Performance of a Natural Convection Conical Solar Dryer: An Experimental Approach

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Abstract: **A prototype of a natural convection conical solar dryer was designed, fabricated and tested at mechanical engineering department at Suez Canal University, Egypt for drying products. The conical solar dryer consists of a conical collector and a drying chamber. Another common natural convection box-type solar dryer was built and tested to compare with the conical one. The traditional sun drying experiments was employed and compared with the two solar-drying units. The conical solar dryer performance was evaluated with cone height to diameter ratio of unity. The experiments of the tested solar dryers were conducted during the month of June 2019. The experimental measurements such as drying air temperatures, moisture content and system drying efficiency were recorded during the working days. Grapes were used as a drying material with an initial weight of 2 kg divided into the four trays. It was found that, the natural convection conical solar dryer reduced the drying time and has a better performance compared with the box-type solar dryer. Also the maximum recorded drying system efficiency was 30% and 44% for box-type solar dryer and conical solar dryer respectively. The daily drying efficiency for box-type and conical solar dryer were 24.3%, 12.87% and 9.93% for the box-type solar dryer for days of 10, 11 and 12/6/2019 respectively and the corresponding values for conical solar dryer were 37.4%, 33.65% and 20.8% respectively. Finally at grapes moisture content of 10% dry basis the drying time was reduced to 23.4% and 45.3% compared with the open sun drying for box-type and conical solar dryer respectively**

Keywords: **Conical; solar dryer; moisture content; system drying efficiency.**

I. INTRODUCTION

Drying is one of the most important applications of solar energy. It is the oldest processes used for drying of agricultural products applied by people especially in the open sun drying mode. In this mode, the product absorb the solar radiation and the generating heat in the interior surface of the product [1]. All products are spread into a thin layer and directly exposed to the sun radiation. The open sun drying mode is the cheapest technology applied in over the world. There is a risk of deterioration due to insect infection, dust and the direct exposure to sun radiation will cause color deterioration [2, 3]. In addition, there is scope for contamination of the dried grapes and it needs a drying time of 20 days and 8-10 days for natural and pretreated grapes respectively [4]. Another improved solar box-drying method was used and loaded with products to be dried in different counters [5]. This method is also cheap and the grapes bunches are spread over trays and has a good quality and protected from dust and insects [6]. In this solar dryer, it requires about 3-4 days for drying 10 kg of grapes [7]. An alternative to the previous methods is the artificial drying process. In this methods, various types of solar dryer are used for drying different products [8]. Many agriculture products such as potatoes and grapes have a surface cracking due to direct solar radiation [9]. So these agriculture products should be dried in indirect solar dryers which mainly consists of solar drying chamber and solar air heater [10]. Solar dryers have been designed, developed and used for drying agricultural products in order to improve the products shelf life [11]. Koyuncu [12] tested the behavior of various designs of low temperature flat plate solar collectors for drying many different products. The results concluded that 1 kg of untreated grapes needs 72 hr to reach 18% (d.b.) moisture content. Most projects of this nature have not been taken by the farmers, because of the unsuitable final design or the expensive costs. Therefore, most researches efforts were directed towards drying devices with small natural convection sizes. However, the use of solar energy technologies is strongly suggested for drying agricultural products to reduce the energy costs. In many countries, the energy used in drying is about 7–15 % of the nation's industrial energy, this is due to the relatively low thermal efficiencies which ranging from 25% to 50% [13]. El-Shiatry et al. [14] dried different products like, tomato, onion, okra and grapes by using solar energy. The results showed that the drying time reduced with a higher product quality. Taylor and Weir [15] designed and fabricated a forced circulation cabinet solar dryer. In their solar dryer, the products exposed directly to the solar radiation and the product acts as an absorber itself. Fadhel et al. [2] studied three different processes for drying grapes. They used natural convection solar dryer, open sun drying mode and solar greenhouse drying. The results concluded that, the solar greenhouse drying is competitive to the natural convection solar drying mode.

