Solar Drying Simulation of Different Products: Lebanese Case

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ABSTRACT

Solar radiation has been used for drying different products for thousands of years. Solar energy was the only energy used until the discovery of fossil fuels sources. These dryers are not very commercialized, and their designs are based on empirical and semi-empirical systems. Therefore, theoretical studies will be of high importance in this field. In this article, a simulation of a direct solar dryer system is developed based on the heat transfers phenomena inside and outside the dryer. This study is applied on five different products to determine instant temperatures of the product, of the internal air of the dryer and of its cover, in addition to the instant water content of the product dried. Finally, a relation between the thermal capacity of the product dried and a defined drying characteristic time will be highlighted.

Key words: Solar drying, drying characteristic time, thermal capacity.

INTRODUCTION

The use of renewable energy sources, such as solar, wind and hydro, is very old, they have been used for centuries before our time and their applications have continued throughout history and until the "industrial revolution", which were abandoned due to the low price of oil. In recent years, due to rising prices of fossil fuels and environmental problems caused using conventional fuels, we have returned to renewable energy sources. Renewable energies are inexhaustible, clean and can be used in a decentralized way (they can be used in the same place where they are produced). In addition, they have the advantage of being complementary, their integration being favorable, for example, photovoltaic solar power provides electricity on sunny days (usually in weak winds), while on cold and windy days, often cloudy, wind turbines can provide more electrical energy. Solar energy can be transformed into other forms of energy, food energy, kinetic energy, thermal energy, electricity or biomass. In addition, it replaced fuels in several sectors, in heating, air conditioning, and especially in solar drying. Solar drying is used for several products such as wood for external and internal use, nutrients for conservation, mud and many others.

There are two major types of drying, natural drying and artificial drying. For artificial drying there are several techniques to be named, examples, drying by Joule effect, by infrared radiation, by high frequency currents and other types. All these types consume a large amount of energy, and in order to minimize the consumption of fuel, several studies have been directed to use renewable energy especially the use of solar energy. In this study, solar energy will be used. Solar drying is one of the most effective and cheapest methods to reduce the moisture content of any element. Therefore, it consists of understanding the mechanisms and parameters involved in this drying in order to give a scientific means to consumers in building their dryers. The thermal balance which governs the system will be conducted, and a simulation study of the water content and the temperature of the product, temperature of the internal dryer's air, and temperature of the cover will be highlighted. Finally, a relation between the thermal capacity and drying characteristic time will be concluded.

SOME REVIEW OF SOLAR DRYERS

Drying is an operation aimed at removing from part of a body, the water absorbed inside. Three types of drying can be distinguished, mechanical drying, chemical drying and thermal drying. However, thermal drying by evaporation of water is the most common method when talking about...
drying. It involves drying by boiling and drying by entrainment. We will limit the study to drying by hot air entrainment. Solar drying systems are generally classified according to their heating modes and the way solar energy can be used, thus, they can be classified into two major groups as follows: Active solar drying systems (often called hybrid solar dryers), Passive solar energy drying systems (conventionally called solar dryers with natural circulation of drying air). Three distinct subclasses can be identified for these two active and passive drying systems (depending on the type of dryer and the mode of use of solar energy), namely, direct type solar dryers, indirect type and mixed type solar dryers.

Direct effect solar dryers

These generally consist of a sealed chamber and a transparent material which covers part or all of it and transmits a large amount of the received solar radiation having short wavelengths (from 0.25 to 2.5 μm). In some dryers, this radiation is captured and then transformed into heat by an absorber which generally consists of a metallic surface painted black. The absorber then emits infrared radiation (between 3 and 30 μm) for which the transparent part is opaque. In other dryers, the transmitted solar radiation is directly used to heat the air. There are two main configurations, greenhouse type dryers where the roof and three walls, east, west and south, are made of a transparent material and semi-greenhouse dryers of which only the roof or the roof and one wall are transparent, the other faces being thermally insulated. Several direct effect solar dryers have been studied and constructed, the following are cited:

Johnson’s dryer: which has a capacity of 0.9 m³ built in 1961 in Dodgeville, Wisconsin, USA. This dryer consists of a roof in the form of a single glazing above a black metal surface which represents the absorber, a fan to circulate the air inside the dryer and perforated slots in the ground to evacuate moist air out. The Performance of this dryer is as follows, the drying of white oak (25 mm) from 60 to 6% humidity is 52 days in summer as for the drying of black oak of the same thickness from 50 to 20% humidity is 72 days in winter (Johnson, 1961).

