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DESIGN AND PERFORMANCE TESTING OF AN INDUSTRIAL-SCALE INDIRECT SOLAR DRYER

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Abstract

In this paper, an indirect solar dryer was developed and tested for drying food. This unit operation is an interesting technique for preservation in agricultural applications. The dryer was designed at industrial scale in order to carry out experiments in real applications and to get concrete results. It operated without additional energy in the passive and active modes, allowing the comparison between the two. The relationship between the solar collector air temperature and the relevant ambience parameters was deduced. The collector efficiency reached 66.56 % with forced ventilation and 46.32 % with natural ventilation. It also increased linearly with the solar radiation varying between 400-800 W/m^2 for air velocities ranging between 1 and 1.40 m/s. The effect of the air velocity on the collector efficiency was negligible for solar intensities close to 800 W/m^2.The tomato drying occurred mainly in the falling drying rate period. On average, the moisture content in dry basis was reduced from 14.32 kg wate$_r$/kg dry matter to 0.14 kg water/kg dry matter. The equilibrium moisture content of tomatoes was reached after 12 h when the system was used with one layer. In the case it was used with four layers, the difference among the four durations of drying was one hour between each tray.

Keywords: Flat-plate solar collector, Drying chamber, Convection, Efficiency, Drying kinetics.

Nomenclatures

A_a	Collector transversal area, m^2
A_s	Surface area of the solar collector, m^2
C_p	Air-specific heat, J/kg °C
DR	Drying rate, kg water/kg dry matter. h
I	Solar radiation on tilted surface of the solar collector, W/m^2
M_d	Dry mass of the product, kg
M_{hf}	Final wet mass of the product, kg
$M_h(t)$	Wet mass of the product at the moment t, kg
m_a	Air mass flow rate, kg/s
R^2	Regression coefficient
T_{amb}	Ambient temperature, °C
T_{as}	Outlet air temperature in the collector, °C
v_a	Air velocity in the solar collector, m/s
X	Water content, kg water/kg dry matter
XR	Moisture ratio of the product at one moment t
X_{eq}	Equilibrium water content, kg water/kg dry matter
X_0	Initial water content, kg water/kg dry matter
$X(t)$	Water content at the moment t, kg water /kg dry matter
$X\ (t+\Delta t)$	Water content at the moment (t+ Δt), kg water/kg dry matter

Greek Symbols

ΔT_a	Air temperature rise, °C
η	Instantaneous thermal efficiency of the solar collector, %
ρ_a	Humid air density, kg/m^3
φ	Relative humidity, %

Abbreviations

FV	Forced Ventilation
NV	Natural Ventilation

1. Introduction

Dehydration is a very interesting technique for preserving fruits and vegetables. It is the healthiest storage mode and the most appropriate method for this aim because it allows preserving the quality of dry products. Thus, the vitamins are preserved and the dried products can be rebuilt later by a simple rehydration. For this purpose, the drying of the agricultural products is used.

In rural areas, the drying of agricultural products usually relies on direct exposure to sunlight. This technique has the advantages of simplicity and the small capital investments, but it requires long drying times that may have adverse consequences to the product quality: the final product may be contaminated from dust and insects or suffer from enzyme and microbial activity (Doymaz) [1]. In order to improve the quality, the sun drying can be replaced with a hot-air drying. But, this artificial mechanical drying is energy intensive and expensive, and ultimately increases the product cost. Bennamoun and Belhamri [2] reported that in the industrialized countries, between 7% and 15% of the industrial energy consumption has been used in the drying systems.

Usually, the drying of agricultural products is conducted under low temperatures, and thus, solar drying of them is widely regarded as the most hopeful alternative to the traditional direct sun drying (Zhimin et al.) [3]. According to Bennamoun and Belhamri [4], Tiris et al. [5] showed the importance of solar drying compared to the natural one. An improvement in the quality of the dried products and reduction in the drying time were observed during solar drying.

Tomato, among other fruits and vegetables can be dried using the solar drying technique; it has a limited shelf life at ambient conditions and is highly perishable. The tomato is also one of the crops that need to be protected from direct solar radiation to avoid undesirable discoloration in the resulting product. These crops should therefore be dried in indirect solar dryer (Doymaz) [1]. In terms of human health, tomato fruit is a major component of daily meals in many countries and constitutes an important source of minerals, vitamins, and antioxidant compounds (Khazaei et al.) [6]. Study of the drying of tomato can be found in the work of Gaware et al. [7] where drying of tomato slices was carried out using five different methods, viz., hot air (HAD), solar cabinet (SCD), heat pump (HPD), microwave vacuum (MVD), and freeze drying (FD). The drying characteristics of tomatoes were also investigated at four temperatures with air by Doymaz [1]. In the paper of Xanthopoulos [8], the drying kinetics and the effective water diffusivity of tomato halves during oven drying were investigated.

Solar dryers can be classified as natural ventilation (passive mode) solar dryers and forced ventilation (active mode) solar dryers. In the natural convection solar dryers, the airflow is usually established by buoyancy- induced airflow. In the forced convection solar dryers, the airflow is provided using fan using fan either operated by electricity/solar module or fossil fuel (Janjai and Bala) [9]. The indirect solar dryer is the oldest type of solar dryers, and it consists of a separate solar collector with a transparent cover on the top and a drying unit with an opaque cover on the top (Janjai and Bala) [9]. The essential advantages of such dryer are: conservation of the quality of the dried product, the possibility of controlling it scientifically and the fact that the rate of drying is definitely high (Belessiotis and Delyannis [10], El-Sebaii and Shalaby [11], Fudholi et al. [12]). There are several types of dryer size, the construction technique of which fulfil the special drying requirements of food products, many of which still operate rather based on experience than on a scientific basis (Belessiotis, Delyannis) [10].

