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Validation of a pepper drying model in a polyethylene tunnel greenhouse

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Abstract

The solar drying of pepper was carried out in a naturally ventilated polyethylene greenhouse. Solar radiation, transmitted through the cover, heated the interior air and the product within greenhouse and then evaporated the water from the product surface. This air, which necessarily became more saturated, was then renewed naturally by the wind and by the chimney effect caused by the temperature difference existing between the temperatures of the air inside and the outside of the greenhouse. The induced air velocity in the greenhouse has been calculated indirectly by measuring the air renewal rate using the "tracer" gas technique. A variable induced air velocity has been introduced in place of the constant forced convection term used by Passamai (1997). The outcome of the proposed model is that the variation of product water loss can be expressed as a function of ventilation rate or induced air velocity, air temperature, product temperature and transmitted solar radiation through a greenhouse cover.

Keywords: Drying; Greenhouse; Model; Radiation; Ventilation

1. Introduction

Tunisia has between 2860 and 3200 hours of sunshine per year and receives a daily average solar energy of 4.8 $kWh\cdot m^{-2}\cdot day^{-1}$. This energy is sufficient, especially in summer, to meet all the energy demand for the drying of agricultural products. Most of these products are dried in a traditional way using sun drying. This is a profitable activity, but it does have some problems due to rain damage, insect and dust contamination. If these products were dehydrated under shelter, it would provide appropriate hygienic conditions. Plastic tunnels are the main greenhouses in the Mediterranean countries, but these can only be used for eight months a year to grow plants under such climate. These tunnels are used during summer time due to the high internal air temperature.

Many scientists have investigated the modelling of solar drying of agricultural products [1–4]. And there are also simulation studies of direct solar dryers [5]. Analytical studies have defined the concept of a characteristic function to study a forced convection greenhouse dryer [6]. Phenomenological models have also been suggested for calculating the evaporation rate for use in the simulation of solar drying process [7].

The aim of the present work is to apply Passamai and Saravia's model [8] for drying pepper in a naturally ventilated greenhouse, in which the drying convection term is calculated from an induced, random and variable air velocity. In a greenhouse, induced velocity is difficult to measure and therefore some experiments were carried out to determine this parameter and the specific coefficient values of the product studied, and then used to model the process of drying pepper inside a naturally ventilated tunnel greenhouse.

2. Drying model

A phenomenological model for drying pepper and using meteorological parameters such as air velocity, moisture content and solar radiation has been proposed by Passamai and Saravia [8]. It uses the energy balance equation for water evaporation from a free surface [9], which is in linear proportion to the drying potential $(P_s - P_v)U^{\alpha}$ [10] and the artificial radiation I. It is written as follows: $J =$

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Nomenclature

a	$= A/m_b$	$m^2 \cdot kg^{-1}$
A	evaporating surface of the product	m^2
C_i	conductance modifying the radiation term in Penman's equation to take into account drying processes	
C_p	overall conductance of mass transfer that modifies Penman's evaporation equation to take into account drying processes	
$f_{\Delta T}$	chimney effect factor	$m \cdot s^{-1} \cdot K^{-1/2}$
f_{wind}	wind factor	
G	net incident horizontal radiation inside greenhouse	$W \cdot m^{-2}$
G_{out}	net incident horizontal radiation outside greenhouse	$W \cdot m^{-2}$
Hr	relative humidity of interior air	
I	lamp radiation (simulating solar radiation)	$W \cdot m^{-2}$
J	density of evaporated mass flux	$kg \cdot s^{-1} \cdot m^{-2}$
m_0	initial weight	kg
m_b	bone dry weight	kg
m_e	final equilibrium weight	kg
m_p	product weight	kg
N	ventilation rate per hour	$hour^{-1}$
P_s	saturated water vapor pressure in moist air	Pa
P_v	water vapour partial pressure in moist air	Pa
$P_s - P_v$	deficit of air saturation	Pa
RE	flux per unit volume of air renewal	$m^3 \cdot s^{-1}$
S	air infiltration surface of greenhouse	m^2
T	temperature	K
t	time	s
T_a	air temperature	K
T_p	product temperature	K
U	constant air velocity	$m \cdot s^{-1}$
U_{int}	air velocity inside the greenhouse	$m \cdot s^{-1}$
U_{wind}	wind velocity	$m \cdot s^{-1}$
V	volume of air in the greenhouse	m^3
X	$= (m_p - m_b)/m_b$ product water content (in time t) on a dry basis	$kg \cdot kg^{-1}$
X_0	$= (m_0 - m_b)/m_b$ initial water content of fresh product on a dry basis	$kg \cdot kg^{-1}$
X_e	$= (m_e - m_b)/m_b$ final humidity of dry product on a dry basis	$kg \cdot kg^{-1}$