Sharma dryer: which has a capacity of 7.1 m³ of wood, was built in Dehra, Dun, India in 1972. This dryer consists of 5.5mm double glazed walls separated by air 37 mm thick. An absorber is placed above the wood in the dryer, two fans to circulate the air, and vents on the south and north walls to extract the humid air from the dryer. The performance of this dryer is as follows, The drying time of several 2.5 cm Indian species is 7 to 16 days and those of 6.2 cm is 25 to 30 days. The drying time recorded with this dryer was 4 times less than that in the open air (Sharma et al.,1972).

Gough dryer: has a capacity of 15 m³, was built in Brisbane, Queensland, Australia in 1981, it consists of a roof and three walls (east, west and north) of single glazing and a layer of polyvinyl, a fan to circulate the air inside the dryer and manual vents in the south wall to extract the humid air from the dryer. The performance of this dryer is as follows, The drying time of cypress (Cypress Pine) (25 mm) from 39% to 12% humidity is 36 days and that of mahogany (50 mm) from 38% to 12% is 72 days (Gough, 1981).

Prestemon dryer: has a capacity of 2.4 m³, was built in Ames, Iowa, USA in 1983. consists of walls and a roof formed by a layer of chipboard, fiberglass and wood black painted frame, a fan that circulates the air inside the dryer and six perforated openings in the north wall to extract the humid air from the dryer. The performance of this dryer is as follows: The drying time of a 25 mm thick hardwood from the green state up to 7-8% humidity was 4 weeks in summer and 6 weeks in spring (Prestemon, 1983). Several indirect effect solar dryers have been studied and constructed, the following are cited thus:

McCormick dryer: has a capacity of 240 m³, was built in Canton, Mississippi, USA in 1980. This dryer uses solar energy in combination with a heat pump system and has a tank for storing hot water about 19 m³. The performance of this dryer is as follows: The contribution rate of solar energy is 23% compared to the total energy used for drying 25 mm thick hardwood (McCormick, 1980).

Lumley and Choong dryer: has a capacity of 0.9m³, was built in Baton Rouge, Louisiana, USA in 1981. This dryer consists of a solar collector located above the drying chamber well insulated in chipboard, and a fan to circulate the air inside the dryer and perforated openings in the north wall to extract the humid air from the dryer. The performance of this dryer is as follows: The drying time of 51 mm thick ash wood with a humidity of 51 to 14% is 19 days, and 25mm thick from 50 to 7% is 20 days. For the red oak growing from a humidity of 82 to 17%, the drying time is 29 days and takes 21 days for the Cypress to go from 88 to 10% humidity (Bahraoui-Baret and Khtira, 1984).

Dryer of Simpson: has a capacity of 9.4 m³ and was built in the Philippines in 1984. It consists of a drying chamber with a wooden frame, a solar collector and a fan which allows air circulation inside the chamber when the temperature of the sensor is higher than that of the chamber. The performance of this dryer is as follows: the drying time of Quercus Rubra (29 mm) from 85% to 10% is 54 days and that of Acer Platonoid (29 mm) from 67% to 8% is 26 days (Simpson and Tschneritz, 1984).

To improve the energy efficiency of solar drying procedures, it is necessary to establish less empirical design rules that
The purpose of modeling solar drying in a greenhouse is to predict water content changes until it reaches the desired value. In addition, the design of the model must consider all the exchanges between the wet product and its environment as well as its behavior during drying, to obtain authentic predictions. We proposed to study the energy and mass balance of a solar dryer in a greenhouse. The behavior of the latter is simulated by a mathematical model based on global balance sheets. Mathematical modeling consists of translating physical phenomena (heat and mass transfer) by a series of equations highlighting the energy state of the various system components constituting the solar dryer (product to be dried, indoor air, roofing), each defined by its intensive thermodynamic variables.

