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Study of solar thermal energy in the north region of Algeria with simulation and modeling of an indirect convective solar drying system

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Abstract

The objective of this work is to study the feasibility and performances of solar thermal energy in the region of Constantine, situated at the north of Algeria and if it is profitable to a farmer to use it. The air solar collector is made with cheap available materials and has given important results with an air heated to more than 60 ºC, with an optimum surface of 3 m^2, inclined with 10 degrees and directed to the south. Also, coupling the air collector with a drying chamber has given other satisfactory results. It was found that solar drying is influenced by the collector parameters in particular its surface, by the exterior ambient conditions such as the velocity and the temperature of the ambient air and also by the dimensions of the agro-alimentary dried product. Adding a heater allow the use of the solar system in unfavorable climatic conditions.

Keywords: Air collector - batch dryer - agro-alimentary products – thin layer - forced convection - Constantine region

1. Introduction

Sun is ever considered as the most important source of renewable energy. Every second sun loses around 4.5×10^9 of tons of its substances which is transformed into radiations, it represents a quantity of about 390×10^9 of tons per day [1]. However, earth is receiving a very small quantity of these radiations which corresponds to 180000×10^9 kW, or in other terms it receives 10^4 the power installed by man, in all forms. The energy putted by sun to our disposition is around 4×10^{17} kWh/year [1]. Solar energy is then considered as a non-terminated source of energy however it comes in a dissipated form and generally we need important surfaces to dispose of sufficient quantities.

The World Energy Council and the Algerian Ministry of Energy and Mining affirm that Algeria receives an average insolation of 2000 hours per year, moreover the high plateau and Sahara is receiving 3900 hours per year [2]. The average solar energy received is 2400 kWh/m^2/year, ranging from 1700 kWh/m^2/year for the coastal region, 1900 kWh/m^2/year for the high plateau, and 2650 kWh/m^2/year for the south [3].

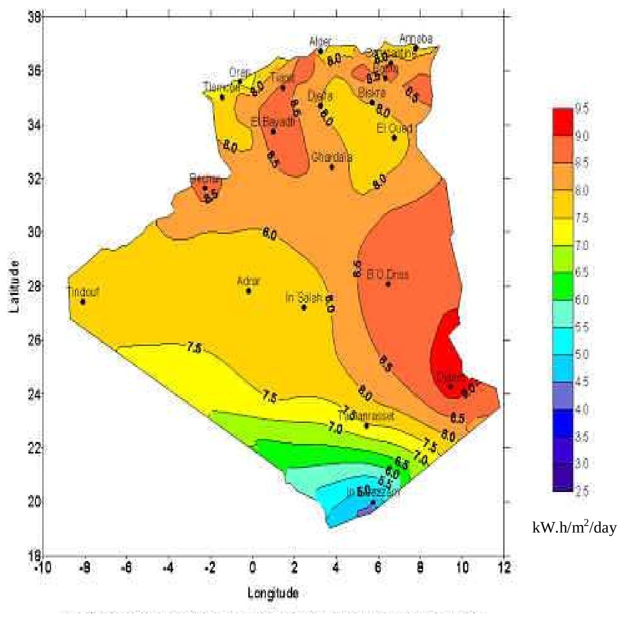

Fig. 1 Normal daily irradiation received in Algeria during the month of July [3]

These given statistics indicates, considering the solar energy point of view, that the country is divided essentially into two important regions the north which represents around 14% of the surface of the country and the south or the Sahara with 86% of the country surface.

Fig.1 shows the normal daily irradiation received by the different regions of Algeria during the month of July. We can see that there are some regions in the north that can have important quantity of irradiations as the Sahara.

It is still common to see in our country regions farmers having direct profits from sun and spreading some of their products on the ground in order to be dried. As this method has the advantage to be a cheap method, it has many disadvantages such as exposing the product for long time to the sun lights, in particular ultra-violet rays, also we need important surfaces and it depends on the climatic conditions.