Greek symbols

ΔT	temperature difference between the inside and the outside	K
α	exponent	

Subscripts

ai	internal air
ao	outside air

$C_p(X)(P_s - P_v)U^\alpha + C_i(X)I$, where $C_p(X)$ and $C_i(X)$ are two conductance dependent on the product water content and α is a non unit exponent. The conductances are calculated for pepper variety "Morron" as follows: $C_p(X) = 1.65(X - X_e) \times 10^{-9}$ $(s \cdot m^{-1})^{1.483}$ and $C_i(X) = (8.29X + 3.83) \times 10^{-9}$ where $\alpha = 0.2$. The authors validated their model at controlled laboratory conditions and in a drying room coupled with an air solar collector. In all their experiments the convection term, U^α was maintained at a constant value and the α, C_p and C_i coefficients values of the product studied were then calculated.

3. Experimental set up and method

The measurements of the tunnel greenhouse used in the drying experiments were as follows: 12 metres long, 8 metres wide, 3.5 metres average height and 96 m^2 floor area. Its cover was polyethylene film, 180 µm thick and had been used for two seasons. Polyethylene netting, used generally as a windbreak, was used as the base of trays to support the product to be dried. The tray length was ten metres; its width was one metre and could hold about 20 kg of pepper. In greenhouse, trays could be arranged two levels and four rows. Four trays were suspended 0.5 metre above the ground and one metre above them were suspended four other trays (i.e., 1.5 metres above the ground) to allow farm-workers to load and unload the crop. The total netting area of eight trays was 80 m^2 and could hold about 160 kg. In the experiment, all trays were loaded and only the middle tray was used to measure different parameters. The product was pre-treated: it was cut up longitudinally in two slices and the stalks and seeds were removed. The airflow and thermal conditions in the greenhouse were simply controlled by a total or partial opening of the vents (Fig. 1). Finally, traditional sun drying experiments were carried out in open air to be used later as reference.

Product mass data: sample initial mass (m_0), dry mass (m_b) and during drying (m_p) were determined using scales (±0.1 g). The total solar radiation outside the greenhouse (G_{out}) and the transmitted solar radiation inside the greenhouse (G) at the drying tray height were measured by two pyranometers. The product temperature change (T_p) and air temperature evolution (T_a) were measured using T type thermocouples. Anemometer sensors were used to measure the wind velocity. However, the average velocity of the air inside the greenhouse was measured indirectly by injecting an inert and non-toxic gas (NO_2) and measuring its logarithmic decrease in concentration over time. The relative humidity (Hr) was also measured. A data logger automatically recorded all experimental measurements. The drying exper-

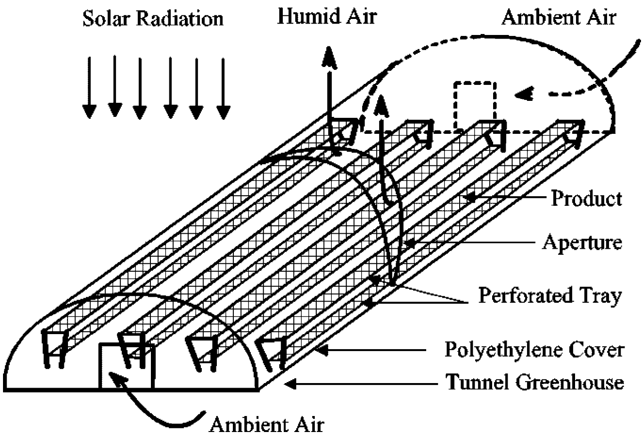

Fig. 1. Tunnel polyethylene greenhouse used as a drying system.

iment lasted for several days and data were captured every ten minutes.