WEATHER DATA

The climatic data used for this study are the radiation, the temperature and the humidity of the ambient air. We took the raw data over several years from the National Meteorological Service of Lebanon, then we calculated the hourly temperatures and humidity for the site located in Beirut, Lebanon. The equation used by Chouard et al. (1977) for the hourly evolution of the outside air temperature is:

\[ T(t) = T_{ae,in} + K_T(t) \cdot (T_{ae,max} - T_{ae,min}) \]  
(1)

Knowing that the maximum temperature \( T_{ae,max} \) and minimum temperature \( T_{ae,min} \) are the local data provided by the meteorological station. We used the values of \( t \) corresponding to the month of April. Figure 1 shows the hourly evolution of the outside temperature measured and simulated with the standard error of the estimate \( ETE = 2.9\% \) \( R^2 = 0.901, \) very high). The simulated ambient air temperature follows the same trend as that of the measured ambient temperature. The equation used Chouard et al. (1977) that gives the evolution of the external relative humidity obtained under the same conditions as that of the ambient air temperature is:

\[ H_r(t) = H_{r,x} + K_r(t) \cdot (H_{r,max} - H_{r,min}) \]  
(2)

Knowing that the maximum relative humidity \( H_{r,max} \) and minimum relative humidity \( H_{r,min} \) are also the local data provided by the meteorological station. We used the values of \( t \) corresponding to the month of April. Figure 2 shows a good agreement in the values of the relative humidity measured and simulated with the standard error of the estimate \( ETE = 2.9\% \) \( R^2 = 0.901, \) very high). It also shows that the evolution of relative humidity varies in opposition to the temperature. It is maximum at sunrise, after a set of values close to saturation, and shows a minimum when the temperature is maximum. Figures 1 and 2 highlights the validity of the hourly temperature, equation (1) and hourly relative humidity, equation (2). Therefore, we can use our numerical model of solar drying as input parameters to obtain the results close to real solar drying cases.

MASS AND HEAT TRANSFER MODELING

The solar drying of the products is based on the contact, under a greenhouse of a regularly renewed air. A ventilation system ensures an air flow in the greenhouse to favor the transfer of pore water into the atmosphere and to evacuate the humid air. The basic elements to build our direct solar dryer model are as follows:

(1) The external environment
(2) Cover
(3) Indoor air
(4) The product to be dried
(5) The support on which the product rests.

The different modes of heat transfer involved inside the greenhouse are:

1. Gains through the roofing material
2. Long wavelength radiative exchanges between the different elements
3. Convection exchanges on the surface of the cover and that of the product
4. Evaporation at product level
5. Air renewal due to the permeability of the greenhouse or mechanical ventilation.

Figure 3 below schematically represents all the elements to be considered and the different processes involved. Each element of the model is characterized by a state variable, mainly the temperature. The product is further characterized by its water content. We will retain the hypothesis of a uniform distribution of different variables. This hypothesis has the advantage of allowing the formulation of equations whose solution will represent the average state of the variables.

**Expression of energy flows**

**Solar radiant fluxes**

These are the fluxes linked to the radiation emitted by the sun and whose wavelength is approximately between 0.25 and 2.5 µm. Assuming that the blanket behaves as a horizontal wall of the same surface as that of the greenhouse floor is sufficient, the determination of the different net balance of the solar flux absorbed by each element is carried out using overall transmission and reflection coefficients not related to the angle of incidence of solar radiation on the different walls. The properties of the cover and the product with respect to solar radiation are average properties which constitute input parameters of the model, Coefficient of transmission \((\tau_c)\) and absorption \((\alpha_c)\) of the cover, Coefficient of absorption \((\alpha_p)\) of the product, and
and reflection of the product ($ρ_p$). The transmissivity of the product ($τ_p$) is zero because it is supposed to be opaque to solar radiation. The net flows absorbed by:

\[ ϕ_{Rc} = R g \,(1 + ρ_p \,τ_p) \]

The product: $ϕ_{cp} = R g \,α_p \,τ_c$.

