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SOLAR DRYING KINETICS OF DATE PALM FRUITS ASSUMING A STEP-WISE AIR TEMPERATURE CHANGE

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Abstract

The effect of drying using a step-wise temperature change was studied considering the case of indirect solar drying of the date palm fruit (*Phoenix dactylifera L.*). The followed procedure consists of building drying kinetics by stages of temperatures resulting from drying, in constant conditions, of the same variety of dates from Algerian and Tunisian origin. A law of daily temperature variation prevailed by 60°C, was deduced from a statement of temperature collected on a laboratory solar dryer prototype. Two drying curve equation models were used and some comparisons were discussed. The results obtained for dates from the two origins highlighted different response times by changing the air temperature and showed the possibility of reaching a fruit with standard moisture content in only one day of drying on the basis of initial water contents ranging from 0.40 to 0.65. This moisture range is in practice allotted to rehydrated dates by water immersion in order to enhance their quality. Experiments conducted in a laboratory solar drier under temperatures oscillating around 50°C and 60°C led to the same end up regarding the drying time ensuring a visually appreciable fruit quality. Results obtained by a simple sensorial test revealed a better quality of date fruits treated by solar drying comparing to those issued from industrial heat treatment units.

Keywords: Solar radiation, Date fruit, Drying

1. Introduction

In food engineering processes, post harvest heat treatments are of a great economic and industrial interest. They allow the safeguarding of the food quality but present the problem of being energetically expensive, particularly when a drying

Nomenclatures

A_o, A_1, b	Fitting coefficients
k	Drying parameter
R	Universal constant of perfect gases, J/mol.K
Rh	Relative humidity, %
r	Determination coefficient
SEE	Standards errors values
T	Temperature, °C
t	Time, s
v	Air velocity, m/s
X	Moisture content, kg water/kg dry matter
X_{eq}	Equilibrium moisture content, kg water/kg dry matter
X_m	Monolayer moisture content, kg water/kg dry matter
X_o	Initial moisture content, kg water/kg dry matter
XR	Reduced moisture content, -

process is used. Solar energy as a clean and less expensive source is well considered in both industrial alternatives and research investigations. In the Maghreb countries, particularly in Algeria, the heat treatment of the date palm fruit by rehydration and drying can be a good application subject of solar energy, supported by a large production of dates (516293 tons according to FAO database) and an excellent solar radiation in the areas of the producing oases.

"Deglet-Nour" variety is a specific date to the region of Maghreb countries and is a climacteric fruit with maturation spread out on the same palm. Dates production is harvested once a year. This situation makes the fruit post-harvest treatment necessary so as to minimize losses and avoid the eventual conservation and storage accidents particularly through rainy year or excessively hot climate.

Traditionally, too wet naturally dates and rehydrated dry dates were brought back to normal moisture by direct exposure to the sun during a few days [1].

Regarding consumer requirements, indirect solar drying would be more suitable by the fact of curtailing drying time and preserving product quality. This could explain the tendency of several authors to deal with the current problems of solar driers in the experiment and simulation fields of the phenomena [2-5].

In fact, as for any drying mode, the solar drying is closely related to the quality of the product that is finally judged by the consumer appreciation. In the case of “Deglet-Nour” date there is available literature [1, 6-12] stating that the fruit quality can be sufficiently characterized by a fair colour with clear appearance and a half-soft consistency. It was noted that the texture firmness is directly related to the fruit water content [13] while the colour is rather related to sugars and enzymatic activities.

In the completely ripen state (Tamr), the fruit contains approximately 85% of total sugar equitably distributed between sucrose and reducing sugars (glucose and fructose) [6] allowing a half-soft mechanical state. The international standard (UN-CEE DF-08) adopts 26% as normal moisture for marketable date. It is also known [1, 14] that a part of this same variety is already overdried on the tree and requires a post-harvest treatment by humidification and drying before being marketed. This treatment enables the bringing back of the fruit to a good quality state by means of hydration and sugar inversion, characterizing a maturation complement, according to the same references.