4. Calculations

To calculate the ventilation rate of the greenhouse, the model of Grimsrud and Sherman [11] was applied. The effective surface of infiltration corresponds to the apertures and doors surfaces. The flux per unit volume of air renewal (RE) was calculated as follows:

$$RE = \frac{NV}{3600} = S\sqrt{f_{\mathrm{wind}}^2 U_{\mathrm{wind}}^2 + f_{\Delta T}^2 \Delta T} \tag{1}$$

The wind and the chimney effect factors had to be determined, so Eq. (1) was transformed into the following form:

$$N^2 = f_1 U_{\mathrm{wind}}^2 + f_2 \Delta T \tag{2}$$

where $f_1 = S^2 f_{\mathrm{wind}}^2 (3600/V)^2$ and $f_2 = S^2 f_{\Delta T}^2 (3600/V)^2$ are respectively the slope and the ordinate at the origin of $N^2/\Delta T = f(U_{\mathrm{wind}}^2/\Delta T)$.

To calculate f_1 and f_2, experimental measurements of the ventilation rate were made using the "tracer" gas technique [12]. This technique enabled the air exchange between the greenhouse and its environment to be quantified. The ventilation rate (N) and the air renewal flux (RE) were then determined and the induced air velocity inside the greenhouse (U_{int}) was calculated using the following relationship: $U_{\mathrm{int}} = (RE\,3600)/S$.

The mass flux density was written as follows:

$$J = -\frac{m_{\mathrm{p}}}{A}\frac{\mathrm{d}X}{\mathrm{d}t} = C_p(X,T)(P_{\mathrm{s}} - P_{\mathrm{v}})U^{\alpha} + C_i(X)I \tag{3}$$

For red pepper variety "Baklouti" α was found to be equal to 0.324, C_{p} equal to $(1.4942 + 0.062(T_{\mathrm{p}} - T_{\mathrm{a}}))(X - X_{\mathrm{e}}) \times 10^{-9}(\mathrm{s{\cdot}m^{-1}})^{1.324}$ and C_i equal to $0.005G^{1.1}(X - X_{\mathrm{e}}) \times 10^{-9}(\mathrm{s{\cdot}m^{-1}})^2$ [13]. C_p depended on the product water content and the temperature while C_i depended only on the product water content. These results were an experimental fact of the correlation.

A mathematical simulation of the drying process of pepper variety "Baklouti" was carried out by solving the following differential equation:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = -a(X - X_{\mathrm{e}}) \times 10^{-9} \times \left\{\left(1.494 + 0.062(T_{\mathrm{p}} - T_{\mathrm{a}})\right)(P_{\mathrm{s}} - P_{\mathrm{v}})(U_{\mathrm{int}})^{0.324} + 0.005G^{2.1}\right\} \tag{4}$$

using the following data: $m_0/m_{\mathrm{b}} = 13.6\ \mathrm{kg{\cdot}kg^{-1}}$, $X_0 = 12.6\ \mathrm{kg{\cdot}kg^{-1}}$, $a = 2.35\ \mathrm{m^2{\cdot}kg^{-1}}$, $X_{\mathrm{e}} = 0.6\ \mathrm{kg{\cdot}kg^{-1}}$, the solar radiation measured inside the greenhouse (G) and the air velocity inside the greenhouse (U_{int}). Eq. (4) was solved by the fourth order Runge–Kutta method.

5. Results

Fig. 2 illustrates the solar radiation measured simultaneously outside and inside the greenhouse. The transmitted solar radiation through the used cover is about 83%. The evolution of external and interior air and product temperatures are shown in Fig. 3. During dehydration, in a greenhouse,

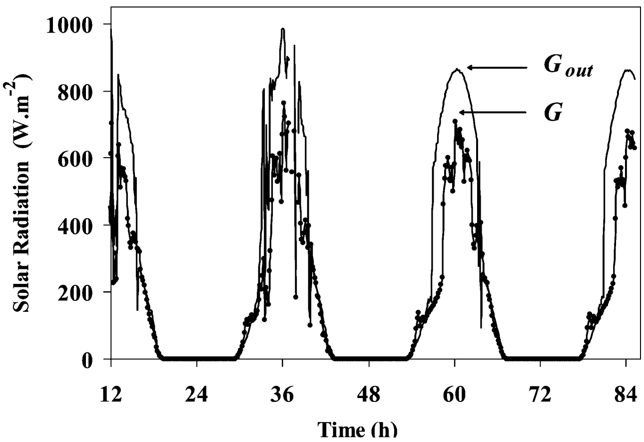

Fig. 2. Variation of solar radiation outside and inside greenhouse.

