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Solar Drying of Date Palm Fruits Simulated as Multi-Step Temperature Drying

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Abstract: A study of the indirect solar drying of date palm fruits, Deglet-Nour variety, was carried out assuming that the air temperature varies by constant stages. Experimental curves of thin layer convective drying (37, 50, 60 and 75°C) and measurements of daily temperature variation collected in solar drying room were considered to obtain a modelled temperature curve. Considering 9 h of drying per day, global kinetic was simulated numerically by using model equations and built by section relatively to the corresponding stage of temperature. Two daily temperature cycles were applied and many initial moisture contents (0.40 -0.80 kg kg $^{-1}$ d.b) were considered. The results obtained, by confrontation with the available literature, reflect the drying behaviour under variable conditions with discontinuity of drying operation by night. It was highlighted that standardized moisture for the trade of the product (26% w.b) was reached in less than one day of drying and that the daily temperature cycle prevailed by stage of 60°C would lead to a final product with an optimal state of quality.

Key words: Solar drying, date palm, model, multi-step, temperature

INTRODUCTION

The solar energy represents one of the sources of nonpolluting and economic energy increasingly requested. In spite of its enormous extent, solar energy remains less used in southern countries particularly in African. Among the interesting applications we can consider the post-harvest heat treatments of the date palm fruit (*Phoenix dactylifera L.*) largely produced in southern Algeria where Saharan arid climate provides a good solar radiation throughout the year. According to FAO data's we can read significant date production for Algeria (516, 293.00 tons in 2005) of which almost 50% are “Deglet-Nour” variety famous in the market. Neverthless only a little quantity is exported towards the European countries (Liu, 2002).

The "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 regime. Dates production is ensured by only one harvest in the year. This situation makes that the post-harvest treatment of this fruit becomes necessary in order to minimize the losses and to avoid the eventual accidents of conservation and storage particularly by rainy year or excessively hot climate.

Traditionally, dates naturally too wet and the rehydrated dry dates were brought back to normal moisture by direct exposure to the sun during a few days (Barreveld, 1993). Regarding consumer requirements, indirect solar drying would be more suitable by the fact of curtailing the drying time and preserving the product quality. This could explain the tendency of several authors to deal with the current problems of the solar driers in the experiment and simulation fields of the phenomena (Kouhila *et al*., 2005; Bennamoun and Belhamri, 2006; Othman *et al*., 2006; El-Beltagy *et al*., 2007). In fact, as for any mode of drying the solar drying is closely related to the quality of the product finally judged by the appreciation of the consumer. In the case of “Deglet-Nour” date we can withdraw available literature (Belarbi, 2001; Barreveld, 1993; Baraem *et al*., 2001; Hasan *et al*., 2005; Mohammad *et al*., 2005; Suad *et al*., 1997) that the quality of this fruit 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 water content of the fruit (Boubekri *et al*., 2007) while the colour is rather related to sugars and the enzymatic activities. In the completely ripen state (tamr), this fruit contains approximately 85% of total sugar equitably distributed

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between sucrose and reducing sugars (glucose and fructose) (Belarbi, 2001) which allows a half-soft mechanical state. The international standard (UN-CEE DF-08) adopts 26% as normal moisture of marketable date. In case of fresh «Deglet-Nour» variety, 30% (w.b) is tolerated as maximum moisture content. It is also known (Barreveld, 1993; Zaid, 2002) that part of this same variety is already over dried on the tree and requires a post-harvest treatment by humidification and drying before arriving on the market. This treatment makes it possible to bring back the fruit to the state of good quality by means of hydration and sugar inversion characterizing a complement of maturation, according to the same references.

The present research is aimed at presenting a procedure to construct sundrying kinetics lying on the assumption that the temperature change in the sundrying box is made according to several stages of constant temperatures through the day. The steps followed in this study are based on experimental data resulting from measurements taken on a solar drier prototype (Laboratory LENREZA, Ouargla University, Algeria) and a hot air convective drier (Drying Laboratory GIA-ENSIA, Massy France). With the procedure suggested in this paper, the sun drying kinetics should allow, knowing the daily temperature evolution, to predict the time of drying and, possibly, the quality by using an indirect non-ventilated drier and without temperature control. Various calculations and data processing were carried out by the scientific computation SCILAB 4.0. Fitting experimental curves and searching for models were carried out by Curve-Expert 1.3 programme. The simulated global drying kinetic was made using a FORTRAN calculation programme executed with Visual-Fortran 5.0 compiler.

