \tau) = k_u \cdot \delta . \frac{\partial^2 T}{\partial y^2} \quad (3)$$

And:

$$\frac{\partial^2 T}{\partial y^2} = -\sum_{n=1}^{\infty} \frac{(2n\pi)\cos(n\pi)}{l^2} \cdot e^{-\alpha \cdot \left(\frac{n\pi}{l}\right)^2 \cdot \tau} \cdot \left[\int_0^{\tau} e^{\alpha \cdot \left(\frac{n\pi}{l}\right)^2 \cdot \theta} \cdot \frac{dT_s(\theta)}{d\tau} d\theta \right] \cdot sin\left(\frac{n\pi}{l} y\right) \quad (4)$$

Initial and boundary conditions are:

$$H(y,0)=\Omega(y) \quad H(0,\tau)=H_0 \quad H(l,\tau)=H_s(\tau) \tag{5}$$

The moisture distribution is discretized by dividing the surface into cuts of thin thickness and each of them into sections of sufficiently small width, as shown in Figure 1.

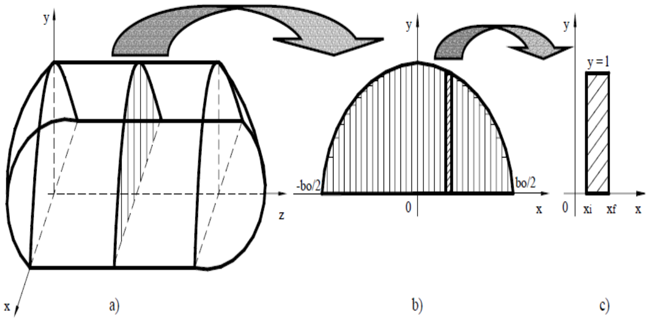

Fig. 1 One-dimensional temperature distribution and humidity

Equation 2 is solved using the separating variables method and the function $v(y,\tau)$.

$$v(y,\tau)=H(y,\tau)-U(y,\tau) \tag{6}$$

$$U(y,\tau)=H_0+\frac{y}{l}\left[H_s(\tau)-H_0\right] \tag{7}$$

The function $v(y,\tau)$ is determined as the solution of de equation 8.

$$\begin{aligned}\frac{\partial v}{\partial\tau}-k_u\cdot\frac{\partial^2 v}{\partial y^2}&=\left[\frac{\partial H}{\partial\tau}-k_u\cdot\frac{\partial^2 H}{\partial y^2}\right]-\left[\frac{\partial U}{\partial\tau}-k_u\cdot\frac{\partial^2 U}{\partial y^2}\right]=\\&=f(y,\tau)-\left[\frac{y}{l}\frac{dH_s}{d\tau}-k_u(0)\right]=f(y,\tau)-\left[\frac{y}{l}\frac{dH_s}{d\tau}\right]=R(y,\tau)\end{aligned} \tag{8}$$

With the following additional conditions

$$\begin{aligned}v(y,0)&=H(y,0)-U(y,0)=\Omega(y)-H_0-\frac{y}{l}\left[H_s(0)-H_0\right]\\v(0,\tau)&=H(0,\tau)-U(0,\tau)=H_0-H_0=0\\v(l,\tau)&=H(l,\tau)-U(l,\tau)=H_s(\tau)-\left[H_0+H_s(\tau)-H_0\right]=0\end{aligned} \tag{9}$$

Then the above problem is reduced to equation 10 and conditions represented in 11.

$$\frac{\partial v}{\partial\tau}-k_u\cdot\frac{\partial^2 v}{\partial y^2}=R(y,\tau) \tag{10}$$

$$\begin{aligned}v(y,0)&=H(y,0)-U(y,0)=\Omega(y)-H_0-\frac{y}{l}\left[H_s(0)-H_0\right]=\beta(y)\\v(0,\tau)&=0\\v(l,\tau)&=0\end{aligned} \tag{11}$$

This last model (equation 10 with the conditions represented in 11) is solved assuming that the solution has the form of a Fourier series; for this the expression 12 is proposed.

$$v(y,\tau)=\sum_{n=1}^{\infty}v_n(\tau)\cdot sin\left(\frac{n\pi}{l}y\right) \tag{12}$$

Then the function $R(y,\tau)$ is designated through expression 13.

$$R(y,\tau)=\sum_{n=1}^{\infty}R_n(\tau)\cdot sin\left(\frac{n\pi}{l}y\right) \tag{13}$$