Raman et al. [16] reviewed many different types of solar drying technologies. They reviewed many agricultural products like, rice, cocoa beans, tea, tobacco, nuts and coffee. They concluded that the solar crop drying is a good method and it dries the agricultural products with more efficiency. El-Sebaii and Shalaby [17] studied the performance of the indirect-mode type forced convection solar dryer in Tanta city for drying mint and thymus. In addition they tested a fourteen mathematical models to specify the suitable one which describe the drying characteristics of these products. They concluded that, Midilli and Kucuk model is the suitable model to describe the drying characteristics of mint. But in case of thymus drying it was found that Page and modified Page models is the best one. Gulcimen et al. [18] used solar air collectors to study the drying characteristics of sweet basil. The results showed that the total sweet basil mass decreased from 0.25 kg to 0.029 kg and solar collector efficiency increased and varied between 29 and 63%. Kabeel and Abdelgaied [19] studied the performance of an indirect solar dryer integrated with HDH desalination system. The results showed that the gain output ratio of their system improved by an average value of 29% compared with the HDH desalination system. Perwez and Kumar [20] studied the performance of the simple plate solar air heater with a mass flow rate varied from 0.009 kg/s to 0.028 kg/s. The results concluded that the outlet temperature maximum rise is about 4.6 °C and the thermal efficiency reached to 35.50%. Khanlari et al. [21] studied the performance enhancement method of the greenhouse solar dryer. It is clear from their results that the average thermal efficiency reached to 56.8% and this new design reduced drying time by30%. In the present work, a natural convection conical solar dryer was designed, fabricated and tested for drying grapes. This solar dryer prototype is not properly investigated or tested by the researchers. Many experimental tests are used to investigate the performance of the conical solar dryer system. On the other hand, these data are used to determine the drying characteristics of grapes taking into account the drying treatment modes. The drying results obtained were compared with the results of the box-type and naturally with products put in a direct open sun drying mode.

II. MATERIALS AND METHODS

2.1 Experimental Setup

The solar dryers were designed, fabricated and the experimental tests performed at faculty of Engineering, Suez Canal University, Egypt. The dryers were constructed with materials that were readily available in the local area. The performance of dryers was evaluated at the month of June 2019. Grapes which used as a drying material were obtained from the public market and cleaned well from dirt. Samples of equal weight and approximately equal in diameter were used. The samples were spread on the drying trays and placed inside the solar dryers. Each test run started at 8:00 A.M. and continued until 5:00 P.M. The initial weight of samples in each drying unit was 2 kg. The samples were distributed in the form of a thin layer to receive the same required amount of solar radiation. Two geometers of solar dryers were tested in natural convection mode namely box-type and conical solar dryers. The conical solar dryers has a ratio of cone height to dryer diameter of unity. The results of naturally drying process with products put in a direct open sun were also obtained and compared.

2.1.1 Box-Type Solar Dryer

The box-type solar dryer has a shape like the home cabinet with slope angle of 30º for the transparent tilted top. The box-type solar dryer has many holes at the bottom and upper surface sides for ventilation. The outlet holes are placed at a higher level of the box. The air movement through the holes brings a thermo-syphon effect which generates an updraft of solar heated air for the drying chamber. Grapes are cleaned and spread on wooden trays that having a wire mesh at the dryer bottom and exposed to solar radiation. Fig. 1-a presents a schematic diagram of the box-type solar dryer with a transparent cover. The frame of the box-type dryer is made of wood sheets. An insulated layer of 5 cm thickness made also of wood was used to reduce the loss of heat through the dryer to the outlet. The solar dryer sides and bottom are painted black to absorb the transmitted solar radiation through the transparent cover. Seven calibrated k-type thermocouples were used for measuring the products surface, drying air, inlet and outlet temperatures. Fig. 2-a shows a photograph of the box-type solar dryer.