The essential part of the indirect solar dryer is the solar collector, indeed much of the works were realized on the solar collectors [13-16]. There are basically two types of collectors: non-concentrating or stationary and concentrating. The first type can be also classified into three categories: Flat plate collectors (FPC), stationary compound parabolic collectors (CPC) and evacuated tube collectors (ETC), Soteris [13].

The principal objective of this study is a construction of an industrial-scale indirect solar dryer that works under the meteorological conditions of Ouargla, Algeria (Latitude: 31° 56’ 57” N – Longitude: 5° 19’ 30” E – Altitude: 138 m). The efficiency of the solar collector dryer designed was determined both in the passive and in the active modes. After this, the solar dryer was tested for drying tomato slices loaded in one tray or in four trays.

2. Literature review

Because of the cost-effective application of solar energy, numerous types of solar dryers have been designed and reported in the literature. Pangavhane and Sawhney [17] treated mainly the tendencies of development of the solar dryers used for the grapes; several typical installations, including traditional methods, were presented. The review paper of Atul Sharma and Chen Nguyen [18] was focused on the available solar dryer's systems. Ramana Murthy [19] reported in his paper review that various types of driers were available to suit the needs of farmers and the dependence of the drying on the characteristics of the product remains still as a problem, for comparison of drying efficiencies of various dryers. Belessiotis and Delyannis [10] concluded in their review, that the economies of solar dryers depended on the cost of the overall drying system and the gain from solar energy utilization, i.e., from the economy of energy. The state of the art of technologies and development of solar dryers was presented in the paper of VijayaVenkataRaman [20]. Indeed, the status of solar drying technologies in developing countries was presented and the various designs of solar dryers, its types and performance analysis were reviewed. Detailed description, fundamentals and previous work performed on solar dryers and solar air heaters, as the vital element for the indirect and mixed modes of solar dryers, were presented in the review paper of El-Sebaii and Shalaby [11]. Mustayen et al. [21] presented in their review a recent study on the design, performance and application of various types of solar dryers available today.

In the study of Shanmugam and Natarajan [22], a forced convection and desiccant integrated solar dryer for drying various agricultural crops was developed in Chennai, India. In India, three other forced convection solar dryers integrated with heat storage material were developed. The first dryer was realized in Tamil Nadu and presented in the paper of Mohanraj and Chandrasekar [23]. The second was presented in the paper of Mohanraj and Chandrasekar [24] and studied under the meteorological conditions of Pollachi. The third dryer was integrated with and without heat storage materials in Pollachi by Mohanraj and Chandrasekar [25]. Montero et al. [26] presented, in their paper, one solar dryer prototype which was designed, constructed, and performance tested for the analysis of the drying kinetics of agro industrial by-products and their possible power valuation.

Bennamoun [27] has reviewed the experience of solar drying in Algeria and presented different designs of solar dryers. According to this paper, only seven solar dryers were developed in our country. One of these devices was an indirect dryer developed in the same region (Ourgla, Algeria) where our industrial-scale indirect solar dryer was built. The specific accomplishment presented in this manuscript in comparison with the one published by Boughali et al. [28] can be summarized as follows: (i) It can operate in the natural ventilation and in the forced ventilation modes without additional energy while the dryer of Boughali et al. [28] used resistor heating. (ii) It has greater dimensions, thus greater drying capacity. (iii) Drying in thin layer as in thick layer is possible, but drying in the dryer of Boughali et al. [28] is only in thin layers. (iv) It was designed to be able to adjust the inclination of the solar collector which is not feasible with the dryer of Boughali et al. [28].

3. Materials and Methods

3.1. Description of the solar dryer

The schematic diagram and photograph of the indirect solar dryer are given in Fig. 1. The solar dryer mainly consists of two parts: the flat-plate solar collector which converting the solar radiation into heat and the drying chamber which containing wet product to dry (Fig. 1 (c)). Hot air is sent by natural or forced ventilation to the drying chamber. The solar dryer was developed based on the technical requirements for drying fruits and vegetables. The choice of the dimensions and materials of the solar dryer was inspired from previous designs and the unavailability of some materials tress at the time of the realization. The principal technical data of the device are summarized in Table 1 where some references are reported justifying the choices.

3.1.1. The solar air collector

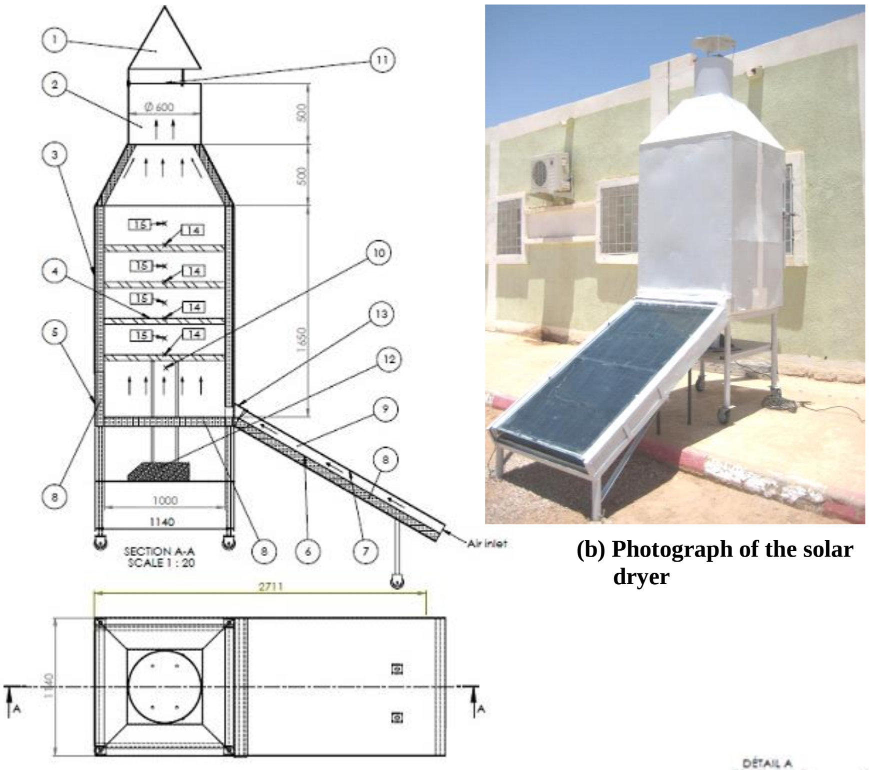
The Flat-Plate Solar collector (FPSC) with total dimensions of 1.90 × 1.14 × 0.16 m^3, is used to heat the air in the part ranging between transparent cover (glass) and absorber plate. The back part and the side walls of the collector are insulated thermally with glass wool. The absorber is a copper plate painted in matt black colour (no reflective) which must transmit energy collected to the air by avoiding all losses (by conduction - convection - radiation) of the various peripheral parts towards outside (Fig.1 (a), (c)). The device was designed to be able to adjust the inclination of the solar collector in a range between 0 ° and 60 °. In the device presented by Montero et al. [26], a range was between 20° and 40 °.