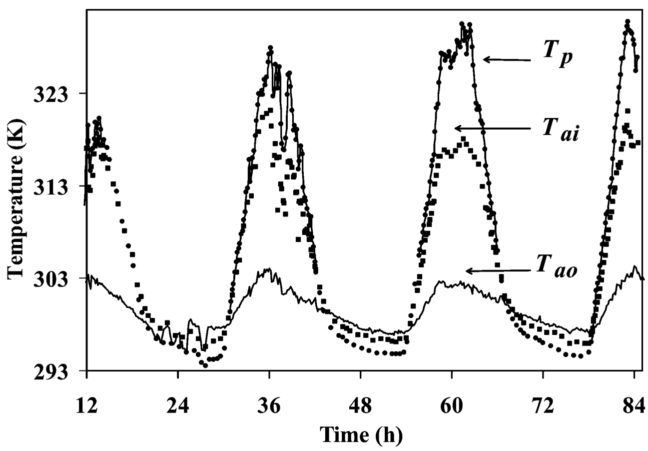

Fig. 3. Variation of product, interior and outside air temperatures in a greenhouse.

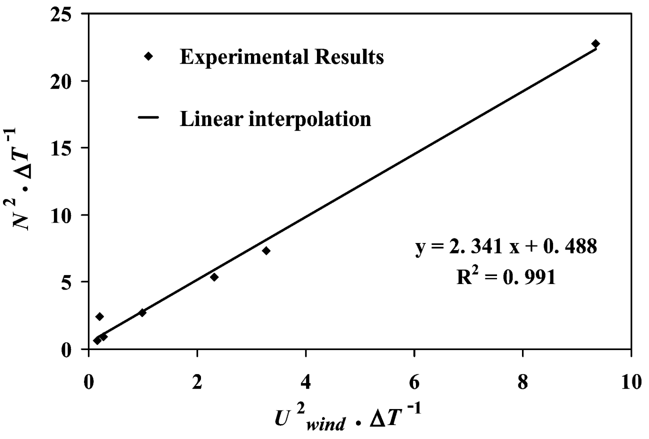

Fig. 4. Relationship of $N^2/\Delta T$ as a function of $U_{\mathrm{wind}}^2/\Delta T$ (the slope $f_1 = 2.341\ \mathrm{h^{-1}{\cdot}m^{-2}{\cdot}s^{-2}}$ and the ordinate at origin $f_2 = 0.488\ \mathrm{h^{-1}{\cdot}K}$).

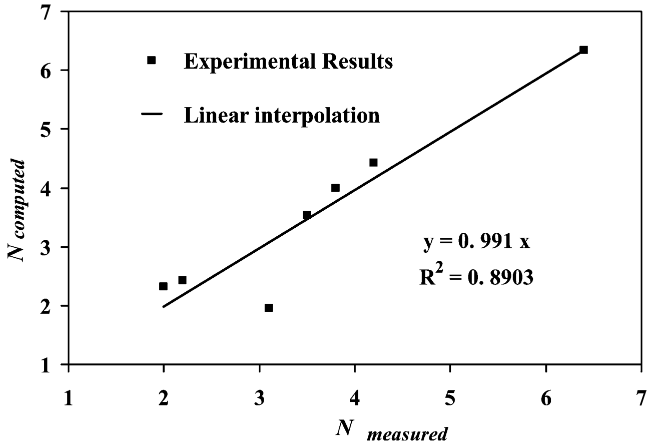

Fig. 5. Comparison between measured and estimated ventilation rate ($R^2 = 0.89$).

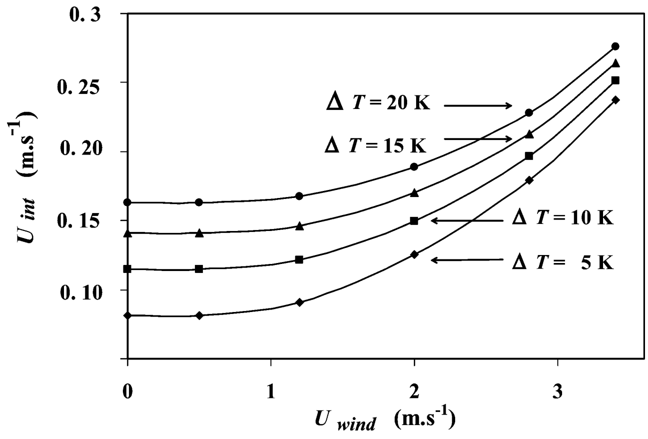

Fig. 6. Evolution of average induced air velocity inside the greenhouse, U_{int}, as a function of wind velocity, U_{wind}, for several temperature differences, ΔT.