The present work is aimed at presenting a solar drying kinetics constructing procedure assuming that the temperature change in the solar drying box is made according to several stages of constant temperatures through the day. The steps followed in this study were based on experimental data resulting from measurements taken on a solar drier prototype (Laboratory LENREZA, Ouargla University, Algeria). With the procedure suggested in this paper, the solar drying kinetics should allow, knowing the daily temperature evolution, the prediction of drying time and, possibly, the quality by using an indirect solar drier. Various calculations and data processing were carried out by SCILAB 4.0. Fitting experimental curves and searching for models were carried out by Curve-Expert 1.3.

2. Materials and Methods

2.1. Solar drier

The solar drier used in this study (Fig. 1) is a laboratory prototype, suitable for the agro-alimentary products, designed and assembled by the energy conversion research unit at LENREZA laboratory (UKMO University, Ouargla, Algeria). It is composed of an air plane solar collector (2.0×1.0×0.13) m with an inclined angle of 16° regarding the horizontal and directed to south. The drying room is made up of coated sheet of (1.0×0.8×0.8) m in dimensions thermally isolated with polystyrene on all the external walls and provided with a chimney in galvanized sheets (1.0×0.02×0.02) m. The total solar radiation received in the captor field is measured in W/m² using a sunshine recorder with digital display through experiment day. The temperature measurements are carried out using thermocouples placed at various places of the drier. The humidity and the air velocity at the entry of the drying room are measured respectively using a digital display probe and a manometer connected to an apparatus TESTO-645 type with computerised data acquisition.

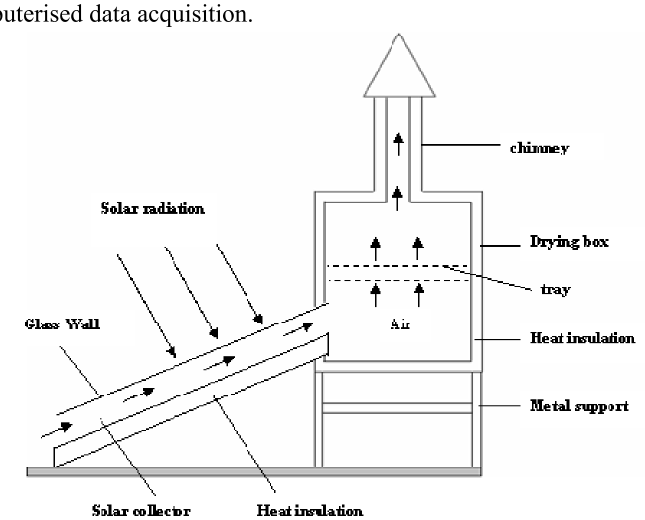

Fig. 1. Solar Dryer Pilot (LENREZA Laboratory).

It should be noted that in our present work, this test bench was only used to recover information on the daily solar radiation and change of the temperature. Some first trials were also conducted. On Fig. 2 are represented the solar radiation curves relating to measure sufficiently spaced in time (June 11, 2007 and March 17, 2008); we obtained practically the same profiles. It can be seen clearly a pick of about 850 W/m² by 12h: 30mn (am) on March 17, 2008.

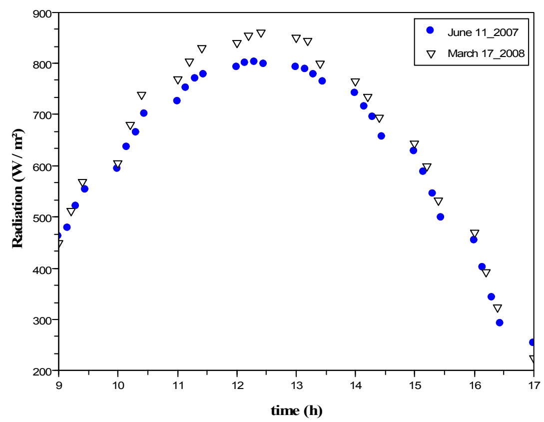

Fig. 2. Solar Radiation over Two Different Days.