MATERIALS AND METHODS

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 (Ouargla University, Algeria). It is composed of an air plane solar collector (2.0×1.0×0.13 m) inclined of an angle of 16° with respect to the horizontal and directed to south. The captor is covered with a glass plate thickness 4 mm bellow which and at a distance of 0.06 m, is deposited an aluminium plate painted black subdue used as absorber. The lateral sides and the lower part are thermally isolated with polystyrene. The drying room is made up of coated sheet of dimensions (1.0×0.8× 0.8 m) thermally isolated with polystyrene on all the external walls and provided with a chimney in galvanized

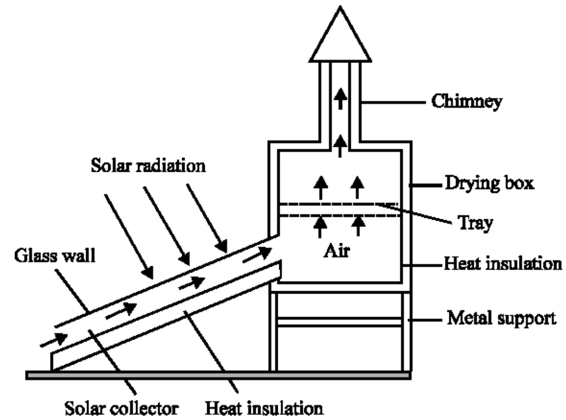

Fig. 1: Sun-dryer pilot (LENREZA Laboratory)

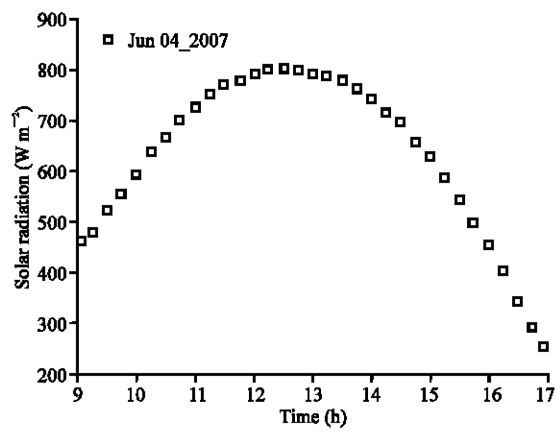

Fig. 2: Daily solar radiation on June 04, 2007

sheets (1.0×0.02×0.02 m) from which the side walls are thermally isolated with polystyrene. The total solar radiation received in the field of the captor is measured in kW/m² using a sunshine recorder with digital display during the day of the experiment. The temperature measurements are carried out using thermocouples placed at various places of the drier (input output of the solar collector, input output of the drying room and on the level of the trays carrying the product to be dried). The set of the thermocouples is connected to one limps of 16 paths connected to an apparatus TESTO-445 which allows the digital posting of acquisitions. The moisture and the air velocity at the entry of the drying room are measured, respectively using a probe with digital display and a manometer connected to an apparatus TESTO-645 type with computerised data acquisition.

It should be noted that in our present study, this test bench was only used to recover information on the daily solar radiation and change of the temperature. On the Fig. 2 we represent the solar radiation curve measured on

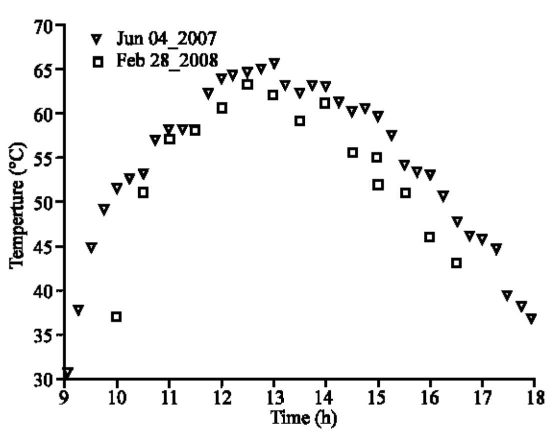

Fig. 3: Daily measured temperature change

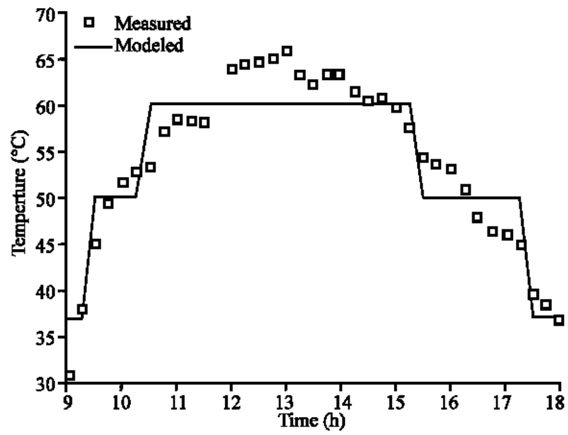

Fig. 4: Daily modelled temperature change Cycle (I)

June 04, 2007 showing a pick of over 800W m^{-2} by 12h: 30 mn (a.m). On Fig. 3 we can easily note that on measures spaced enough in time (February 28, 2006 and June 04, 2007), we obtained practically the same profiles for the temperature at the entry of the drying room with few degrees, in less, seen in the measured values collected on February, witch may be due to the effect of winter climate.