3.1.2. The drying chamber

The drying chamber is a parallelepiped form with total dimensions of 1.14 × 1.14 × 1.66 m^3. It was made of galvanized iron 7 cm thick and well insulated with 7 cm thick glass wool. It was placed on a support at 1 m from the ground and can be oriented, continuously facing the sun on movable wheel to increase the absorbed incident solar energy. Four trays distant from/to each other of 25 centimetres can be used to carry the wet product to dry. The drying chamber ends by a chimney being used to evacuate the humid air naturally or in active mode with a blower (Fig. 1(a) and 1 (b)).

3.2. Tomato samples

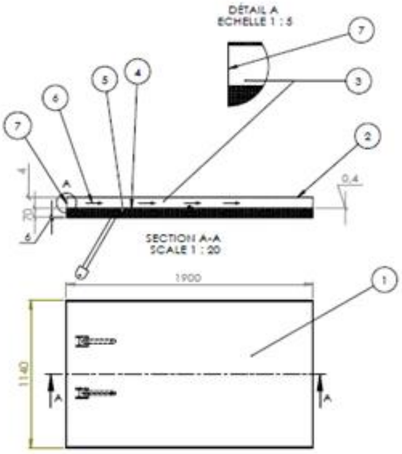
In this study, tomato (L. esculentum) was chosen as the product to be dried because of its limited shelf life at ambient conditions and its high perishability. Good quality fruits were purchased from a local fruit market of Ouargla (Algeria). Tomatoes were washed into water to remove skin dirt, cut into slices of 1 cm thickness. Seeds were removed and the slices obtained were uniformly laid out on the trays of the indirect solar dryer.



(1)Top hood (2) Chimney (3) Door (4)Drying tray (5) Drying chamber (6)Absorber (Copper) (7) Transparent cover (8)Insulator (Glass wool) (9) Air duct (10)Anemometer position (11) Position of the fan (12) Balance (13) Flexible connector (14) Product Temperature thermocouple (15)Temperature–relative humidity thermocouples.

(a) Schematic diagram of the solar dryer

(b) Photograph of the solar dryer



(1)Air solar collector (2)Transparent cover (3)Air duct (4)Absorber (Copper) (5)Insulator (Glass wool) (6)Air direction (7)Thermocouple positions in collector (Inlet and outlet)

(c) Diagram of the solar collector and locations of the measuring parameters.

Fig. 1. Schematic diagram and photograph of the indirect solar dryer.

Table 1. Technical data of the solar dryer designed.

Collector	Material	Sheet galvanized
	External dimensions	1.90 ×1.14 × 0.16 m^3
	Cover	Ordinary glass [3, 24, 29,30]
	Thickness of the cover	0.004 m [29,31]
	Absorber	Copper [22,23,24,30]
	Thickness of the absorber	0.0005 m
	Distance (Cover - Absorber)	0.06 m [27]
	Heat insulation	Glass wool [23,24]
	Thickness of the insulator	0.07 m
	Angle of inclination	Variable (0 – 60°)
Drying chamber	External dimensions	1.14 × 1.14 × 1.66 m^3
	Heat insulation	Glass wool [23,24]
	Loading	Simple door located on the back face of the drying chamber
	Number of trays	1 for drying in thick layer 4 for drying in thin layers
	Dimensions of trays	1.00 × 1.00 × 0.05 m^3 (Thin layer)
		1.00 × 1.00 × 0.20 m^3 (Thick layer)

3.3. Instrumentation and measurements

In all experiments, the sought parameters were measured with appropriate instruments. Several probes were used by fixing them at different locations of the dryer (Fig. 1 (a); (c)) and which are connected to a multi-function instrument (C.A 1051 - CHAUVIN ARNOUX, FRANCE) at the time of the measurements. The specifications of the measuring instruments with parameters measured are mentioned in Table 2.

3.4. Experimental procedure

The experiments were conducted at Laboratory of Process Engineering at the University of Ouargla, Algeria (Latitude: 31° 56’ 57” N –Longitude: 5° 19’ 30” E – Altitude: 138 m). The performance of the indirect solar dryer was continuously monitored during March–June 2012. Two types of studies were done on the solar dryer: Tests with the solar collector and solar drying tests. Various measuring devices were used to investigate the effects of the environmental and operating parameters on the performance of the dryer. The sought parameters were measured with appropriate instruments (Table 2). The measurement locations are indicated in (Fig. 1 (a) and (c)).