The experience of convective drying of agro-alimentary products in Algeria is a recent one. We can refer to just few experimental works dealing with apricot [4], dates [5], grapes and some medicinal plants [6], which use convective solar drying.

In this work we focus on the region of Constantine which is at the north east of Algeria and study the performances and if it is useful to use a simple and inexpensive solar air collector with application to drying of agro-alimentary products.

2. Mathematical study and modeling

2.1. Characteristics of the region

For studying climate of a region, many data are necessary such as humidity, sun, snow and others. The knowledge of these factors is required because it affects the human activities and their habitudes in particular production and energy consumption.

Constantine is situated at the north east of Algeria, more precisely, at 6°37 east (longitude) and 36°17 north (latitude). The altitude of this city varies from 493 m to 721 m; the average altitude is of about 625 m, it is far of about 86 km from the sea. It is situated in a zone characterized by a cold winter with mean temperatures around 10°C and relative humidity attempting 70% and a hot summer with mean temperatures of about 35 °C and can reach 40°C and more, with a relative humidity around 50%.

It is confirmed [7-8] that Capderou model [9], used for the atlas of Algeria, can well predict the distribution of the direct, diffusion and global radiations during the representative days of the months, in particular in July with small registered errors.

This model supposes that the direct flux received by horizontal plane surface is written in the following form:

$$P_{dir,h} = I_0 \; C \; \tau_{dir} \qquad (1)$$

Where:

$P_{dir,h}$: is the direct flux received by a plane surface (in W/m^2).

I_0: is the received flux. Generally, it is equal to 1353 W/m^2.

C: is a constant that depends on the day in which flux is calculated. It is equal to [10]:

$$C = 1 + 0.033\cos(360.d/365) \qquad (2)$$

d: represents the number of the day in the year.

τ_{dir}: is the coefficient of transmission of the direct radiations. It is presented as function of the climatic conditions, the geographic position and specific parameters that depend of the sun position.

Fig. 2 shows the variations of the direct and the diffuse radiations during a representative day of the month of July for Constantine region. It is clear that the region can dispose of important quantities of energy that can be exploited, in particular between 10 a.m. and 3 p.m

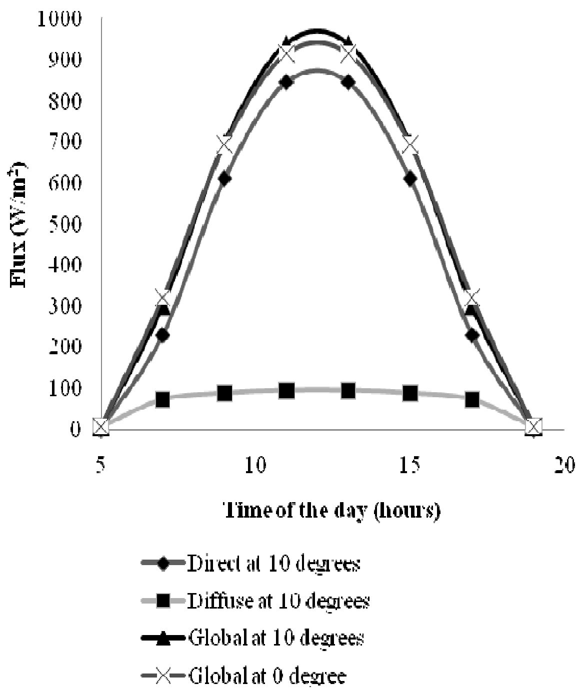

Fig. 2 Variation of the direct and diffuse flux radiations during the representative day of the month of July for Constantine region.