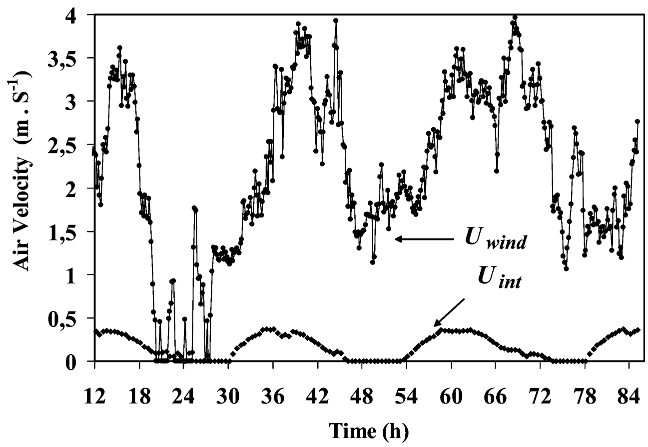

Fig. 7. Evolution of outside wind velocity and induced air velocity inside the greenhouse in the course of time.

the product temperature always exceeded interior air temperature in daytime because of direct absorption of solar radiation, whereas in a conventional tunnel dehydrator the product temperature is always equal to the interior air (drying air). At night, interior air and product temperatures were lower then outside air temperature because the polyethylene greenhouse cover was not totally opaque to the infrared radiation. This led heat losses to create a climate colder than the outside one. This phenomenon has been called "inversion of temperature" [14]. Fig. 4 shows the relationship of $N^2/\Delta T$ as a function of $U_{\mathrm{wind}}^2/\Delta T$. The values of the slope (f_1) and the ordinate at origin (f_2) are $2.341\ \mathrm{h^{-1}{\cdot}m^{-2}{\cdot}s^2}$ and $0.488\ \mathrm{h^{-1}{\cdot}K}$, respectively. These results are specific to the tunnel greenhouse used in this experiment. To verify these results, the computed ventilation rate was plotted as a function of the measured ventilation rate (Fig. 5). The linear regression-squared value is $R^2 = 0.89$. Fig. 6 illustrates the variations of computed internal air velocity (U_{int}) as a function of measured wind velocity (U_{wind}) for several temperature differences (ΔT). It confirms that although the wind velocity is high, the air movement in the greenhouse remains low and can be determined. Fig. 7 shows the variation of outside wind velocity and air velocity inside the greenhouse in the course of time. Fig. 8 shows the calculated and measured drying curves for open-air drying over 120 hours (between time $t = 12$ and $t = 132$ hours). The decrease of the product water content was mainly in daytime. In the first two nights (between $t = 18$ and $t = 32$ hours and $t = 42$ and $t = 56$ hours), the air temperature remained high and the average wind velocity was between one and two $\mathrm{m{\cdot}s^{-1}}$. These conditions permitted to dehydrate the product as long as the product water content (X) was superior to two. In the third night (between $t = 66$ and $t = 80$ hours), the product water content (X) became inferior to two so the climatic conditions did not permit more water loss but a slight increase in product water content due to the excessive moisture in open air. Fig. 9 shows that at night in the greenhouse (between $t = 18$ and $t = 32$ hours, $t = 42$ and $t = 56$ hours and $t = 66$ and $t = 80$ hours), the product water content did not decrease and the condensation on the product did not appear. This was due respectively to the lower induced air velocity and to the cover that protected the product. Fig. 9 shows also the theoretical and experimental drying curves in the green-

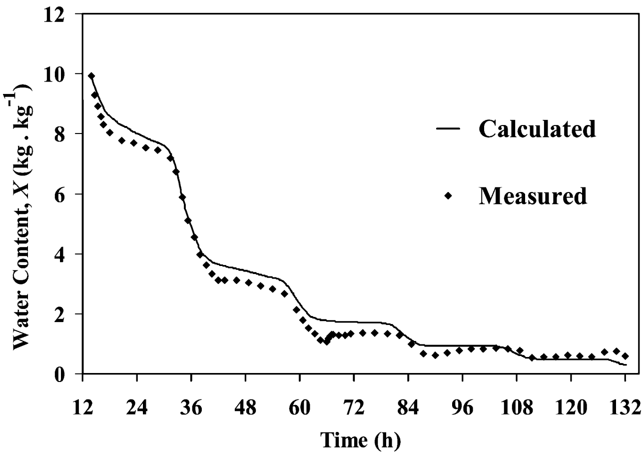

Fig. 8. Measured and calculated water content of product in open-air drying trial. Test performed between September 1st (14 h 40 min) and September 5th (13 h 50 min) 2000.