Hot air convective drier: Experimental drying curves used in this study were collected from automatic measurements collected from the pilot drier installed at the drying laboratory of the Food process engineering department at ENSIA Massy (France). This drying apparatus was previously used and described in several works (Boudhrioua *et al*., 2002, 2003). It is a hot air convective drier automatically controlled in temperature, relative humidity and air velocity, with computerised data acquisition. The automatic weighing programmed according to the user choice in addition to controlled operational parameters offer a better accuracy to the physical behaviour description of the air and product during drying. The good level in accuracy may lead to best results in the model proposed to describe the involved thermo-mass transfers. In the present study, we used four thin layer drying kinetics of Deglet-Nour date of southern Algerian origin, under operating conditions 37, 50, 60 and 75°C with ambient relative humidity and a speed of 1.5 m s^{-1} of air drying as presented by Boubekri *et al*. (2007). It would be useful to note here that the dried samples, in the exploited experiments, represent sorted and classified dates as naturally dry category (drying on the tree by hot climate) which were rehydrated beforehand by ultra pure water dipping thus allowing ensuring initial moisture content before drying of about 0.5 kg water per kg of dry matter.

Data processing and calculation procedure: It was already mentioned that the objective of this study was to make simulated solar drying kinetics starting from a staged curve model of the average temperature evolution in the drying room during the day. Information on the internal mechanisms and the physical behaviour of the product is ensured by experimental drying curves of convective hot air drying of the considered product, at the correspondent temperatures realised on the daily evolution temperature curve from the solar drier. In the following lines we will expose the adopted assumptions and the various steps of our proposed procedure in a logical succession.

Assumptions:

- The temperature evolution in the drying room is considered to be by constant stages as shown typically on the Fig. 4.
- Drying process continues with repetition of the same temperature cycle until obtaining the desired final water content, knowing that the operation stops by the night.
- The product is placed on only one tray and is spread out on the thin layer.
- The average air velocity crossing the drying room is supposed to be constant.
- The average relative humidity of the air in the drying room is considered to be constant on each stage of temperature.
- The moisture content of the product evolves according to the thin layer drying kinetic relating to each stage of temperature in the room.

Evolution of the air drying temperature: The plotting of model curve related to temperature evolution was done by

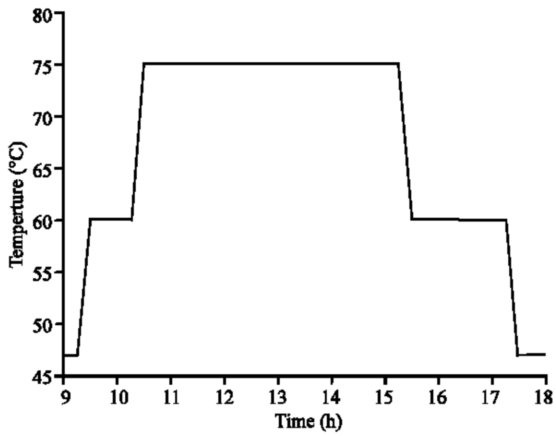

Fig. 5: Daily modelled temperature change Cycle (II)

determination of average values able to be accepted on reasonable intervals of time. 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 (Boubekri *et al*., 2007). The typical temperature curve thus obtained starting from the real curve of the solar drier, is given by the Fig. 4. The temperature varies between the average values of 37, 50 and 60°C. Moreover, in order to allow a second application of the proposed procedure, we supposed another possible situation where the temperature varies between 50, 60 and 75°C. This situation is given by the Fig. 5.