2.2. Sample preparation

Dates were harvested in Oued-Righ region in Algeria and sorted as Deglet-Nour dry dates. At the laboratory, samples have been sorted into lots of fruit with uniform average dimensions of 1.55 cm in diameter and 3.5 cm in length. Only clear fruits were retained; already brown or physically altered dates were rejected. Samples were then sealed in plastic bags and stored at +4°C. During the day prior to each drying test, corresponding samples were rehydrated during 12 h in distilled water at 26°C, and then relaxed in dark place during nearly 5 hours. The moisture content reached after this preparation was about 0.55 kg/kg dry basis.

2.3. Experimental procedure

Prior to each test the drying box was checked to ensure homogenous air temperature. Prepared samples were settled out in single layer on a metallic tray. Inlet air temperature and mass loss of the product were recorded by twenty minutes intervals over nine drying hours per day. Initial moisture content for each dying test was measured on a laboratory analyser using a sample of 3 g weight.

3. Data Source and Simulation

3.1. Drying curves under constant conditions

In the present study, we used four thin layer drying kinetics of "Deglet-Nour" date of southern Algerian origin, under operating conditions 37°C, 50°C, 60°C and 75°C with ambient relative humidity and a velocity of 1.5 m/s of drying air as presented by Boubekri et al. [13]. These experimental drying curves were taken from automatic measurements collected from a hot air convective pilot drier using hard dry dates rehydrated in distilled water at 30°C during eight hours, as mentioned in the above reference. In the other hand, in order to get a comparative idea, we used drying curves of Tunisian Deglet-Nour date variety as a mathematical model proposed by Kechaou and Maalej [15]. In such study, air drying temperatures were ranging from 30 to 70°C, air velocity from 0.95 to 2.7 m/s and relative humidity from 11% to 47%. The used samples were fresh Deglet-Nour dates cultivar purchased on the market from south of Tunisia. In both two references, particles sizes were averaged to 3.5 cm in length and 1.6 cm in cross diameter.

3.2. Data processing

It was already mentioned that the objective of this study was to make simulated solar drying kinetics assuming a step-wise temperature change of the inlet air in the drying room during the day. In the following lines we will expose the adopted assumptions and the various steps of our proposed procedure in a logical succession.

3.2.1. Assumptions

a) The temperature evolution in the drying room is considered to be by constant stages as shown typically on the Fig. 3.
b) Drying process is conducted by repeating the same temperature cycle until obtaining the desired final water content, knowing that the operation stops by the night.
c) The product is placed on only one tray and is spread out in thin layer.
d) The average air velocity crossing the drying room is supposed to be constant.
e) The average relative humidity of the air in the drying room is considered to be constant on each stage of temperature.
f) The moisture content of the product varies according to the thin layer drying kinetic relating to each temperature stage in the room.

3.2.2. Air drying temperature evolution

The plotting of model curve related to temperature evolution was performed by determination of acceptable average values on reasonable time intervals. This logically supposes to acquire the kinetics of drying relating to these values of temperature. In the case of our study we tried to realise the temperatures, according to available kinetics [13]. The typical temperature curve, obtained from the real curve of the solar drier, is given by Fig. 3.

The temperature varies around the average values of 37°C, 50°C and 60°C. Moreover, in order to allow a second application of the suggested procedure, we supposed another possible situation where the temperature varies around 50°C, 60°C and 75°C. This situation is illustrated by Fig. 4 which represents the case of a stronger sunning or the case of an additional heating source.