The first experiments were carried out on the solar collector in the natural and forced ventilations. The solar collector was oriented directly towards the equator, facing south to maximize the incident solar radiation on it. It was tilted to an angle about 32°, a value equal to the latitude of the location [13,28,32,33]. In the forced ventilation, the air blower of 75 W power was switched on and the air velocity in the solar collector was adjusted to three different velocities (1, 1.15 and 1.40 m/s) using a manual valve connected to the air inlet.

In the solar drying tests, there were two kinds of experiments: Drying test in one thin layer and drying test in four thin layers. 2.12 kg of fresh tomato was used for the one tray test, and the initial water content was 14.32 kg water/kg dry matter. One tray was loaded as thin layer where tomato slices were carefully and orderly placed. The air preheated in the solar collector crosses the tray. Drying started at 7:00 a.m. and continued until 19:00 p.m. The changes in mass of tomato were monitored at 15 min intervals for the first three hours and 30 min for subsequent drying times to equilibrium. In the second test, the four trays of the dryer were loaded as thin layers, where 260 g of tomato slices were carefully and orderly placed with an initial water content of 14.06 kg $_{\text{water}}$/kg $_{\text{dry matter}}$. The drying process was continued until the product achieved its final mass at which the mass does not decrease significantly with increasing drying time. This final mass was considered as the equilibrium mass value. Then the drying process was continued until the product achieved its equilibrium moisture content X_{eq} [34]. After each drying test, the bone dry mass of tomato, M_d, was determined by drying the entire dried product (M_{heq}), during 24 hours, in a regulated drying oven at 105 °C (Climatic chamber BINDER – APT. line ^{TM} KBF – ICH) [35]. In fact, the dry mass is the measurement of the mass of the product when completely dried i.e. dry matter is what remains after all of the water is evaporated out of a product. Thus, the initial and equilibrium moisture contents of tomato were determined [35].

Table 2. Specifications of the measuring instruments.

Parameters	Instruments	Accuracies	Resolutions
Ambient Temperature	Thermo-hygrometer	± 2% of reading ± 0.1 °C	0.1 °C
Ambient Humidity		± 1% of reading ± 1.5 %	0.1 %
Solar radiation	Kipp and Zonen pyrometer	0.1 W/m^2	/
Air temperatures in the collector	Chromel-alumel K-type thermocouples	± 0.01 °C	/
Air Velocity in the collector	Thermo-anemometer with hot wire	± 3% of reading ± 0.03 m/s	- 0.01 m/s
Mass of tomato	Digital balance (KERN balance, series FCB) (Max. capacity = 10.1 kg)	± 0.1 g	/

3.5. Data analysis

Among the most and main significant parameters usually used for performance estimation of any solar drying system reported by several works are the thermal efficiency (η) of solar collector and the outlet air temperature (T_{as}) (Montero et al. [26] and El-Sebaii et al. [30]). In this study, we are interested in the thermal efficiency and temperature rise ($\Delta T_a = T_{as} - T_{amb}$) instead of T_{as} because, for example, if the outlet air temperature is 40 °C for one solar collector does not mean that it is more efficient that another collector whose temperature is 35 °C for a same solar intensity and a same air velocity. It would be more proper to compare their air temperature rises. In addition, among variables which influence the thermal efficiency of solar collectors and the outlet air temperature, we took into account the solar radiation (I) and air velocity (v_a) through the collector.

The instantaneous thermal efficiency of the solar collector (Dattatreya et al. [31]) was estimated by using Eq. (1):

$$\eta = \frac{C_p\, m_a\; (T_{as} - T_{amb})}{A_s\; I} \tag{1}$$

Equation (2) was used to obtain the air mass flow rate in the collector:

$$m_a = \rho_a \bullet v_a \bullet A_a \tag{2}$$

The instantaneous moisture content on dry basis which is the mass of water present in the product per unit mass of the dry matter in the product, was defined by using Eq. (3):

$$X(t) = \frac{M_h\,(t) - M\mathrm{d}}{Md} \tag{3}$$

The equilibrium moisture content was calculated from Eq. (4):

$$X_{eq} = \frac{M_{hf} - M_{\mathrm{d}}}{M_d} \tag{4}$$

In order to normalize the drying curves, the data involving the dry basis moisture content versus time were transformed to a dimensionless parameter called the moisture ratio versus time. The moisture ratio of the product at the moment t was calculated using Eq. (5):

$$XR = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} \tag{5}$$

The drying rate (Aishi and Feiyan) during the drying process was determined by using Eq. (6): [36]

$$DR = \frac{X(t) - X(t+\Delta t)}{\Delta t} \tag{6}$$

4. Results and Discussion

4.1. Tests with solar collector

4.1.1. Variations of the external parameters

The variations of the measured solar radiation (I), ambient temperature (T_{amb}) and relative humidity of ambient air (φ) during experiments are shown in Fig. 2. A maximum solar intensity was observed at 1: 00 p.m. and it varied between 765 and 850 W/m^2 corresponding respectively to the first day (14/03/012) and the last day (25/04/2012) of the study period. The ambient air temperature was low at the beginning and the end of the day. The maximums were recorded during peak sunshine between noon and 03: 00 p.m. regardless of the day. Average ambient temperatures in these hours were 29.3 and 36.9 °C on 14/03/2012 and 25/04/2012, and they decreased to 22.7 and 32.1 °C respectively, outside the hours of sunshine around 06: 00 p.m. The relative humidity has a reverse trend to that of the ambient temperature. It decreased from about 36.4% to 12.5% the first day of experimental period and from 27.7% to 6.2 % on the last day. All these results are in good agreement with El-Beltagy et al. [29], VijayaVenkataRaman et al. [20] and El-Sebaii [30]).