Where:

$$R_n(\tau)=\frac{2}{l}\cdot\int_0^l R(y,\tau)\cdot sin\left(\frac{n\pi}{l}y\right)dy=\frac{2}{l}\left[\int_0^l f(y,\tau)-\frac{y}{l}\frac{dH_s}{d\tau}\right]\cdot sin\left(\frac{n\pi}{l}y\right)dy \tag{14}$$

And

$$R(y,\tau)=\sum_{n=1}^{\infty}\left[\frac{2}{l}\cdot\int_0^l R(y,\tau)\cdot sin\left(\frac{n\pi}{l}y\right)dy\right]\cdot sin\left(\frac{n\pi}{l}y\right) \tag{15}$$

Substituting expressions 12 and 15 into equation 10 gives:

$$\left[\sum_{n=1}^{\infty}v_n(\tau)\cdot sin\left(\frac{n\pi}{l}y\right)\right]_{\tau}-k_u\cdot\left[\sum_{n=1}^{\infty}v_n(\tau)\cdot sin\left(\frac{n\pi}{l}y\right)\right]_{yy}=\left[\sum_{n=1}^{\infty}R_n(\tau)\cdot sin\left(\frac{n\pi}{l}y\right)\right] \tag{16}$$

Grouping terms from the previous equation is obtained:

$$\sum_{n=1}^{\infty}\left\{V'_n(\tau)+k_u\cdot\left(\frac{n\pi}{l}\right)^2\cdot v_n(\tau)-R_n(\tau)\right\}\cdot\sin\left(\frac{n\pi}{l}y\right)=0 \tag{17}$$

This expression is valid for all n=1, 2, 3, …., ∞; and it is true that:

$$V'_n(\tau)+k_u\cdot\left(\frac{n\pi}{l}\right)^2\cdot v_n(\tau)=R_n(\tau) \tag{18}$$

It is necessary to find $v_n(\tau)$ as a solution of differential equation 18.

$$\begin{aligned}v(y,0)&=\beta(y)=\Omega(y)-H_0-\frac{y}{l}\left[H_0-H_s(0)\right]=\\&=\sum_{n=1}^{\infty}v_n(0)\cdot\sin\left(\frac{n\pi}{l}y\right)\end{aligned} \tag{19}$$

For the calculation of $v_n(0)$ the expression 20 is used.

$$v_n(0)=\frac{2}{l}\cdot\int_0^l\left[\beta(y)\right]\cdot\sin\left(\frac{n\pi}{l}y\right)dy \tag{20}$$

The function $\Omega(y)$ is variable respect to length, so that:

$$v_n(0)=\frac{2H_s(0)\cdot\cos(n\pi)}{n\pi}+\frac{2\left[H_0-H_s(0)\right]\cdot\sin(n\pi)}{n^2\pi^2}+\frac{2\left[n\pi\int_0^l H_1(y)\cdot\sin\left(\frac{n\pi}{l}\right)dy-H_0\cdot l\right]}{n\pi\cdot l} \tag{21}$$

Differential equation 18 is solved using the condition set out in 21.

$$v_n(\tau)=e^{-k_u\left(\frac{n\pi}{l}\right)^2\cdot\tau}\cdot\left[\cos(n\pi)\cdot\left(A+\frac{2H_s(0)}{n\pi}\right)+B\right] \tag{22}$$

Where:

$$A=\frac{2\cdot\int_0^{\tau}e^{k_u\left(\frac{n\pi}{l}\right)^2\cdot\theta}\cdot R_n(\theta)d\theta-2\cdot\left[H_1-H_s(0)\right]}{n\pi} \tag{23}$$

and

$$B=\frac{2\cdot\left[H_0-H_s(0)\right]\cdot sin(n\pi)}{n^2\pi^2}+\frac{2\cdot\left[n\pi\int_0^l H_1(y)\cdot sin\left(\frac{n\pi}{l}y\right)dy-H_0\cdot l\right]}{n\pi\cdot l} \tag{24}$$

The value of $v(y,\tau)$ is given by the following equation

$$v(y,\tau)=\sum_{n=1}^{\infty}\left\{e^{-k_u\left(\frac{n\pi}{l}\right)^2\cdot\tau}\cdot\left[\cos(n\pi)\left(A+\frac{2H_s(0)}{n\pi}\right)+B\right]\right\}\cdot\sin\left(\frac{n\pi}{l}y\right) \tag{25}$$