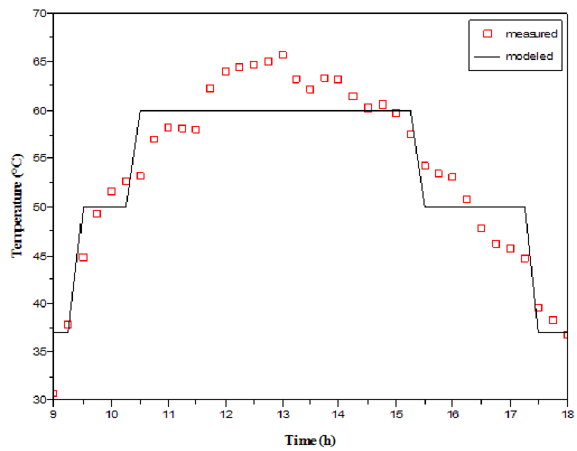

Fig. 3. Daily Measured and Modelled Temperature Change in Drying Room - Cycle (I).

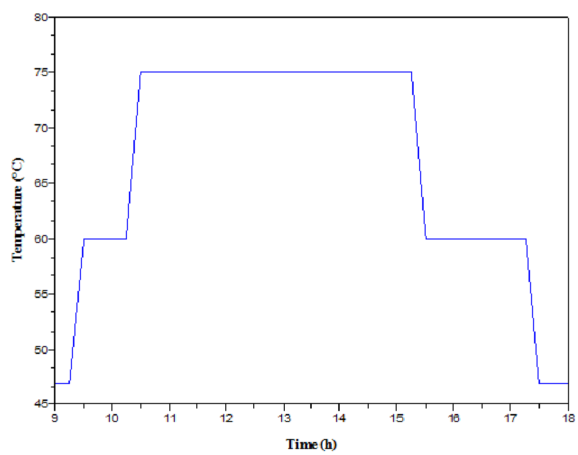

Fig. 4. Daily Modelled Temperature Change - Cycle (II).

3.2.3. Curve model equations

In order to allow a numerical construction of the solar drying kinetics by sections, we need to adopt a mathematical model able to build up drying curves. On one hand we will fit each of the curves given by Boubekri et al. [13] to a model equation and on the other hand, in order to have a comparison idea, we will use a model equation given by Kechaou and Maalej [15] adopted and validated for Tunisian Deglet-Nour dates.

***Model* 1:**

Among several model equations applied and compared on Curve-Expert we chose to adopt an exponential model of the form:

$$XR(t) = A_0 + A_1 e^{-bt} \tag{1}$$

where *XR* represents the reduced moisture content given by the following relation

$$XR(t) = \frac{X(t) - X_{eq}}{X_o - X_{eq}} \tag{2}$$

The equilibrium moisture content, X_{eq}, is calculated according to Kechaou and Maalej [15] by the relation given bellow:

$$\frac{X_{eq}}{X_m} = \frac{C \times K \times Rh}{(1 - K \times Rh)(1 - K \times Rh + C \times K \times Rh)} \tag{3}$$

with,

$$C = 1.514 \times 10^{-9} e^{61089/RT}$$

$$K = 72765 e^{-11710/RT}$$

$$X_m = 1.067 \times 10^{-9} e^{47614/RT}$$

The results of the fitting carried out by this exponential model are summarized below (Table 1) with the estimation standards errors values *SEE* and the determination coefficients *r*.

Table 1. Fitting Coefficients of Drying Kinetics at Various Temperatures.

***T* (°C)**	A_0	A_1	***b***	***SEE***	***r***
35	0.429751	0.568082	0.0003581	0.004515	0.999506
45	0.383953	0.609753	0.0006023	0.003143	0.999802
60	0.418958	0.571939	0.0014651	0.007354	0.999352
75	0.378088	0.593352	0.0025939	0.013448	0.997527

***Model* 2:**

It is an exponential drying curve proposed by Kechaou and Maalej [15]

$$XR(t) = \frac{X(t) - X_{eq}}{X_o - X_{eq}} = e^{-k\sqrt{t}} \tag{4}$$

where X_{eq} is calculated using Eq. (3) and the drying parameter, *k*, is given bellow:

$$k = 0.083 + 1.839 \times 10^{-4} \left(1 + v^{2.487}\right) X_o e^{0.074T} \tag{5}$$

3.3. Obtaining the simulated drying kinetics

Taking into account the above assumptions and averaging temperatures cycle by stage as well as the model equations of the correspondent drying kinetics, we carried out the construction of global drying kinetics using a routine calculation written in Fortran and having the following tasks as exposed bellow.