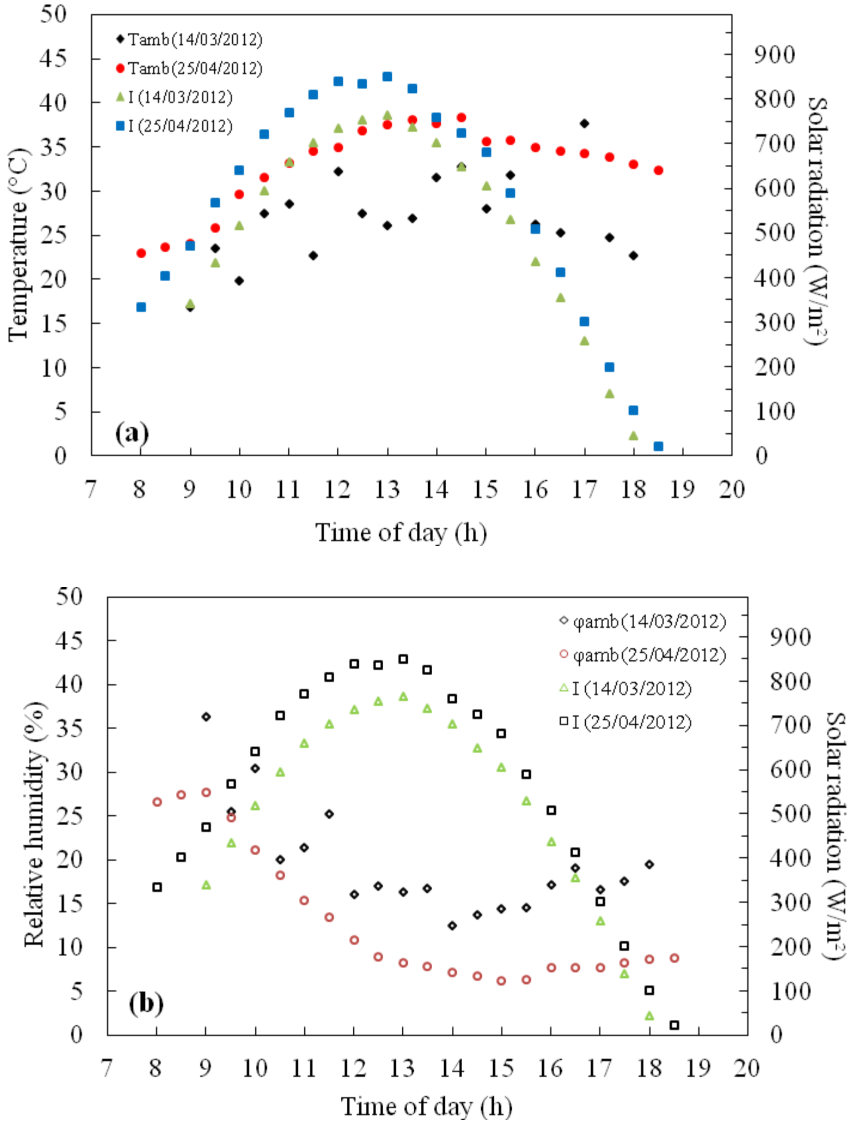


Fig. 2. Evolutions of the external parameters during two typical days.
(a) Variations of the solar radiation and ambient temperature vs. time.
(b) Variations of the solar radiation and relative humidity vs. time.

4.1.2. Variations of the solar collector temperatures

The comparison of the rise of air, absorber and glass cover temperatures of the solar collector are reported in Fig.3. The experiments were carried in the natural and forced ventilations and the variations of temperatures (ΔT_a) between the outlet (T_{as}) and the inlet (T_{amb}) air temperatures, the variations of temperatures (ΔT_{abs}) between the outlet (T_{abss}) and the inlet (T_{abse}) of the absorber temperatures and the variations of temperatures (ΔT_{cov}) between the outlet (T_{covs}) and the inlet (T_{cove}) cover temperatures of the collector are also presented. The variations of temperatures were low at the beginning and the end of the day reached to maximum values during peak sunshine hours regardless of the mode, which is in good agreement with the theoretical study of Bennamoun and Belhamri [2]. The temperature variations of the collector are less significant in the forced ventilation compared to the natural ventilation. This effect can be attributed to the ventilation of air which ensures the convection heating of the absorber. The average outlet collector air temperature rise over ambient air temperature was found to be 19.5 °C during the natural ventilation and 7.1 °C during the forced one; in the investigation of Montero et al. [26], the air temperature rise was 4°C in the forced ventilation case.

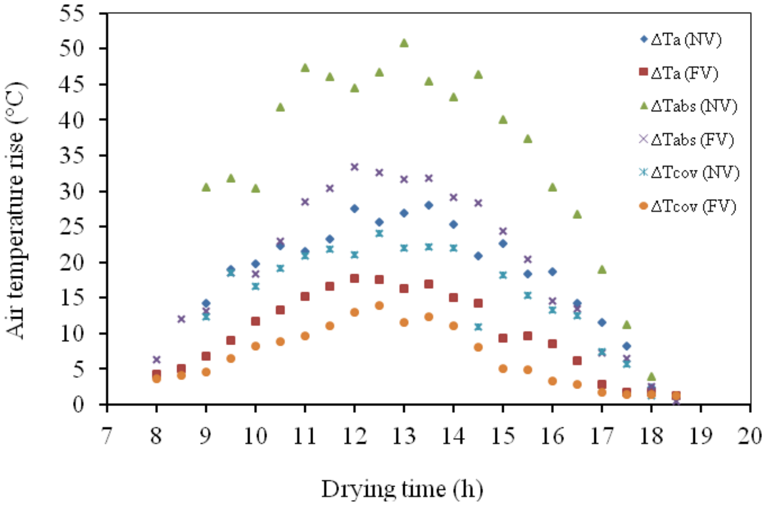


Fig. 3. Evolutions of the collector temperatures as a function of time of day.