2.1.2 Conical Solar Dryer

Fig. 1-b shows a schematic diagram of the conical solar dryer new type which has a single covered conical collector shape combined with a bed dryer. The heated air acquired by the transparent cover is made of plastic which transparent the solar radiation and limits the heat loss. The main body of the dryer is made of wooden board with additional insulated layers made also of wood to reduce the loss of solar heat. All sides and bottom of the conical dryers are painted black internally to absorb the solar radiation transmitted through the transparent cover. Air inlet holes are provided at the bottom of the bed dryer and an air exit port from chimney provided on the top cone section area of the dryer. Grapes are spread on the four trays, which have wire mesh at the dryer top bed and exposed directly to solar radiation. The upper chimney is used to pass the warm moist air by the natural draught creating a partial vacuum and drawing the fresh air through the base holes which provided at the dryer bottom. Ambient air enters the dryer through the bottom holes and passes through the grapes spread on the wire mesh with a high temperature coming from the solar radiation through the transparent.

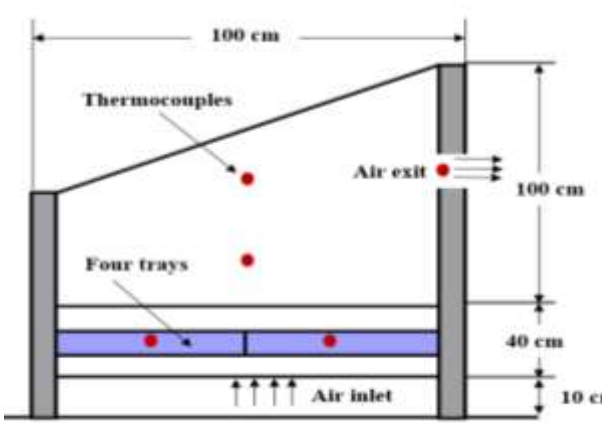
In this work two models of solar dryers were designed and fabricated with the same area. The conical solar dryer has a height to diameter ratio of unity and the box type solar dryer area is equal to 1 m^2. The same weights of samples were maintained simultaneously inside the two dryers. The measurements were performed and recorded at the same time under the same climate conditions. The drying chamber contains four drying racks with an equal area. The design parameters of the conical solar dryer with height to diameter ratio of unity (L/D=1.0) are shown in Table 1. Fig. 2-b shows a photograph of the conical solar dryer.

2.2 Measurements and Instrumentation

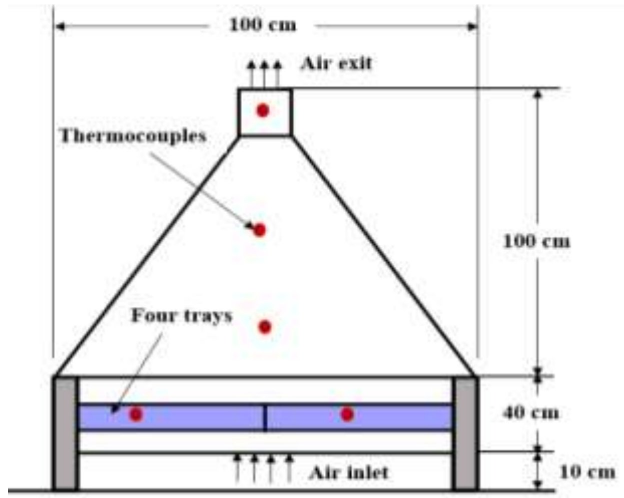
The measuring instruments can be divided into weather station, weights and temperatures devices. During each test, the products were weighted periodically using an electronic balance of $\pm$0.01 gm sensitivity by removing them from the unit for approximately 20 seconds. Thermocouples (type-k) were used to measure the drying air temperatures inside the dryers. The thermocouples were fixed inside the box- type and conical solar dryer at four different positions distributed at equally spacing inside the midline and at the four trays. For each dryer, another two thermocouples were used to measure the air temperature at the inlet and exit of the dryer. Another thermocouple was also used for measuring the surface temperature of the grapes surface as shown in Fig. 1. The weather characteristics such as solar radiation intensity, wind speed and the air dry bulb temperature were measured by solar watt meter, anemometer and mercury thermometers respectively. Solar power meter was used to measure the intensity of solar radiation. The mercury thermometers with an accuracy of $\pm$0.5 °C was used to measure the ambient dry air temperature. Fig. 3 shows a photograph of the digital balance, k-type thermocouples, solar power meter and the wind speed meter used in the experiment setup.