Replacing equations 25 and 7 in equation 6 gives the expression 26, which is the mathematical model for calculating the laterite mineral moisture distribution exposed to solar drying.

$$H(y,\tau)=\sum_{n=1}^{\infty}\left\{e^{-k_u\left(\frac{n\pi}{l}\right)^2\cdot\tau}\cdot\left[\cos(n\pi)\left(A+\frac{2H_s(0)}{n\pi}\right)+B\right]\right\}\cdot\sin\left(\frac{n\pi}{l}y\right)+ \quad (26)$$

$$+H_0+\frac{y}{l}\left[H_s(\tau)-H_0\right]$$

When $\Omega(y)=H_1$, the model is reduced to the equations 27 and 28:

$$v_n(0)=\frac{2\left(H_s(0)-H_1\right)\cdot\cos(n\pi)}{n\pi}+\frac{2\left(H_0-H_s(0)\right)\cdot sen(n\pi)}{n^2\pi^2}- \quad (27)$$

$$-\frac{2\left(H_0-H_1\right)}{n\pi}$$

$$v_n(\tau)=e^{-k_u\left(\frac{n\pi}{l}\right)^2\cdot\tau}\cdot\left[\cos(n\pi)\cdot A^*+B^*\right] \quad (28)$$

Where

$$A^*=\frac{2\cdot\int_0^{\tau}e^{k_u\left(\frac{n\pi}{l}\right)^2\cdot\theta}\cdot R_n(\theta)\,d\theta-2\left[H_1-H_s(0)\right]}{n\pi} \quad (29)$$

and

$$B^*=\frac{2\left\lfloor H_0-H_s(0)\right\rfloor\cdot\sin(n\pi)}{n^2\pi^2}-\frac{2\left(H_0-H_1\right)}{n\pi} \quad (30)$$

The drying rate in function of thickness and time is determined by the following equation:

$$v(y,\tau)=\sum_{n=1}^{\infty}\left\{e^{-k_u\left(\frac{n\pi}{l}\right)^2\cdot\tau}\cdot\left[\cos(n\pi)\cdot\left(A^*\right)+B^*\right]\right\}\cdot\sin\left(\frac{n\pi}{l}y\right) \quad (31)$$

The mathematical model represented by equation 32 is used when the initial moisture content of the material remains constant.

$$H(y,\tau)=\sum_{n=1}^{\infty}\left\{e^{-k_u\left(\frac{n\pi}{l}\right)^2\cdot\tau}\cdot\left[\cos(n\pi)\cdot\left(A^*\right)+B^*\right]\right\}\cdot\sin\left(\frac{n\pi}{l}y\right)+ \quad (32)$$

$$+H_0+\frac{y}{l}\left[H_s(\tau)-H_0\right]$$

Experiments design

In scientific investigations different types of experimental designs can be used, however, due to the characteristics of the studied process and the available resources, a multifactorial design was used with the following characteristics:

- Measurements were made in three deposits of laterite mineral to eliminate the influence of the mechanical process of deposit formation. These were oriented longitudinally in the north-south direction.
- The samples for the measurement of the humidity of the lateritic mineral were taken on the deposit surface, thus ensuring correct measurements with the available instrumentation.
- In each deposit three measurement points were placed in different sections and for the subsequent analysis the average result was considered. Measurements were made during 14 non-consecutive days where climatic variability determined various experimental conditions in terms of initial material moisture values and meteorological parameters. The deposit cross sections were triangular. Measurements were made at west and east slope points of the deposits

The drying rate of the lateritic mineral during the natural drying process depends on several variables, including: the mass of material exposed to drying, the angle of repose, the dimensions of the deposits and the initial and final moisture of the material. The variables were measured directly in the deposits. We also considered the meteorological parameters that influence the natural drying. The particularities of the variables are described below.

Mass exposed to drying, angle of repose and dimensions of the deposits: Three mineral deposits with triangular cross-section were built; two were formed with 500 tons of material and the other with 700 tons. It was experimented with a resting angle of 61 degrees. The dimensions of the mineral deposits were 140 m in length and 3,2 m in width of the base, for the deposits of 500 tons; While the one of 700 tons had a length of 140 m and a width of the base of 5,49 m.