2.2. Presentation of the solar collector

We would like to study the behavior of a flat air collector and to make it easy for construction, for support and maintenance, in order to have a rapid feedback of the investment. In this fashion, we have used cheap and available materials. As, presented in Fig.3 It is constituted of a Pyrex glass 1cm thick used as a cover with emissivity coefficient ε = 0.9. We have use a 1 mm thick aluminium plate painted in black in order to increase the heat conduction characteristics, in particular absorptivity and emissivity. They have respectively the following values: α = 0.95 and ε = 0.96. This painted plate is used as the absorber. Finally, a polystyrene plate is used as an insulator, in order to limit the exchange heat with the ambient environment. It has a thick of about 4 cm. It is important to note that air flows between the absorber and the insulator but a vacuum volume is constituted between the cover and the absorber in order to limit the loss of heat converted from solar radiations. The space between the glass and the absorber is the same between the absorber and the insulator and it is equal to 2.5cm. During modeling the collector, for Constantine region and for July period, we have found that the collector must be inclined with 10 degrees as it is represented in Fig. 2, and directed to the south. These obtained results are with agreement with other modeling results [1, 11-12].

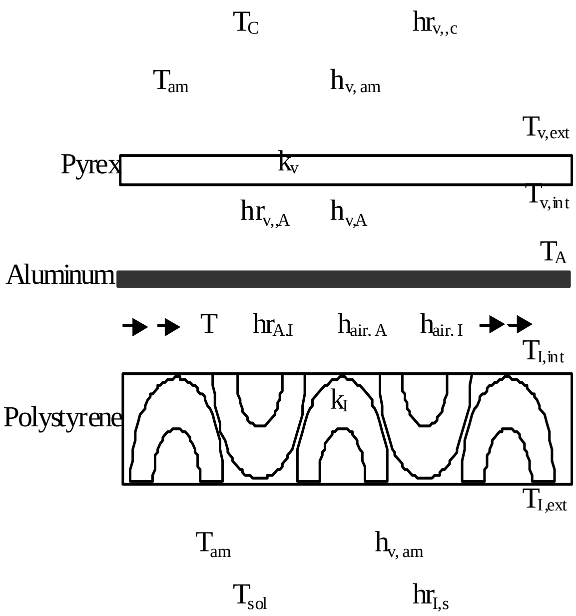

Fig.3 Diagram of the solar air collector used in this study. c: skier vault, v: glass, am: ambient media, A: absorber, I: insulator, ext: exterior, int: interior, sol: ground, hr: adapted radiative exchange coefficient ($W/m^2.K$), h: coefficient of heat transfer by convection ($W/m^2.K$), k: adapted conductive exchange coefficient ($W/m^2.K$).

2.3. Governing equations of the solar collector

To study the presented collector a "step by step" method is chosen [10]. It consists on taking a fictitious segment of this collector then effectuating heat balances on the different compounds of the collector. It directs to six differential equations.

The study of the external surface of the glass gives radiative and convective exchanges between the exterior media and conductive exchange with the interior surface of the same glass but also a quantity of energy is absorbed by the glass. The representing equation is written in the following form:

$$\frac{m_v\,.\,Cp_v}{surf}\left(\frac{d\,T_{v,ext}}{d\,t}\right)=P_v+hr_{v,c}\,.\,(T_c-T_{v,ext})+h_{v,am}\,.\,(T_{am}-T_{v,ext})+k_v\,.\,(T_{v,\mathrm{int}}-T_{v,ext}) \quad (3)$$

surf represents the surface of the slice and Cp is the specific heat (J/kg.K).

P_v is the flux of radiation absorbed by the glass calculated in W/m^2. It depends on the direct and the diffuse flux. It is written in the following form [10]:

$$P_v = P_{dir}\,.\alpha_{dir,v} + P_{dif}\,.\alpha_{dif,v} \quad (4)$$

For the internal surface of the cover glass, there is conductive exchange with its external surface and radiative and convective exchanges with the absorber. It is represented in the following form:

$$\frac{m_v\,.\,Cp_v}{surf}\left(\frac{d\,T_{v,\mathrm{int}}}{d\,t}\right)=hr_{v,A}\,.\,(T_A-T_{v,\mathrm{int}})+h_{v,A}\,.\,(T_A-T_{v,\mathrm{int}})+k_v\,.\,(T_{v,ext}-T_{v,\mathrm{int}}) \quad (5)$$