**Infrared radiative fluxes**

They correspond with the radiations emitted by the different elements of the greenhouse, considering the temperatures of these bodies, in the infrared range of long wavelength (5 to 50µm). Obviously, the sky is also included as a source of radiation. The net balance of the energy absorbed or lost by each of the bodies is the result of these simultaneous emissions, considering multiple reflections on each of the different elements. The total flux received by the cover of the external environment is written as follows:

\[ \Phi_{Icv} = σε_c(T_v^4 - T_c^4) \quad (W/m^2) \]

With the temperature of the sky is given by the relation of Swinbank (1963): $T_v = 0.0552 \, T_a$; ($T_a$ = outside air temperature (K)) Infrared radiative flux within the model. We restrict the exchange by infrared radiation to the product coverage medium. The net flow lost by the product area $S_p$ is equal to the net flow gained by that of the coverage $S_c$. This flow is still equal to the net flow exchanged between $S_p$ and $S_c$. So, we have equality: $ϕ_{ipc} = -ϕ_{ipc}$

The flow of energy exchanged between the surface of the product and that of the cover is given by the relation:

\[ \Phi_{ipc} = \frac{σ}{ε_p \,ε_c} \left( T_c^4 - T_p^4 \right) \quad (W/\text{m}^2) \]

**Convective flows**

Whatever the type of convection (free or forced) and whatever the flow regime of the fluid (laminar or turbulent), the heat exchanged is written as:

\[ h \, S \,(T_s - T_f) \quad (W) \]

With $T_s$, $T_f$: respective temperatures of solid and fluid.

**Convective exchange outside environment / cover**

This exchange reflects the effect of the wind on the outside of the cover. The convection coefficient is given by the equation of Mc Adams (1954):

\[ h_e = a + b \, U \nu \,(W.m^{-2}.\degree C^{-1}) \]

With $a = 5.67 \, W.m^{-2}.\degree C^{-1}$ and $b = 3.86 \, W.m^{-3}.\degree C^{-1}$

**Convective exchange within the model**

The convective exchange due to the renewal of indoor air is a special case that is, the flow is linked to the difference in internal energy between the incoming air and the outgoing air. The power exchanged is expressed by the relation:

\[ ϕ_c = ρ \, Q \, Cp(T_{ia} - T_{we}) \quad (W) \]

The product $ρ \, V \, Cp$ is usually designated as the heat capacity ($C_c$) of the body expressed in $J/\degree C$ and which quantifies the total energy that the body must store to increase its temperature by one degree.

**Thermal inertia**

The thermal inertia corresponds to the variation of internal energy contained by a body between two instants. It will be defined by the following differential relation:

\[ ϕ_i = ρ \, V \, Cp \, \frac{dT}{dt} \quad (W) \]

The product $ρ \, V \, Cp$ is usually designated as the heat capacity ($C_c$) of the body expressed in $J/\degree C$ and which quantifies the total energy that the body must store to increase its temperature by one degree.

**Thermal balance on the cover**

\[ ϕ_{Rc} + ϕ_{Icv} + ϕ_{Icp} - ϕ_{Ccae} + ϕ_{ciac} = ϕ_{ic} \]

$ϕ_{Rc}$ = net flux of solar radiation received by the cover $ϕ_{Icv}$ = flux of infrared radiation emitted towards the sky $ϕ_{Icp}$ = flux of infrared radiation emitted towards the product $ϕ_{Ccae}$ = convective flow of the cover towards the outside air $ϕ_{ciac}$ = convective flow of the cover towards the indoor air $ϕ_{ic}$ = thermal inertia accumulation flow of the cover

\[ C_c \, \frac{dT_c}{dt} = R g \, σ \, ε_c \left( 1 + τ_c \, ρ_p \right) + σ \, ε_c \left( T_p^4 - T_c^4 \right) + \frac{σ}{ε_p \,ε_c} \left( T_p^4 - T_c^4 \right) + h_{ce}(T_{ae} - T_c) + h_{ci}(T_{ia} - T_c) \]
Indoor air heat balance

\[ \Phi_{Cpia} - \Phi_{Ciae} - \Phi_{Ciac} = \Phi_{iia} \]

With: \( \Phi_{Cpia} \) = convective flow of the product towards the indoor air
\( \Phi_{Ciae} \) = convective flow from indoor air to outdoor air
\( \Phi_{Ciac} \) = convective flow of indoor air to the cover
\( \Phi_{iia} \) = thermal inertia accumulation flow of indoor air

\[ \rho \cdot V \cdot C_{pia} \frac{dT_i}{dt} = h_{pi} \cdot S_p (T_p - T_i) + h_{ci} \cdot S_c (T_c - T_i) - \rho \cdot V \cdot C_{iia} (T_{iia} - T_{iia}) \]

Thermal balance on the product to be dried

\[ \Phi_{Rp} + \Phi_{Ipc} - \Phi_{Cpia} - m \cdot L v = \Phi_{ip} \]