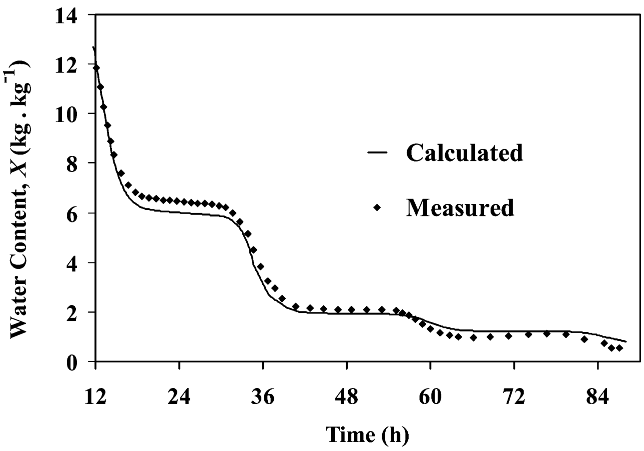

Fig. 9. Measured and calculated water content of product in a greenhouse drying trial. Test performed between August 11th (12 h 40 min) and August 14th (13 h 50 min) 2000.

house where 20 kg of fresh pepper, per tray, are dried over 78 hours (between $t = 12$ and $t = 90$ hours) with a water loss of 16.6 kg. Theoretical and experimental curves fit reasonably within an error between 2 and 8%. For all trays, the water loss obtained from 160 kg of fresh pepper was 132.8 kg. The comparison between open-air and greenhouse drying (Fig. 10) shows that the drying time period to attain the final humidity of the product ($X_e = 0.6$) was the same: 78 hours (at time $t = 90$ hours). The only difference was that over the three first days, the kinetics of drying were faster for the case of greenhouse drying, for example the product humidity attained for open-air and greenhouse drying respectively was 8 and 6.6 at $t = 18$ hours, 3.1 and 2.2 at $t = 40$ hours and 1.1 and 0.9 at $t = 64$ hours. 78 hours is an ideal time period for open air and greenhouse drying. It is therefore necessary to stop the operation of drying at this level to avoid any product water content increase as the case witnessed in open air-drying experiment.

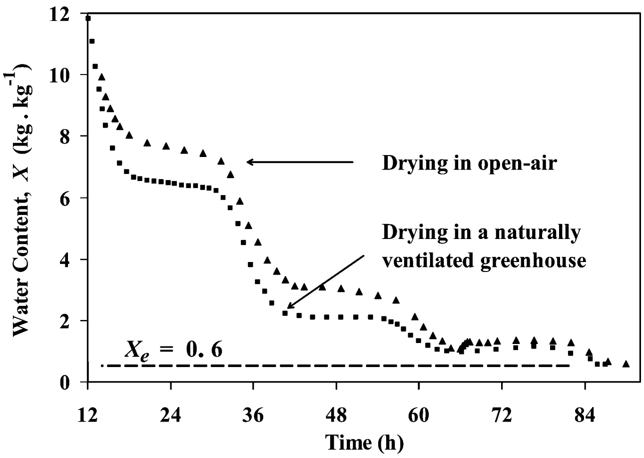

Fig. 10. Comparison between open-air and greenhouse drying.

6. Conclusions

In a naturally ventilated greenhouse, despite variation over time, the air temperature, transmitted solar radiation and air change rate are sufficient to make a drying operation of an agricultural product possible. In the case of pepper, at the end of the drying process, there is a weight reduction of more than 83%. A model, previously validated in laboratory conditions, gave satisfactory predictions of solar drying process in a naturally ventilated greenhouse. Quality studies must be undertaken to confirm the improvements in final product quality, although these were an improvement of the product aspect is already noted visually, as well as better hygienic conditions. Finally, the drying operation carried out will permit the exploitation of polyethylene greenhouses in summertime when they are not used.

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