The absorber has received the transmitted part of the flux by the glass. It presents radiative and convective exchanges with the internal surface of the glass, radiative exchange with the internal surface of the insulator and convective exchange with the air flowing in this part of the collector. All of these exchanges are represented by the following equation:

$$\frac{m_A\,.\,Cp_A}{surf}\left(\frac{d\,T_A}{d\,t}\right)=h_{v,A}\,.\,(T_{v,\mathrm{int}}-T_A)+hr_{v,A}\,.\,(T_{v,\mathrm{int}}-T_A)+hr_{A,I}\,.\,(T_{I,\mathrm{int}}-T_A)+h_{air,A}\,.\,(T^*-T_A)+P_A \quad (6)$$

* is to note the precedent tray.

As the thickness of the absorber is not important, we consider that there is no loss of the heat between the two surfaces of the absorber.

P_A represents the total absorbed flux, function of the direct and diffuse radiations received by the absorber. The following equation is used to calculate this portion on flux [10]:

$$P_A=\alpha_A\,\frac{P_{dir}\,.\tau_{dir}+P_{dif}\,.\tau_{dif}}{1-(1-\alpha_A)\;\rho_{dir}} \quad (7)$$

ρ is representing the reflectivity and it is calculated using the classical electromagnetic theories [13].

Generally, the diffuse radiation is assimilated to a direct

one with an incidence angle of about 60 degrees.
The air flows between the absorber and the internal surface of the insulator with convective exchanges. The following equation is used:

$$\dot{m}_{am}.Cp_{air}(T-T^*)=surf.\,h_{air,A}.(T_A-T^*)+surf.\,h_{air,A}.(T_{I,\text{int}}-T^*) \quad (8)$$

$\dot{m}$ is representing the mass flow rate of the air (kg/s).

The heat balance effectuated on the internal surface of the insulator gives radiative exchanges with the absorber, convective one with the air and conductive exchange with the exterior surface of the insulator. The following equation is well describing the result:

$$\frac{m_I\,.\,Cp_I}{surf}\left(\frac{d\,T_{I,\text{int}}}{d\,t}\right)=hr_{A,I}\,.\,(T_A-T_{I,\text{int}})+k_I\,.\,(T_{I,ext}-T_{I,\text{int}})+h_{air,A}\,.\,(T^*-T_{I,\text{int}}) \quad (9)$$

The external surface of the insulator has radiative and convective exchanges with ambient media and conductive exchange with the internal surface of the insulator. It is represented by the equation:

$$\frac{m_I\,.\,Cp_I}{surf}\left(\frac{d\,T_{I,ext}}{d\,t}\right)=k_I\,.\,(T_{I,\text{int}}-T_{,ext})+hr_{sol,I}\,.\,(T_{sol}-T_{I,ext})+h_{v,am}\,.\,(T_{am}-T_{I,ext}) \quad (10)$$

2.4. Presentation of the drying chamber

The premeditated drying system is having 1m*1m*1m volume. Its entrance is connected to the exit of the solar collector. By this way, the heated air will flow into the drying chamber. This last is constructed with brick material and covered with polystyrene used as an insulator. It containes ten horizontal perfored trays that allow the vertical flow of the heated air through these trays. In a comparison betwwen indirect solar drying using forced convection and natural convection, it was found that forced convection drying shows better results with a homogeneous dried product [11]. For this, a fan is added at the top of the drying chamber. Also, we have studied the possibility to add a heater in the region between the collector and the drying chamber. It allows performing drying during unfavorable climatic conditions. It is used when the temperature of the heated air is less than 50 ºC.
The internal chart is represented in figure 4.