Lateritic mineral initial and final moisture: The initial moisture is considered an independent variable and, at the same time, a reference parameter because it allows to estimate the incidence of material moisture in the solar drying process. Their value varies randomly because it depends on the region meteorological conditions at the time of the process implementation and the hydrogeological characteristics of the operation deposit. Measurements were taken in the longitudinal deposits slopes. In the case of the final humidity measurements were taken at the end of the experiments.

Weather Variables: For the monitoring of these variables, the Davis EZ-Mount Groweather was used to measure and record the following meteorological variables on a computer: solar radiation, temperature, relative humidity, direction and air velocity. These variables have a random behavior so they could not be preset for experimentation.

III. RESULTS AND DISCUSSION

Figure 2 shows the behavior of the material moisture content as a function of time. The reduction of the moisture content below 1.618 % in the east slope is observed. Reductions in the material moisture content are obtained from 9:00 until 13:30 hours. After this time the humidity of the laterite mineral remains practically constant. In the morning (from 6:00 to 9:00 hours) is due to the low levels of solar radiation existing at that time and in the afternoon (from 13:30 to 18 hours) behavior can be attributed to the effect of shade which is generated by the inclination of the drying surface and the daily movement of the sun.

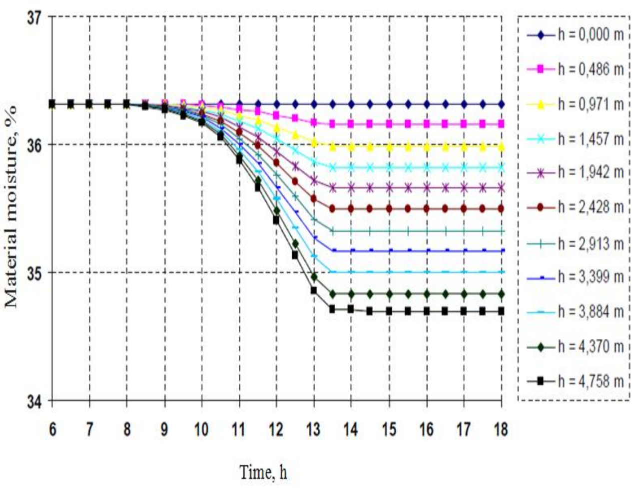

Fig. 2 Behavior of the lateritic mineral moisture distribution in the east slope, from the base to the drying surface.

In the western slope (Figure 3) for laterite mineral layers located between 0 and 2,428 m in height are obtained reductions in the moisture content less than 2.5 %, while in the layers closest to the drying surface (from h = 3.884 m to h = 4.758 m) the levels of reduction ranges from 3.2 to 4.2 %. This suggests that to reduce the humidity of the material between 5 and 6 % is necessary to develop the process of solar drying for a time of approximately 10 days if the weather conditions remain similar to those used in the simulations. Similar results have been obtained in the experimental tests developed.

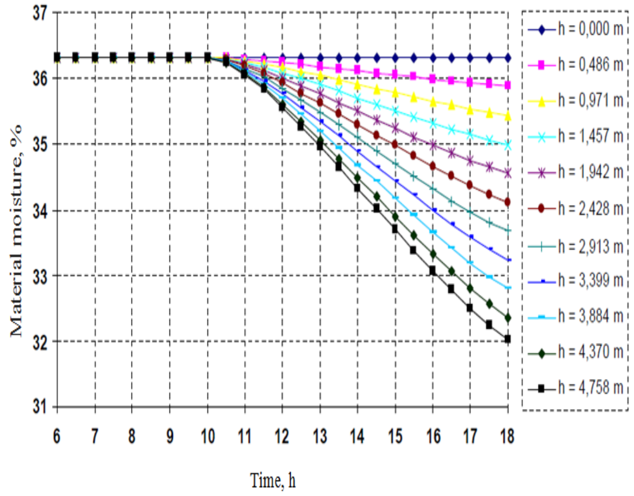

Fig. 3 Behavior of the lateritic mineral moisture distribution in the west slope, from the base to the drying surface.

The behavior of the lateritic mineral moisture distribution in the east slope depending on the drying thickness is shown in figure 4. The figure show reductions in moisture (greater than 1,5) to the layers that are at a distance of 29.1 cm from the surface of the slopes east.