Fitting of the drying kinetics: In order to allow a numerical construction of the solar drying kinetics by sections, we need to adopt a mathematical model for each experimental curve. Among several model equations applied and compared on Curve-Expert we chose to adopt an exponential model of the form:

$$XR(t) = A_0 + A_1.\exp(-b.t) \qquad (1)$$

Where XR represents the reduced moisture content given by the following relation,

$$XR(t) = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} \qquad (2)$$

Where:

X(t) = Denotes the moisture content (kg water kg^{-1} dry matter)

X0 = Denotes the initial moisture content

Xeq = Represents the equilibrum moisture content calculated according to Kechaou and Maalej (1999) by the relation given bellow:

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

with,

$C = 1.514e\text{-}09 \exp[61089 / R.T]$

$K = 72765 \exp[-11710 / R.T]$

$X_m = 1.067e\text{-}09 \exp[47614 / R.T]$

Where, R [J mol^{-1}.K] represents the universal constant of perfect gases, T [K] the absolute temperature and Rh the relative humidity of the air.

The results of the fitting carried out by this exponential model are recapitulated in Table 1 with the values of standards errors of estimation SEE and the determination coefficients r.

Obtaining the global drying kinetic: Taking account of the above assumptions allowed and realising the cycle of the temperatures by stage and 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:

- Choice of the temperature cycle (curve model T [°C] = f (time)).
- Initialization of time (time = 0.0).
- Introduction of the data (Xin, Xfinal, dtime, parameters (A0, A1 and b), temperatures of drying, average relative humidities, duration of each stage of temperature).
- Time = time+dtime (Incrementing of time).
- Calculation of X(t) on the first section using the first stage of temperature.
- ....
- Calculation of X(t) on section i on the basis of X(t) at the end of the section (i-1).
- ....
- Calculation of X(t) on the last section of the temperature cycle.
- Compare X(t) with Xfinal.
- Stop calculations if Xfinal reached.
- If Xfinal not reached, restart again the procedure over a second period (physically a second day of drying).
- Repeat the procedure until obtaining Xfinal.

Table 1: Fitting coefficients of drying kinetics at various temperatures

T (°C)	A0	A1	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

NB. The calculation of the moisture content at every moment is ensured by two integrated subroutines which allow obtaining the values of the equilibrium moisture content and the reduced moisture content, each one under the suitable physical conditions.

It is interesting to mention that in a more general application, the calculation programme should initially build the temperature stages by calculation of means and standard deviations on intervals of preset times then to choose the relatively suitable drying kinetics, starting from a greater number of beforehand stored kinetics. This complement of procedure makes the model better close to the real phenomena but requires the availability of significant volume of experimental data.

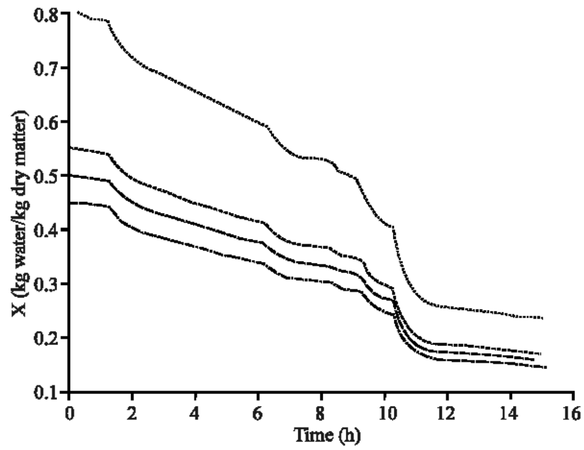

Fig. 6: Simulated sun drying kinetics with different initial moisture contents (0.45, 0.50, 0.55 and 0.80)

RESULTS AND DISCUSSION

The numerical applications of the exposed procedure carried out on two examples of daily temperature cycles, one modelled on the basis of real measurement (Fig. 4) and the other (Fig. 5) inspired representing the case of a stronger sunning or in case of an additional source of energy. In each of the two cases various values of initial water contents were tested. In addition each application counts nine hours of drying per day and the built kinetics can go beyond one day in case where the final water content required is not reached yet. In such a situation drying is stopped by the night and the product is then preserved under hermetic conditions to avoid any possible rehumidification.

The general behaviour of the kinetics obtained goes in the direction favourable to the logic adopted at the beginning. On Fig. 6 and 7, we can observe a mass loss of water more or less significant relatively to the used stage of temperature. The difference in mass loss is also readable by comparing on Fig. 7 the two cycles of applied temperatures.