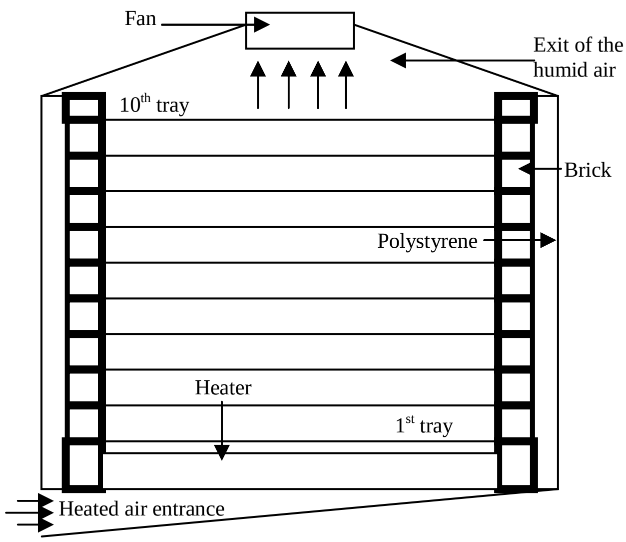

Fig. 4 Internal diagram of the drying chamber

2.5. Governing equations of the drying chamber

Heat and mass balance is established to the different parts of the drying chamber and the air flowing in it, leading to the following equations:

Balance effectuated for the air which flows between two trays with an exchange with interior walls:

$$\dot{m}_{ach}\,Cp_{air}\,(T^*_{ach}-T_{ach})=h_{ach,f}\,S_f\,(T_{ach}-T_f)+4h_{ach.,pi}\,S_v\,(T_{ach}-T_{pi}) \quad (11)$$

Balance effectuate between the product and the heated air:

$$m_f \,.\, Cp_f \,.\left(\frac{d\,T_f}{d\,t}\right) = h_{ach,f} \,.\, S_f \,.\left(T_{ach} - T_f\right) - Pev \qquad (12)$$

Balance in the internal surface of the brick wall:

$$\frac{mp_b}{4} \,.\, Cp_b \,.\left(\frac{d\,T_{pi}}{d\,t}\right) = h_{achpi} \,.\, S_v \,.\left(T_{ach} - T_{pi}\right) + k_b \,.\, S_v \,.\left(T_p - T_{pe}\right) \quad (13)$$

Balance at the polystyrene wall:

$$\frac{mp_p}{4} \,.\, Cp_p \,.\left(\frac{d\,T_{pe}}{d\,t}\right) = k_p \,.\, S_v \,.\left(T_p - T_{pe}\right) + h_{am,pe} \,.\, S_v \,.\left(T_{am} - T_{pe}\right) + hr \,.\, S_v \,.\left(T_c - T_{pe}\right) \qquad (14)$$

Balance at the intermediate surface between brick wall and polystyrene:

$$\frac{mp_p}{4} \,.\, Cp_p \,.\left(\frac{d\,Tp}{d\,t}\right) + k_p \,.\, S_v \,.\left(T_{pe} - T_p\right) = \frac{mp_p}{4} \,.\, Cp_p \,.\left(\frac{d\,Tp}{d\,t}\right) + k_p \,.\, S_v \,.\left(T_{pe} - T_p\right) \qquad (15)$$

Where:
p: polystyrene, b:brick, e: exterior, i: interior, f: product, ach: heated air
S_v represents surface of one chamber dryer wall calculated in m^2.
Pev is a function of the drying kinetic.

3. Results and discussions

Generally, during drying and in particular during food drying, many parameters are neglected such as shrinkage phenomenon that takes place during the process. In our simulation we have taken into consideration this, by effectuating a repetitive calculus of the physical characteristics changes of the product in time and space.

As it is mentionned before, the study is applied for Constantine region during the representative day of July period which is the 15th of July. The collector is inclined with an optimum angle of 10 degrees and directed to the south. Also, the previous study of the collector [12] has given an optimum $3m^2$ as optimum surface. In this way, all the following results are presented according to these optimum factors.