With: \( \Phi_{Rp} \) = net flux of solar radiation received by the product
\( \Phi_{Ipc} \) = flux of infrared radiation emitted towards the cover
\( \Phi_{Cpia} \) = convective flow of the product towards the indoor air
\( \Phi_{ip} \) = thermal inertia accumulation flow of the product
\( m \) = mass flow of water evaporated from the product
\( L v \) = latent heat of vaporization of water

\[ m \cdot C_{p} \frac{dT_p}{dt} = R_g \cdot S_p \cdot \alpha_p \cdot T_p - \frac{\sigma \cdot S_p}{\varepsilon_p + 1} (T_p^4 - T_c^4) + h_{pi} \cdot S_p (T_p - T_i) - \dot{m} \cdot L v \]

Mass heat capacity

To calculate the heat capacity of a wet product, we used:

\[ C_{p} = \frac{1}{1 + x} C_{p dry} + \frac{x}{1 + x} C_{p water} \]

Mass balance: Evaporated water flow

When a wet product is placed in a gaseous atmosphere containing water vapor, there is generally exchanges of water vapor between the two phases (solid, vapor), either the product absorbs water and renews, or on the contrary it loses water to the benefit of the atmosphere, until the thermodynamic equilibrium is established. The losses in mass of water or the quantity of water evaporated are expressed by the following equation:

\[ \frac{dm}{dt} = M_s \cdot (\frac{- dX}{dt}) \]

Material transfer can be calculated from the value of the flux, based on the following equation:

\[ M_s \left(\frac{-dX}{dt}\right) = KS (P_{sat} - P_v) \quad \text{(Kg}_{\text{water}}/\text{s}) \]

The transfer coefficient \( K \) is deduced from the convective exchange coefficient by the Lewis relation: \( K = \frac{h}{\rho C_v} \) and its equivalent for heat transfer is exchange coefficient \( Q = h S (T_a - T_d) \)
The quantity of heat is linked to that of material via the latent heat of vaporization:

\[ Q = M_s \left(\frac{-dX}{dt}\right) L v \]

The drying speed at constant phase:

\[ \left(\frac{-dX}{dt}\right)_1 = \frac{S_p}{M_s L v} \left[ R_g a_p \tau_c + h_{cp} (T_{at} - T_h) - \frac{\sigma}{1 + \frac{\varepsilon_p}{\varepsilon_c} - 1} (T_h^4 - T_a^4) \right] \]

With the wet temperature calculated as:

\[ T_h = (-0.4911 T_{ae} + 8.2385) H r^2 + (1.0248 T_{ae} - 5.25) H r + 0.4501 T_{ae} - 2.5987 \]

PARAMETERS AND MODEL SIMULATION PROCEDURE

The conceptual model of the greenhouse already defined, remains to give it a concrete form to make its use effective by the resolution of the system of equation formulated. These balances determine a system of nonlinear differential equations whose unknowns are the state variables \( (, T_p, X) \). This system of equations shown in the calculation flow chart 1 will be solved by the Runge-Kutta method of order 4 in the MATLAB environment. The design of the model can integrate as input for the consideration of local climatic conditions varying over time (examples are, sunshine \( R_g \), outside ambient temperatures \( T_{ae} \), relative outdoor humidity \( H_r \)) of the location of the drying device. Temperatures, relative humidity of the outside air and solar radiation are each reconstituted hourly by an evolution law chosen from the literature. Two types of input parameters were introduced into the model, the primary parameters are fixed input parameters and scalable input parameters.
In this category, the fixed input parameters are those linked to the geometric and physical characteristics of the greenhouse and its elements. These data remain constant during a given simulation of greenhouse operation, and the scalable input parameters are those which may vary during the simulation that is, they essentially correspond to external climatic data. The secondary parameters calculated by the model from primary parameters. The program provides the simulation results at each resolution time step. The criterion for stopping the simulation is fixed on the occurrence of the condition that the simulation time has elapsed. The results of the simulation constitute the outputs of the model:

The cover temperature (Tc)
Indoor air temperature (Tia)
Product temperature (Tp)
The dry base water content of the product (X).