Based on the experimental results obtained, the air temperature at the outlet of the collector was observed to be much higher than the ambient air, which is in good agreement with results obtained by Hossain and Bala [37]. The rise in air temperature (ΔT_a) at the outlet of the collector above ambient air temperature against solar radiation is shown in Fig. 4. The air temperature rise in the collector increased linearly with the increase of solar radiation. The air temperature rise was low at the forced ventilation if compared to the natural ventilation. The following regression equations were developed for the air temperature rise at the collector outlet with solar radiation:

Natural ventilation: $\Delta T_a = 0.030\ I + 4.361$ ($R^2 = 0.9727$) (7-a)

Forced ventilation: $\Delta T_a = 0.026\ I - 4.458$ ($R^2 = 0.9858$) (8-a)

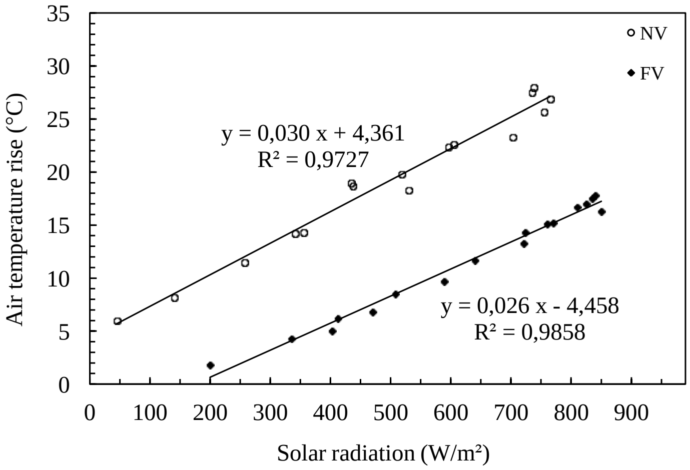


Fig. 4. Air temperature rise at the outlet of the collector vs. solar radiation.

The difference in temperature (T_{as} - T_{ae}) is proportional to the solar radiation what gives a precise idea on the intensity of the connection between (T_{as} - T_{ae}) and the solar radiation which is strong in this case. The slopes are equal to 0.030 and 0.026 for the natural convection and the forced convection, respectively. By admitting that the ambient temperature is equal the inlet collector air temperature Azharul Karim and Hawlader [38] we have:

Natural ventilation: $$T_{as} = 0.030\ I + 4.361 + T_{amb} \tag{7-b}$$

Forced ventilation: $$T_{as} = 0.026\ I - 4.458 + T_{amb} \tag{8-b}$$

4.1.3. Variations of the solar collector efficiency

The temporal evolution of the collector efficiency with solar radiation and time of the day are represented in Fig. 5. Regarding the efficiency (ƞ), the variables on which this propriety depends are the solar radiation and the velocity of the air flow in the collector. The same results were reported by Azharul Karim [38], Chemkhi et al. [39] and Montero et al. [26]. For a constant value of the solar radiation, the increase in air velocity implies an increase in the efficiency of the collector. The effect of the forced ventilation (FV) in the efficiency is so strong compared to the natural ventilation (NV). In the case of the natural ventilation, the efficiency values vary between 26.61% and 46.32 % with an average value of 32.32 %, while in the forced ventilation (FV), the efficiency values vary between 33.45% and 66.56 % with an average of 51.33 %. The maximum value 66.56% is reached at noon. Figure 5 shows, also, that the collector efficiency increases at the end of day in spite of reduction in the solar radiation. This effect is due to the energy stored by the collector during a maximum of solar intensity.

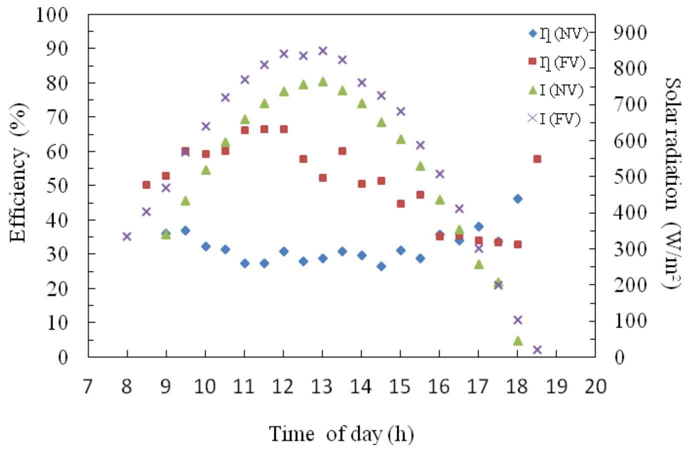


Fig. 5. Variation of collector efficiency with solar radiation and time of day.

Figure 6 represents the temporal evolution of the collector air temperature rise for different air velocities inside the collector. The collector air temperature rise is inversely proportional to the air velocity. The air temperature rise is very large, shows that the air temperature in the natural ventilation (NV) case is higher than that in the forced ventilation (FV) case.

Figure 7 shows the effect of the solar radiation on the collector efficiency in the case of the forced ventilation (FV). The collector efficiency increases linearly with the increase of solar radiation in the interval of 400 and 800 W/m^2 with the air velocities ranging between 1 and 1.40 m/s. The effect of the air velocity on the collector efficiency is negligible when the solar intensity is close to 800 W/m^2. Studies on the same variations and effects were examined in the works of [26,38,40]. These works resulted in similar behaviors of the flat plate solar collector for drying applications and a similar influence of the solar radiation and the air velocity was obtained.