The ambient temperatures are given by the metheorological service of the region. It varies from 25 ºC at 5 a.m to 28.6 ºC at 9 p.m and passes by a maximum of 39 ºC between 11 a.m and 1 p.m, as it is shown in Fig. 5. It shows also the quantity of radiation absorbed by the glass. It attains a maximum of 132 W/m^2 between 11 a.m and 1 p.m, leading to the reduction of the quantity captivated by the absorbed. Regarding the flux obtained by the absorber, it has the same form as the global radiations, presented in Fig. 2 and reach a maximum of 715 W/m^2 during the same lap of times mentionned before. A special attention is given to the representation of the temperature of exit from the solar collector where two parts are distinghished. The first part is before 8 a.m, we can see the temperature of the exit of the collector is still near the ambient one in despite of the radiations received approximating a flux of 500 W/m^2. It is deduced that the received energy is used to warm the solar air collector and the air is not heated before this time. The tempearture reached at 8 a.m is 35 ºC. The second studied part is after 8 a.m, the form of the temperature is the same as the received energy by the absorber and the ambient temperature. It increases with the increase of these two parameters and decreases with their decrease. Therefore, the maximum of the temperature is reached around 2 p.m, while the maximum of the radiations is attained around 12 a.m. In the same case, we can observe that there is no received energy at 7 p.m, however the temperature of the heated air is still important. We can deduce that the studied system is presenting a time of reaction and inertia to the variable conditions of heating of around 1 hour. Similar observation can be found in other research works [12, 15-17].

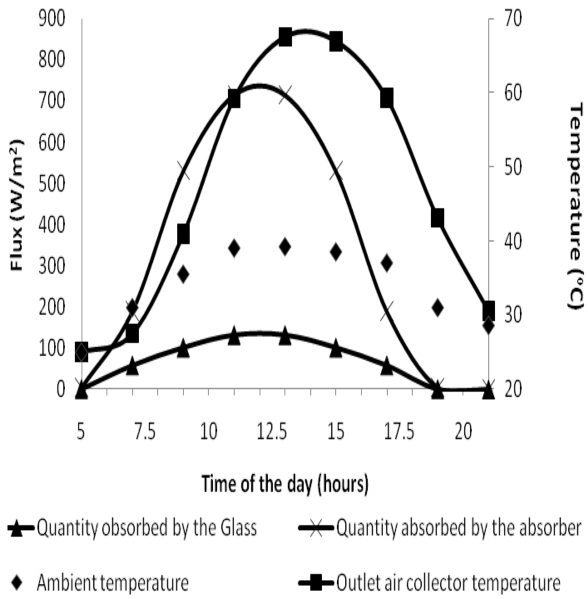

Fig. 5 Some results given by the inclined solar collector

The surface of the collector is an important parameter. It is used for the calculation of the cost of the collector and then for its payback. It was found that for the condition of 0.5 m/s for the ambient air velocity, increasing the surface of the collector leads to the increse of the tempearature of the absorber, as it is shown in Fig. 6. However and for constant condition of $3m^2$ collector surface, the effect of the air velocity has an inverse effect, which means that the increse of the ambient air velocity leads to the decreases of the temperature of the absorber. In many studies, the additition of grooves were a solution to increase the time of stay of the heated air inside the collector and then it permits to exchange more energy [18-19]. However it is clear that this idea will increase the price of the collector. Of course, the temperature of the absorber has a direct effect on the temperature of the heated air. These obtained results are in confirmation with others [13].

The agroalimentary simulated product is onion and it was chosen because of its swift deterioration caused be the important quantities of water contained in the product.