First we choose the temperature cycle (curve model T°C=f(time)) then introduce required data values. We calculate the moisture content for each section considering the temperature stage according to the temperature cycle in use. At each step the calculated value is compared with the desired final moisture content. If the desired value is not reached we restart again the procedure over a second period (a second day of drying).

4. Results and Discussions

The numerical applications of the exposed procedure carried out on two examples of daily temperature cycles (Figs. 3 and 4). In each of the two cases various values of initial water contents were tested using two cases of drying curve equations according to the models noted above. In addition each application lasts nine hours of drying per day and the built kinetics can go beyond one day in case where the final required water content is not yet reached. In such a situation drying is stopped by night and the product is then preserved under hermetic conditions to avoid any possible rehumidification.

The general behaviour of the obtained kinetics goes in the direction favourable to the logic adopted at the beginning. On Figs. 5 and 6 we can observe a water loss more or less significant relatively to the used stage of temperature. The difference in mass loss is also readable by comparing on Fig. 6 the two cycles of applied temperatures.

The assumption of drying kinetics built by sections was justified in some other background studies. Indeed Benmoussa [16] studied the effect of variable conditions on the drying kinetics of clay balls carrying experiments by practice of air temperature jump and relieving phases. The author noted that a passage from 26°C to 52°C makes that the physical behaviour of the product joins the kinetics of

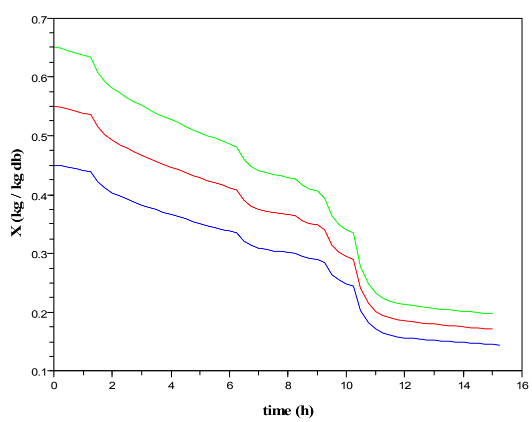

Fig. 5. Simulated Solar Drying Curves for Different X_0 Using Temperature Cycle (I) according to *Model* (1).

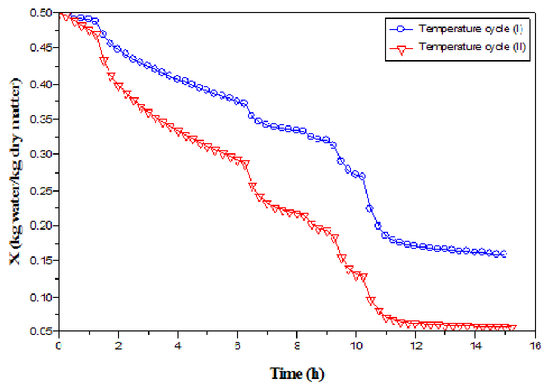

Fig. 6. Simulated Solar Drying Curves according to *Model* (1) and Using Two Different Daily Temperature Cycles (I, II).

air temperature jump and relieving phases. The author noted that a passage from 26°C to 52°C makes that the physical behaviour of the product joins the kinetics of 52°C in fifteen minutes response time, probably due to the inertia of the system which makes that the temperature change cannot be brutal. This observation was confirmed by Bennamoun and Belhamri [3] while modelling the solar drying of seedless grapes using a diffusive model taking into account the variable conditions of the air and the shrinking of the product. In addition Benaouda and Belhamel [17], used also a model of heat mass transfer obeying to the Fick's law, and obtained simulated kinetics of solar drying of the plums whose behaviour is similar to that presented in this study, in case of a drier without controlled temperature.