Table 1: The design parameters of conical solar dryer with L/D =1.0

No.	General properities	Value
1	Location,	30° 35' North, 32° 16' East
2	Drying area,	1.0 m^2
3	Dryer maximum diameter,	1.0 m
4	Dryer height,	1.0 m
5	Chimney material,	Galvanized iron sheet
6	Chimney height,	0.30 m
7	Chimney diameter,	0.20 m
8	Insulation material,	Wood and foam
9	Thickness of insulation,	0.05 m
10	Thickness of plastic sheet,	0.001 m



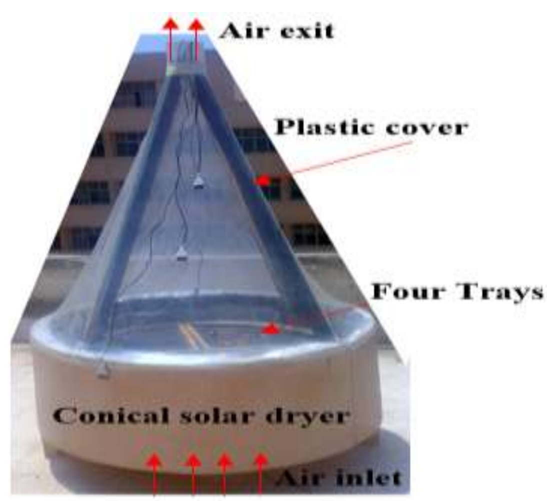
(a) Box-type solar dryer



(b) Conical solar dryer

Fig. (1): The schematic diagram of the box-type and conical solar dryer.

(a) Box-type solar dryer



(b) Conical solar dryer

Fig. (2): Photograph of the box-type and conical solar dryer.

(a) Digital balance

(b) k-type thermocouples

(a) Solar power meter

(b) Wind speed meter

Fig. 3. Photograph of the digital balance, k-type thermocouples, solar power meter and the wind speed meter used in the experiment setup.

2.3 Mathematical Modeling of Drying Process

Several models are performed to explain the drying process mechanisms, the drying characteristics of the different agricultural products and evaluate the solar dryer's performance. In this section the product moisture content, drying system efficiency and the daily drying efficiencies will be discussed.

2.3.1 Product moisture content

The dry basis moisture content M_d (% d.b.) can be defined as the present product weight moisture per unit product weight of the dry matter and can be expressed by the following equation [9]:

$$M_d = (m - m_d) / m_d \quad (1)$$

Where m and m_d are the instantaneous and the fully dried weight respectively.

The product instantaneous moisture content is calculated as follows [8]:

$$M_d = [(M_o + 1)\ m_t / m] - 1 \quad (2)$$

2.3.2 Drying system efficiency

The drying system efficiency is defined as the ratio between the required energy to evaporate the moisture to the supplied energy into the solar dryer. The drying system efficiency can be calculated from the following mathematical formula [22]:

$$\eta_s = m_v \times h_{fg} \,/\, I \times A \times t \qquad (3)$$

Where m_v is the mass of moisture evaporated, h_{fg} is the latent heat of vaporization of moisture (kJ/kg), ($I \times A \times t$) is the input solar energy into the dryer (J); A is the dryer area (m^2), t is the time in seconds (s),

2.3.3 Daily drying efficiency

The daily drying efficiency is the arithmetic average values of the instantaneous drying efficiencies, and it can be calculated from the following equation.