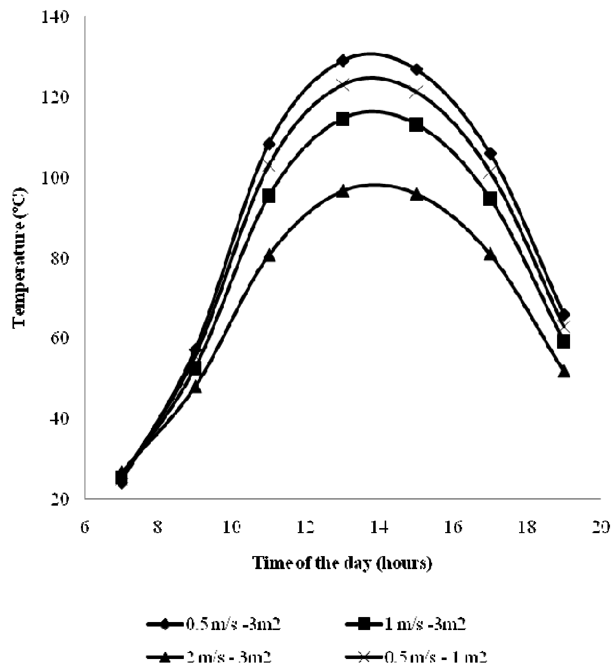

Fig. 6 Influence of the ambient air velocity and surface of the collector on the outlet temperature of the absorber

Drying process, for the different trays, is happening with a non-homogeneous manner as it is presented in Fig. 7. In this fact, first trays profit of the obtained heated more than last ones. The air acumulates the evaporated water from the products. This will decrease the evaporative power of the heated air leading to an increase of the moisture content of the product for the last layers, as it is shown in the figure. Also, it shows that 3 m^2 collector surface was sufficient to attain, in one day, the equilibrium moisture content contrary to 1 m^2 collector surface.

Fig. 8 shows the variation of the heated air humidity and its tempearure during its cross of the multiple trays of the drying chamber for a constant time t = 60 minutes. Also, these results are registered during drying in unfavorable conditions, when the heater is used for all the process time. Drying is perfomed with constant temperature of 50 ºC.

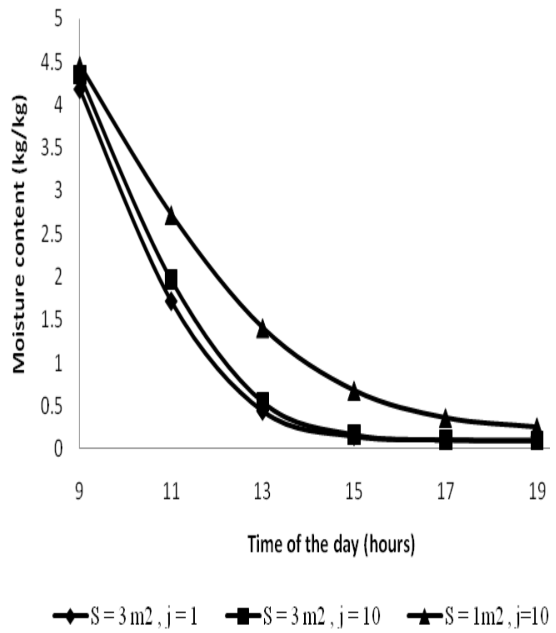

Fig. 7 Variation of the moisture content during solar drying of onion. S: the surface of the collector, j: the number of the tray.

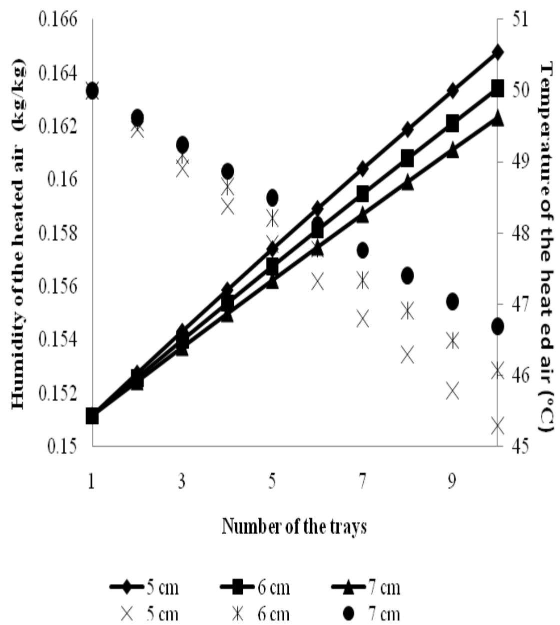

Fig. 8 Variation of the heated air humidity and its temperature during drying and influence of the product diameter. The humidity is represented by the continious lines and the temperature by points.