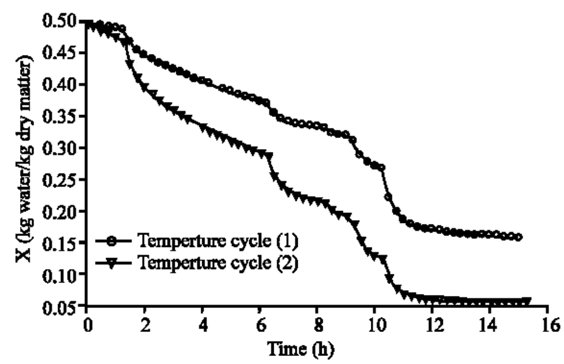

Fig. 7: Simulated sundrying kinetics for two different daily temperature cycle

The assumption of drying kinetics built by sections was justified in some other former studies. Indeed Benmoussa (1989) studied the effect of variable conditions on the drying kinetics of clay balls carrying experiments by practice of jump of air temperature and phases of relieving. The author noted that a passage from 26-52°C makes that the physical behaviour of the product joined the kinetics of 52°C in 15 min 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 (2006) while modelling the solar drying of seedless grapes using a diffusive model taking account of the variable conditions of the air and the shrinking of the product. In addition (Benaouda and Belhamel, 2006) used also a model of heat mass transfers 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.

However, in the context of this research we cannot restrict the discussion to the physical and numerical aspects without looking to the quality of the dried product. In logic of this viewpoint and by mean of several

Table 2: Sun drying times of Dglet-Nour dates to reach Xfinal=0.35 kg kg^{-1} d.b Case (I) Temperature curve as presented in Fig. 4 Case (II) Temperature curve as presented in Fig. 5

X0 (kg water kg^{-1} 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	0.37

applications of the calculation program, we showed on table (Table 2) the durations of drying allowing to reach the normal moisture recommended by the international standards for the marketing of the studied date variety; 26% (wet basis) which deals with a water content of 0.35 kg water kg^{-1} of dry matter. The values of tested initial water contents cover the beach of the contents met in practice and being able to join one of the two situations:

- Case of naturally fresh humid Deglet-Nour dates variety collected to approximately 0.35% (w.b) that equals a water content of approximately 0.54 kg kg^{-1} on dry basis. It is also the case of other varieties of dates (invert sugar date categories) at once collected in a premature state of fear of too wet and rainy climatic conditions (Barreveld, 1993; Zaid, 2002).
- Case of the dry collected Deglet-Nour dates (by hot climate or by problem of irregular irrigation) and having undergone a rehydration. Indeed in a parallel study we could see that to preserve the quality of this kind of dates it would be better to practise a hydration at temperatures lower than those supporting the activity of the enzymes causing sugar inversion and colour browning. In fact, this is possible while remaining around 30°C for durations of about six to eight hours what would allow water contents from 0.48-0.65 (dry basis) without already starting tanning or an over softening of texture.

In this same context, we notice on table (Table 2) that the durations of drying varying between 2 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. So in the almost cases it could be possible to avoid the cost and the consequences of the product conservation by the night without needing additional source of energy to ensure a continuous drying process. In addition we notice also on table (Table 2) the results of the durations of drying obtained by applying the second cycle of daily temperature (Fig. 5) dominated by the stage of 75°C by using the same initial water contents. Though the durations obtained in this case appear shorter, the quality viewpoint of the finished product leads 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 tanning and the hardening of the fruit (Belarbi, 2001). While at the temperatures of 35 and 50°C this one undergoes a complement of maturation (Hamdi and Hamdi, 1991). It can be slightly softened but its colour is not affected. We can, as arises from the same sources, as the stage of 60°C, dominating over the first model curve of temperature (Fig. 4) in the first case of application ensures a speed of drying faster without however deteriorating quality, in particular colour and texture aspects.

CONCLUSION

The present study was the subject of implementation of the assumption that solar drying by indirect drier, not controlled, with air collector could be regarded physically as a convective hot air drying at variable temperature. The obtained results seem of a good agreement with known physical behaviours with respect to convective drying, as well for the general behaviour of the kinetics simulated only for the short durations of drying. The generalization of the procedure exposed to other agroalimentary products as well as the experimental validation, require a greater margin of thin layer drying kinetics choice beside of solar drying kinetics to expect for various products. Moreover the adoption by assumption of only one tray by suitability with the principle of thin layer drying does not present an aberrant limitation at the method applied. 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 of them, thus building consequently a model curve of daily temperature change specific to each layer of product by tray. The investigation in the direction of the points raised above could be then the subject of an independent study. In addition it comes out from this study that the first used curve model temperature dominated by the stage of 60°C is well appropriate with the desired state of quality for the final product. Finally it was checked that the obtaining "Deglet-Nour" date of marketable quality is practically feasible by the means of solar drying under optimum conditions for quality, cost and duration of treatment.

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