In addition Fig. 7 shows that the simulated solar drying kinetics based on the second model corresponding to Tunisian date highlighted faster water loss compared with that of Algerian date simulated by the first model. It seems that structural differences relating to the state of permeability of the fruit skin would be at the origin of this situation.

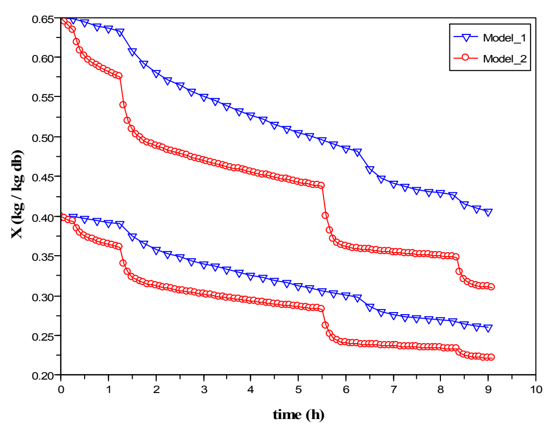

Fig. 7. Simulated Solar Drying Curves according to *Model* (1) and *Model* (2) Applying Temperature - Cycle (I).

Indeed the model suggested by Kechaou and Maalej [15] results from drying experiments practiced on naturally fresh dates, whereas the model equation applied for Algerian date results from experiments using rehydrated hard dry dates.

Among the first tests of drying practised on an indirect laboratory solar drier (LENREZA), the curves obtained for two tests using temperatures oscillating around 50°C and 60°C are shown on the Fig. 8 which displays the behaviour of the water loss through one drying day (09 hours) on the basis of dry dates (0.14 kg/kg d.b) hydrated to approximately (0.61 kg/kg d.b). The reading of these curves clearly confirms the possibility of obtaining a date with standard moisture content (26% w.b or 0.35 kg/kg d.b) in less than one day of drying. The interest of this observation lies on the fact that it is possible to avoid the problem of discontinuity of the drying operation and the problem of safety conservation of the product by night.

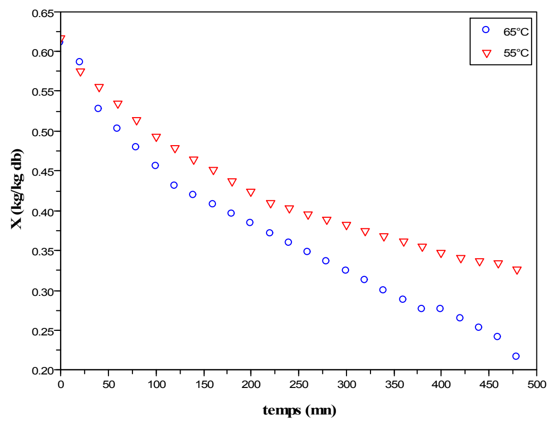

Fig. 8. Experimental Solar Drying Curves with X_o=0.61 kg/kg d.b.

However in the context of this work we cannot restrict the discussion to the physical and numerical aspects without looking to the quality of the dried product. According to this viewpoint and by means of several applications of the calculation program, we showed on Tables 2 and 3 the durations of drying allowing to reach the normal recommended moisture by the international standards for the marketing of the studied date variety that is 26% (wet basis). The values of initial used moisture contents cover the range of the contents encountered in practice and being able to join one of the two situations:

a) Case of naturally fresh humid Deglet-Nour dates variety collected at approximately 35% (w.b) equivalent to a water content of approximately 0.54 kg/kg on dry basis.

b) Case of the dry collected Deglet-Nour dates (by hot climate) and having undergone a rehydration.

In this same context, we notice on Tables 2 and 3 that the durations of drying varying between 1 h and 9 h always remain in the same day, except for 0.60 and 0.65 initial moisture values where the first drying day was slightly exceeded in case of applying the first curve equation model (Algerian date). So in almost all cases it could be possible to avoid the cost and the consequences of the product conservation by night.