Knowing these output parameters will allow us to assess the evolution of the drying speed and therefore the evolution of the evaporation flux under given climatic conditions. The estimation of the roof temperature, will allow us estimate the heating needs of the greenhouse in order to compensate for the losses. The estimation of the indoor air temperature will make it possible to estimate the needs for the quantity of energy to be injected into the system, therefore, to estimate the ventilation needs.

Characteristic drying curve

The concept of the characteristic drying curve, noted C.C.S., was developed by Van Meel in 1957. The objective is to model the drying speed, it is a way of examining whether, despite the complexity of the phenomena at the microscopic level (that is to say, in the pores of the medium), it is possible at the macroscopic level to obtain a certain simplicity of interpretation of the experimental results (Moyne, 1985), (Midilli and kucuk, 2003) and the same behavior model of the product studied, whatever the conditions of the experiment. The approach consists in "normalizing" the average water contents and the drying speeds to obtain a single curve for a given product of determined dimensions and independently and of the aero thermal conditions (speed, temperature, and hygrometry of the drying air), (Doymaz, 2007), (Ait Mohammed al et al., 2005). This notion of characteristic drying curve was taken up by J. Van Brakel (1980). To apply the concept of the characteristic drying curve, the use of certain correlations of the form is required. The normalized or reduced water content $X_r$ is expressed by:

$$X_r = \frac{X(t) - X_{eq}}{\bar{X}_r - \bar{X}_{eq}}$$

It is difficult to determine the value of the critical water content, then to be able to make the theoretical calculation, $\bar{X}_r$ is taken equal to $X_i$.

RESULTS OF THE SIMULATION

The simulation of the model will highlight the operation of the solar dryer in a well-defined climate. The mathematical model will study different products drying process. The digital simulation model is based on the thermal, mass and correlation balances which give the variations in the climatic parameters (solar radiation, relative humidity and outdoor air temperature over time) already formulated. These balances determine a system of nonlinear differential equations whose unknowns are the state variables (Tia, Tc, Tp, X). This system of equation is solved by applying the Runge-Kutta method of order 4 using Matlab (2019b) software. As an application of the numerical system, five products were considered which their properties are summarized in table 1. Figures 4, 5 and 6 below shows that the variations of the temperature in function of time present 3 peaks that correspond to 2p.m. of each day. Between two successive peaks, the variations are identical, and they represent a "plateau" for the night hours (between 8p.m. and 6a.m.), that correspond to sunshine and sunrise.

### Table 1: Physical properties of products dried.

<table>
<thead>
<tr>
<th>Product</th>
<th>Emissivité</th>
<th>Coefficient d’absorption solaire</th>
<th>Thermal Capacity (J/kg.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beech</td>
<td>0.92</td>
<td>0.44</td>
<td>2100 [16,22]</td>
</tr>
<tr>
<td>Red fir</td>
<td>0.92</td>
<td>0.44</td>
<td>2300 [16,22]</td>
</tr>
<tr>
<td>Mud</td>
<td>0.9</td>
<td>0.8</td>
<td>1182 [20]</td>
</tr>
<tr>
<td>Absinthe</td>
<td>0.7</td>
<td>0.87</td>
<td>1112 [18,19,21]</td>
</tr>
<tr>
<td>Geranium</td>
<td>0.73</td>
<td>0.9</td>
<td>1520 [18,19,21]</td>
</tr>
</tbody>
</table>

The simulation is applied for 3 days duration (1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> of April 2019) in Beirut, Lebanon.
We can notice also that for the same temperature, the maximums that corresponds to peaks highlighted are increasing in function of time. For example, the case of Geranium, we have table 2. As an explication of this maximum increase, it is due to the decrease in the water content of the product with time, for this fact, the part of the solar energy absorbed by the product that serves to increase the maximum temperature ($T_{max}$) is increased and that will represent an equal increase in the maximum temperature of the internal air and maximum temperature of the cover.

Figure 7 shows the simulation of the variation of water
Table 2: Maximum temperature variations during drying time.

<table>
<thead>
<tr>
<th></th>
<th>Max Tc (˚C)</th>
<th>Max Tia (˚C)</th>
<th>Max Tp (˚C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>48.69</td>
<td>61.04</td>
<td>81.4</td>
</tr>
<tr>
<td>Day 2</td>
<td>53.39</td>
<td>68.13</td>
<td>92.26</td>
</tr>
<tr>
<td>Day 3</td>
<td>55.68</td>
<td>71.5</td>
<td>97.23</td>
</tr>
</tbody>
</table>

Figure 7: Variation of water content X in function of time t.