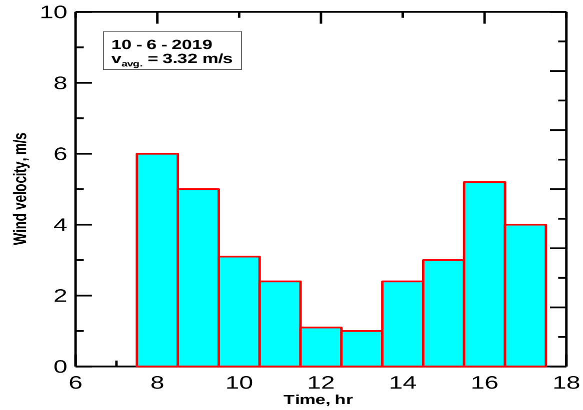
$$\eta_d = \frac{1}{n}\sum_{i=1}^{i=n} \eta_s \qquad (4)$$

Where n is the number of interval.

III. RESULTS AND DISCUSSIONS

Measurements were performed during the month of June for ten days and a three days were selected according to the weather conditions. The selected three days were in summer season (10, 11 and 12/ 6/2019) to study the behavior of the conical solar dryer. During these experimental days, the variations of the solar radiation, ambient and wind velocity with time are shown in Figs. 4 and 5 for three drying days of June 2019. Fig. 4 shows the variations of wind velocity during the corresponding working days with day time. This figure also shows the average wind velocity during these days. From this figure it can be noticed that, the average wind velocity ranged from 2.5 m/s (11/6/2019) to 3.32 m/s (10/6/2019). Fig. 5 presents the variations of the global solar radiation and ambient temperature during the working days with day time. From this figure it can be seen that, the global solar radiation increased during the day hours after sunrise and reached a maximum value at noon time, after that it starts to decrease again. Any solar radiation fluctuations, was due to the instability of the weather conditions during the day. The maximum values of the global solar radiation for June are 990, 995 and 1050 W/m^2 for 10, 11 and 12/6/2019 respectively.

Fig. 6 presents the variations of the grapes surface and drying air temperatures for box-type and conical solar dryer during the three working days with time. The drying air temperatures in solar dryers changed from morning to evening. This was observed that, the grapes surface temperature in the drying units was higher than ambient temperatures, whereas it was lower than the drying air temperature. Also, it is clear that the grapes surface temperature and the drying air temperature for conical solar dryer are greater than the box-type solar dryer. This indicates that the drying rate in the conical solar drying unit is higher than the box-type and the open sun drying mode. Increasing the temperature of air gives it more evaporative power to reduce the total drying time for grapes. In addition there was a significant difference between the drying air and ambient temperatures as well as between grapes surface and ambient temperatures, which is quite sufficient to dry any agricultural products.



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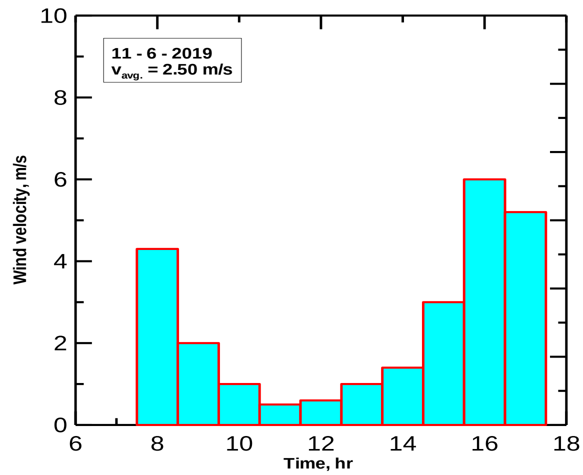