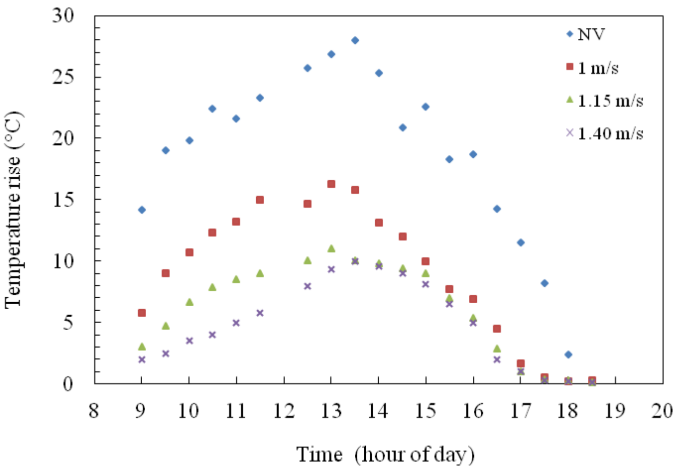


Fig. 6. Effect of the velocity on the air temperature rise at the outlet of the collector.

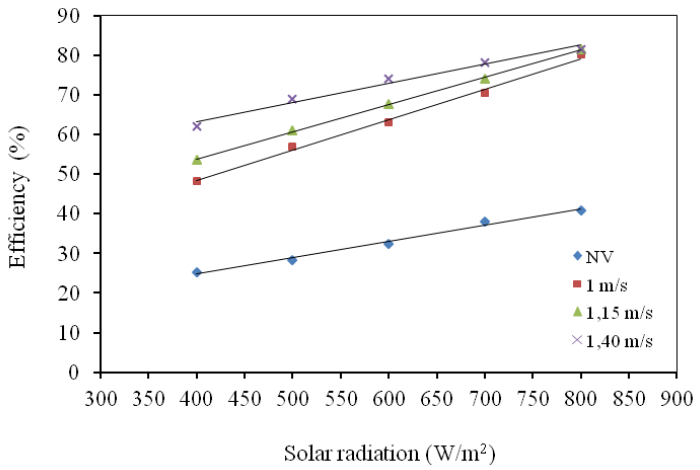


Fig. 7. Effect of the solar radiation on the efficiency for various velocities.

4.2. Solar drying tests

4.2.1. First drying test: Use of one tray

The variation of the moisture content vs. drying time is reported in Fig. 8. It can be seen that the moisture content of the product decreases continuously with time to reach an end value. The mass loss is considerable at the beginning of drying. The mass decreases by 0.6 kg in the first two hours of drying, thus representing 28.30 % of the initial wet mass. The moisture content of tomato was reduced from 14.32 to 0.14 kg water/kg dry matter after 12 h of drying time. In the solar dryer of Boughali et al. [28] which was developed with additional energy, the drying of tomato at 50 °C took 14 h. The contact air-dried product generates a coupled heat and mass transfer and the moisture reduction during the initial stage is due to the evaporation of the free moisture from the outer surface of the tomatoes. The drying occurs in the falling rate period which suggests diffusion – controlled type drying mechanism, Shanmugam et al. [22].

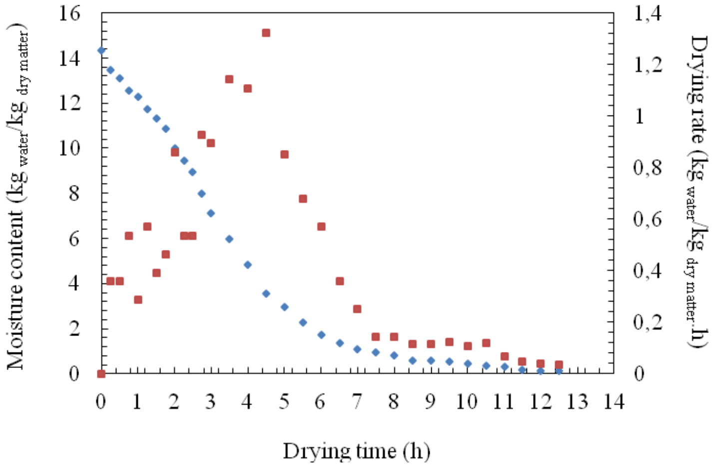


Fig. 8. Variations of the moisture content and drying rate vs. drying time.

Drying rate versus moisture content of tomatoes during solar drying is shown in Fig. 9. The curve DR = f (t) (Fig.8) and Fig. 9 show a short adaptation phase followed by a dominant falling drying rate phase during the solar drying of tomato slices (Boughali et al. [28] and Doymaz [1]). The adaptation phase (setting of temperature), lasted approximately 2 hours 45min, thus representing 22.92 % of the total drying time. At this time, the values of the wet mass, water content and drying rate of tomatoes were 1.26 kg, 8 kg water/kg dry matter and 3.714 kg water/kg dry matter. h, respectively.

The second phase began towards 9:45 a.m. and finished towards 19:00 p.m. (end of drying); it is the period when the surface is not vapor saturated. The moisture diffusion is controlled by internal water transfer while the water content at the exchange surface continuously decreases (Belessiotis and Delyannis) [10]. The drying rate was higher at higher moisture content, at the beginning of drying, and it decreased as moisture content reduced, although more moisture was evaporated from the outer surface and outer layers of tomato (Belessiotis and Delyannis) [10]. As the drying process proceeded, the moisture content at the surface decreased and the evaporation zone moved from the surface to the tomato inside. Therefore, less evaporation took place and the drying rate decreased with time as well as the moisture content. Similar results have been obtained by other authors (El-Sebaii et al. [34], Akanbi et al. [41] and Akpinar [42]) and they are in good agreement with the theory (Daguenet [43] and Nadeau, Puiggali [44]).