Table 3: Initial water content and reduced drying equation for different products.

<table>
<thead>
<tr>
<th>Initial water content (kg water /kg Ms)</th>
<th>F (Xr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beech</td>
<td>1.65 * Xr - 1.31 * Xr^2 + 0.66 * Xr^3 [16]</td>
</tr>
<tr>
<td>Red fir</td>
<td>1.45 * Xr - 0.97 * Xr^2 + 0.52 * Xr^3 [16]</td>
</tr>
<tr>
<td>Mud</td>
<td>2.37 * Xr - 3.3 * Xr^2 + 1.92 * Xr^3 [16]</td>
</tr>
<tr>
<td>Absinthe</td>
<td>0.0491 * Xr + 1.3789 * Xr^2 - 2.4970 * Xr^3 + 2.4753 * Xr^4 [17]</td>
</tr>
<tr>
<td>Geranium</td>
<td>1.3171 * Xr + 0.6568 * Xr^2 - 4.1959 * Xr^3 + 3.2026 * Xr^4 [17]</td>
</tr>
</tbody>
</table>

content in function of time and that is for the five products considered. Table 3 below shows initial water content and reduced drying curve equation for all the products considered in the simulation. Different curves are obtained by using for each product the characteristic drying function f(Xr) obtained experimentally by different researchers. Note that, for the geranium, absinthe, and the mud, the initial water content varies from 4.1, 3.9, and 5.1 kg water/kg Ms on the left vertical axis, and for fir and beach, the initial water content is 0.667 kg water/kg Ms on the right vertical axis.

ROLE OF THE THERMAL CAPACITY OF THE PRODUCTS

We noticed that whatever the product, the decrease in water content presents two kinds of variations, rapid variations (2 and 4) and slow variations (1, 3, and 5). Rapid and slow variations correspond successively to the hours of day and night. We have defined a characteristic time of drying in function of the products stretched. This characteristic time drying in function of the products stretched. This characteristic time correspond to the time of drying the product from 40% to 13% in water content terms. For this purpose, we ran the simulation again by starting all products with an equal water content of 0.667 kg water/kg Ms (which corresponds to 40%) to arrive at a final water content of 0.667 kg water/kg Ms (which corresponds to 40%) to arrive at a final water content 0.15 kg water/kg Ms (which corresponds to 13%) as shown in Figure 8. We then plot the variation of the thermal capacity as a function of the characteristic time of the products as shown in figure 9. We can notice that the different points are on a straight line of equation:

\[
C_p = at + b, \text{ with } a > b.
\]

with \( a = 143.71 \) J/h.kg.K and \( b = -771.55 \) J/kg.K.

Therefore, the characteristic time is an increasing function of the thermal capacity \( C_p \). The thermal capacity is a quantity which reflects the capacity of a material to accumulate energy, in thermal form for a given mass, when its temperature increases. A large thermal capacity means that a large amount of energy can be stored, with a relatively small increase in temperature. However, the drying time of a product depends on its temperature, which means that the greater the \( C_p \) of the product, the greater is the characteristic time. The curve of figure 9 obtained can be completed and validated by doing the calculation and simulation for other products.
CONCLUSION

Haven highlighted the need for drying different products, we set ourselves the objective of increasing the interest of solar drying, particularly that with direct effect, by a theoretical study considering Lebanese climatic conditions. First, we calculated the hourly outside air temperature, outside relative humidity and the intensity of the solar radiation received by the cover of the dryer considering the first three days of April 2019. Then, we carefully introduced these results in the simulation program. This allowed us to simulate the operation of a direct solar dryer in a Lebanese climate, that of the city of Beirut. Secondly, we applied the simulation introduced to fir, beech, geranium, absinthe, and mud. This simulation resulted as, the cover temperature, the internal air temperature, the product temperature and its water content. After that, we highlighted a relation between the thermal capacity of a product and a defined characteristic time that needs to be validated in future researches. Finally, optimization of drying could be examined by playing on the structure and geometric parameters of the dryer. In addition, experimental work should be associated with these theoretical studies in order to validate all the parameters examined and verify their influence on the drying characteristic time and on the quality of the dried products.

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