The obtained results confirm the acquisition and accumulation of humidity of the product by the heated air. The humidity of this last increases from 0.15 kg/kg for the first layer to more than 0.164 kg/kg for the last tray. Hovewer, it has an inverse influence on the temperature of the heated air which decreases from 50 ºC to around 45 ºC, as it is shown in the figure. In consequence the evaporative power of the air will also decrease. This difference will disappear with time as the quantity of water existing in the product decrease. In addition, the figure shows that increasing the diameter of the product will increase the drying time as we will have more matter to dry. This result is in agreement with others [12, 20-21].

The observation of more results, such as the temperature of the product should give better understand of its behavior during the process. As shown in figure 9, the product temperature profile is divided essentially into two periods. For the first period, the heated air serves fundamentally to the evaporation of the surface water from the products and we can have the decrease of the product humidity without an important change in the temperature of the dried product. However, for the second part, the heated air serves to the evaporation of the interior water of the product but also to the increse of its temperature until reaching the temperature of the heated air.

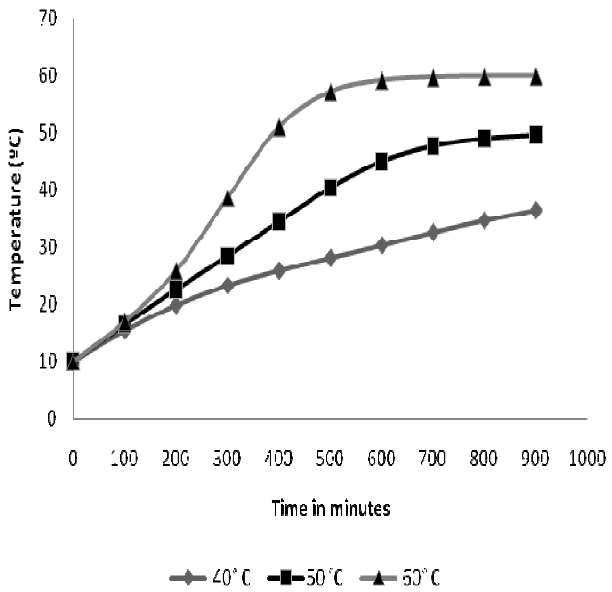

Fig.9 Variation of the product temperature for air heated at different temperatures.

The figure confirms that heated air temperature is an influent parameter as found by others [11-12].

4. Conclusion

Our study has shown that by exploiting the solar irradiation of Constantine we can develop an efficient drying system for foods. In this way, the study of a simple collector made with glass, aluminum and polystyrene can give excellent results with an outlet air temperature exceeding the 60ºC, with an optimum surface of 3m^2, inclined with 10 degrees and directed to the south.. However, it was found that the received energy has two roles; for first times the received energy serves to warm the collector and serves, after that, to heat the air. Also, the results have shown that coupling the collector with a drying chamber, made with just bricks and polystyrene supporting ten trays can be profitable to the user. The addition of a heater that can be utilized in unfavorable conditions like in winter or in the night allows the use of the dryer.

For an optimum use of the dryer, it is important to know and to take in consideration the influent parameters; in our case we have found that ambient air characteristics, surface of the collector, dimensions of the product are influent parameters.

As the materials used for the construction of the solar dryer are available and inexpensive, the payback will present a swift investment return. The use of photovoltaic cells for the function of the fan and a photovoltaic battery for the heater with charges regulator to store the surplus energy can be recommended. In one hand, they will give total independence regarding electrical energy. On the other hand, they will increase the time of the feedback

More agricultural products should be studied in different seasons and conditions.

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