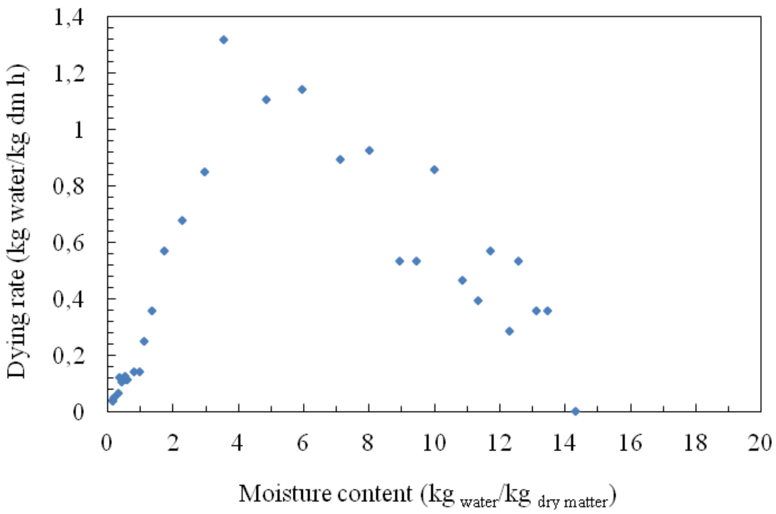


Fig. 9. Variation of the drying rate of tomato slices vs. moisture content.

The Relationships concerning the drying rate and moisture content, at drying conditions (air velocity = 1.40 m/s, average inlet temperature = 47 °C and average inlet humidity = 13 %) during the first test, are presented as follows:

$$X = -0.0043\,t^4 + 0.099\,t^3 - 0.561\,t^2 - 1.3333t + 14.083 \quad (R^2 = 0.9984) \qquad (9)$$

$$DR = -0.0022\,t^4 + 0.07t^3 - 0.7246t^2 + 2.4933t + 0.02 \quad (R^2 = 0.8457) \qquad (10)$$

$$DR = -0.0009\,X^3 - 0.0365\,X^2 + 0.7335\,\mathrm{X} - 0.143 \quad (R^2 = 0.8605) \qquad (11)$$

From these equations, it is possible to estimate the moisture content at any drying time and to estimate, also, the drying rate at any drying time and for any moisture content.

4.2.2. Second drying test: Use of the four trays

Figure 10 shows the temporal variation of the moisture content ratio of the tomato for several heights. The four curves start to separate at the end of the first hour from drying. Indeed, the two first separate from both others in a considerable way. We can see, already, that at the end of the second hour the first curve is spirit to separate from the other three curves in a more significant way: this is due to the reduction in water content and to its increase in space, i.e. the height (the sub-bases are crossed by a hotter and less saturated air). The difference between the four durations of drying was one hour between each tray. Similar results were found by El-Sebaii [30] and Akpinar [42].

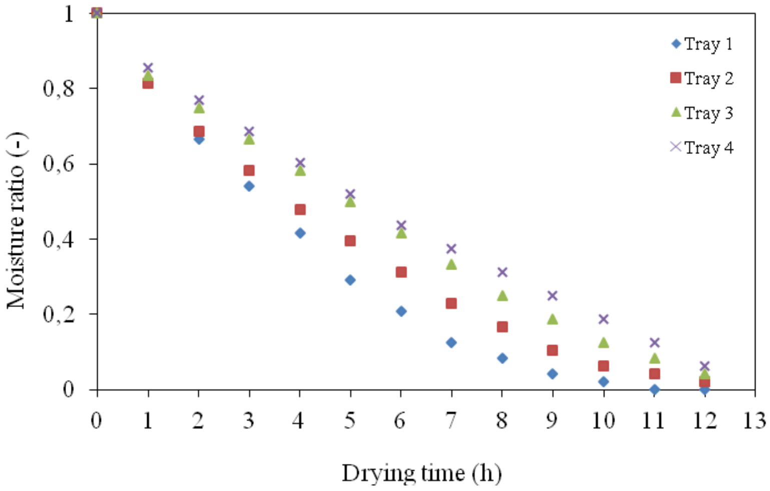


Fig. 10. Evolution of moisture ratio during solar drying of tomato slices deposited on four trays.

5. Conclusions

The aim of this work is to make an experimental study and performance testing on an indirect solar dryer designed and realized at Laboratory of Process Engineering (University Kasdi Merbah, Ouargla) in the south-east of Algeria. The main conclusions of this study can be summarized as follows:

- The increase in solar radiation has more influence on the solar collector temperatures in the natural ventilation than in the forced ventilation.
- In the natural ventilation, the collector efficiency values vary between 26.61 and 46.32 % with an average of 32.32 % and in the forced ventilation, the collector efficiency values vary between 33.45 and 66.56 % with an average

of 51.33 %. It can be concluded that the forced convection solar dryer is more suitable.

- The collector efficiency increases linearly with the increase in solar radiation ($400\leq I \leq 800$ W/m^2) for air velocities fixed between 1 and 1.40 m/s, but the effect of the air velocity on the collector efficiency is negligible for solar radiation close to 800 W/m^2.
- Solar drying of tomato occurs mainly in the falling rate period while passing by a short phase of temperature setting representing 22.92 % of the total time in the case of single thin layer. Thus, the moisture content of the tomato is reduced from 14.32 to 0.14 kg water/ kg dry matter after 12 h of drying time.
- When four trays of the dryer are used, the difference between the four durations of drying is one hour between each tray and the following one.

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