Table 2. Sun Drying Times of Dglet-Nour Dates to Reach X_{final}=0.35 kg/kg d.b According to *Model* (1).

X_o (kg water/kg dry matter)	Drying time (h)	
	Case (I)	Case (II)
0.40	2.37	1.50
0.45	5.12	2.12
0.50	6.62	3.25
0.55	8.87	4.50
0.60	9.37	6.00
0.65	9.62	6.37

Case (I) Temperature curve as presented in Fig. 3.
Case (II) Temperature curve as presented in Fig. 4.

Table 3. Sun Drying Times of Dglet-Nour Dates to Reach X_{final}=0.35 kg/kg d.b According to *Model* (2).

X_o (kg water/kg dry matter)	Drying time (h)	
	Case (I)	Case (II)
0.40	1.28	1.00
0.45	1.83	1.37
0.50	4.92	1.62
0.55	5.53	2.83
0.60	5.70	4.33
0.65	7.92	5.50

Case (I) Temperature curve as presented in Fig. 3.
Case (II) Temperature curve as presented in Fig. 4.

In addition we notice also on tables (Tables 2 and 3) the results of the durations of drying obtained by applying the second cycle of daily temperature (Fig. 4) which is dominated by the stage of 75°C considering the same initial water contents and applying the two curve equation models mentioned above. Though the durations obtained in this case appear shorter, the quality viewpoint of the finished product leads us to prefer the preceding case, at least for this variety of dates. Indeed a number of rather recent studies show that the 75°C treatment quickly induces the darkening and the hardening of the fruit [6]. While at the temperatures of 35°C and 50°C this later undergoes a complement of maturation [18]. It can be slightly softened but its colour is not affected.

We can notify, as arises from the same sources, that the stage of 60°C dominating the first temperature cycle(I) (Fig. 3) and applying the model (1) for the drying curves, ensures a faster drying rate without any damage on product quality, particularly, colour and texture aspects.

The present study was ended by a simple sensorial test which was conducted with six frequent consumers of fresh date fruits. They were asked to classify three samples coming from two industrial treatment units and those issued from the laboratory solar drier. Three criteria were considered: mouth feel of texture, hand tested elasticity and visual colour appreciation of the fruit particle. Using three scoring levels, the obtained results showed that for each adopted criteria the fruit treated by the solar drier was ranked as the first by five of the six control panels.

Such a result could be supported by similar comments reported by Chua et al.[19] showing that the use of step-wise air temperature variation leads to a better quality product and makes possible to reduce the drying time to reach the desired moisture content in case of a step-down temperature profile.

5. Conclusions

The effect of variable air conditions on drying kinetics of dates was studied on the basis of the assumption of staged variation in temperature of drying air. It was checked that solar drying kinetics by indirect drier could be obtained and physically considered as a succession of convective drying kinetics under variable temperature by constant stages.

The obtained results seem to be of a good agreement with known physical behaviours with respect to convective drying. First trials conducted on the laboratory solar drier confirm the simulated behaviour of drying regarding the feasibility of low duration (one day) to reach standard moisture content for safe storage and marketing.

Moreover the adoption by assumption of only one tray with convenience to the principle of thin layer drying does not present an aberrant limitation at the applied method. The passage to several trays in the drying room can be done easily knowing the conditions of inlet and exit of the air in each one, thus building consequently a model curve of daily temperature change specific to each layer of product by tray. The investigation towards points raised above could be then the subject of an independent study.

In addition it is revealed from this study that the first used temperature curve model dominated by the stage of 60°C is well appropriate with the desired state of quality for the final product. The difference in the amount of the water loss between the two applied models for two different origins of date fruit requires more attention to confirm its cause. Finally the assumptions checked through this study as well as the practised tests encourage the use of solar energy as an economic alternative for the drying of the date palm fruit ensuring an optimal process-quality ratio.

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