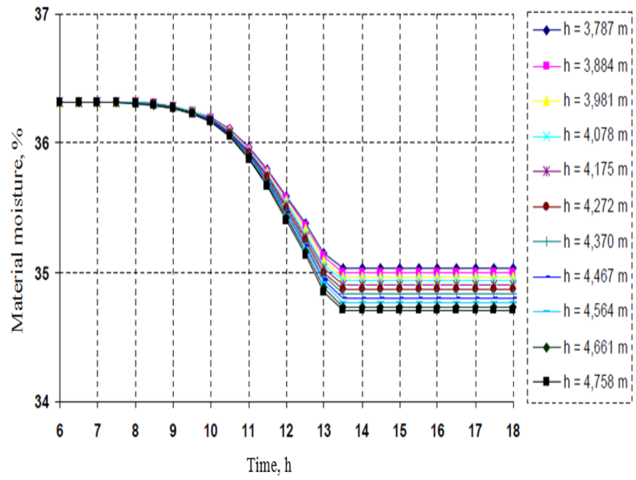

Fig. 4 Behavior of the lateritic mineral moisture distribution in the eastern slope depending on the drying thickness.

The figure 5 show reductions in moisture (greater than 3,5) to the layers that are at a distance of 87.4 cm from the surface of the slopes east.

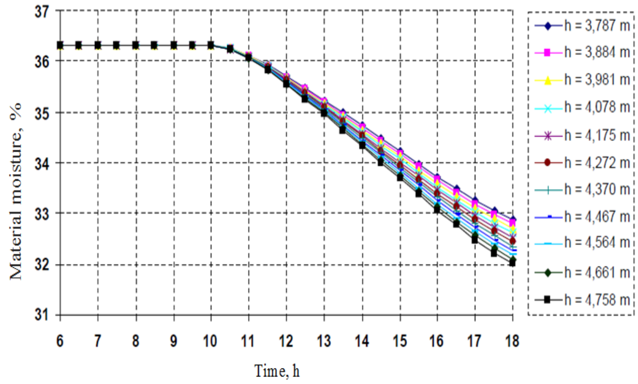

Fig. 5 Behavior of the lateritic mineral moisture distribution in the west slope depending on the drying thickness.

The previous results confirm that during the solar drying process of the lateritic mineral the transport of moisture is produced by the combined effects of temperature and humidity gradients. The first acts mainly in the layers close to the drying surface as a result of the heating experienced by the material in that area; the second acts on the inner layers as a consequence of the difference in moisture concentration between the different zones.

These behaviors suggest that during the solar drying process movement of moisture is mixed and includes the combined effects of vapor diffusion due to gradients of vapor partial pressure, the liquid diffusion due to the gradients moisture concentration and the movement of liquid due to the forces capillary and gravitational. The results suggest that the practical implementation of the process can be done with asymmetric surfaces whose western slope is much larger than the east slope, in this way it would be possible to reduce the slope of the west slope and would make correspond the greater surface of solar capture of the surface with the time when greater solar radiation hits.

IV. CONCLUSIONS

The mathematical models (expressions 26 and 32) allow to calculate the moisture distribution of the lateritic mineral during solar drying and make it possible to predict the drying time to which the material must be subjected in order to reduce its humidity from a known initial value to another value desired. They are obtained by analytically solving the differential equation of moisture exchange in a porous solid, for the specific boundary problems of the process investigated.

The movement of moisture during solar drying occurs mainly because of the temperature gradients and humidity concentration generated during the process and the capillary and gravitational forces acting on the liquid column present in the lateritic mineral. The existence of a mixed moisture transport mechanism was determined to include the combined effects of vapor diffusion, liquid diffusion and liquid movement.

In the solar drying simulations the moisture of the laterite mineral was reduced by 1,5 and 3,5 % to the layers that are separated about 29 and 87 cm from the surface of the east and west slopes, respectively. At these slopes the humidity was reduced by 0,429 and 0,694 % on average; and in the whole area the reduction was 0.562 %, for a drying time of 12 hours counted from 6:00 in the morning.

Nomenclature:

H - Material moisture, kg/kg.

K_u - Moisture conduction coefficient, m^2/s.

τ - Drying time, s.

δ - Thermal coefficient of humidity conduction, 1/°C.

T - Material temperature, °C.

$\Omega(y)$ - Function that characterizes the change of H_0 with the time (τ) and position (y), kg/kg.

H_0- Initial material moisture, kg/kg.

$H_s(\tau)$ - Material moisture on the drying surface (y=1), kg/kg.

l - Surface length, m

θ - Surface inclination respect to the horizontal plane, degrees

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