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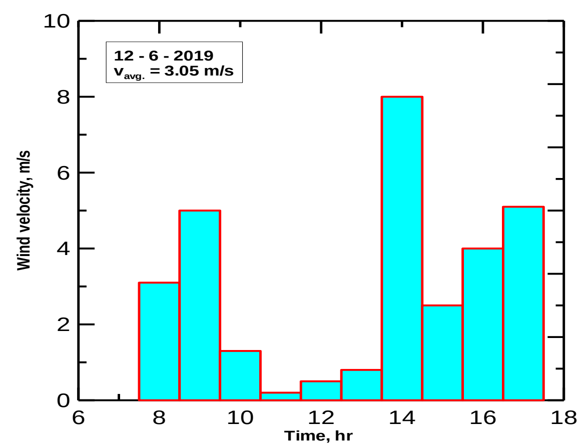

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Fig. 4. The corresponding variations of wind velocity for the same working days showing the average velocity

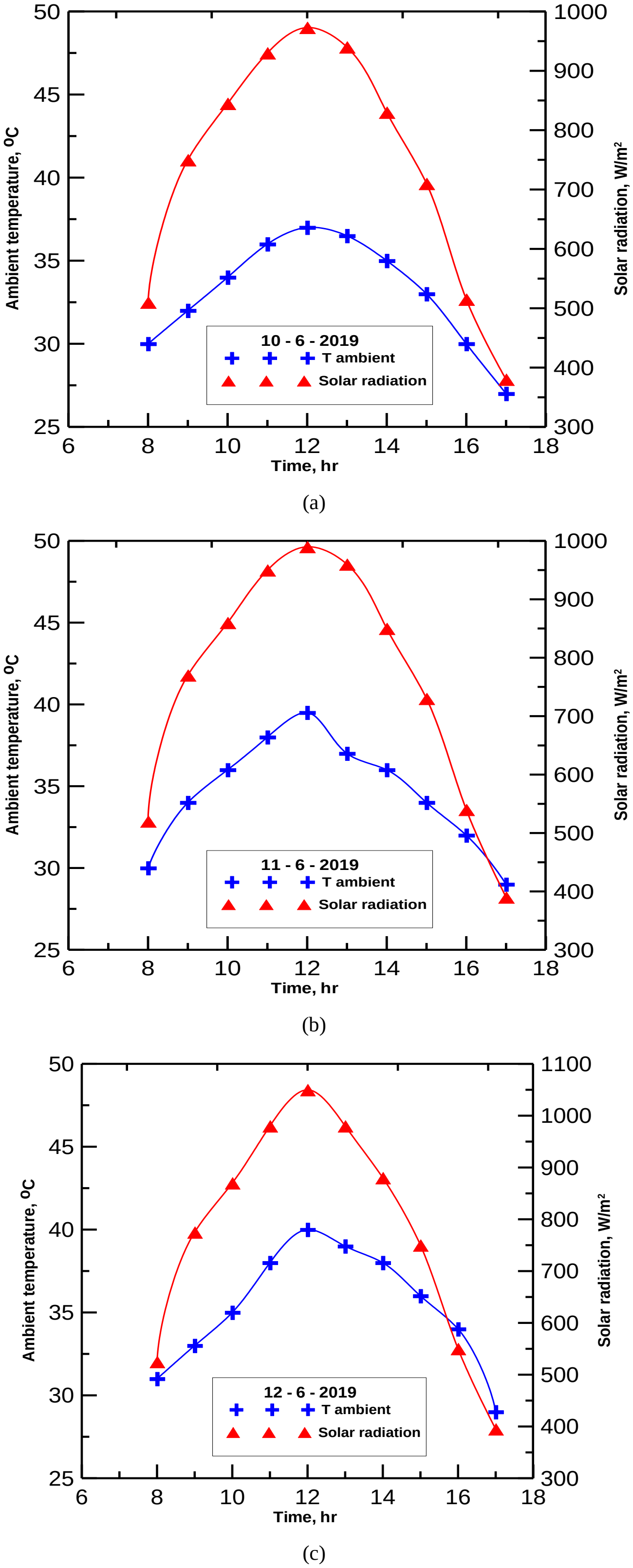


Fig. 5. The hourly variations of solar radiation and measured dry bulb temperatures during the three working days.

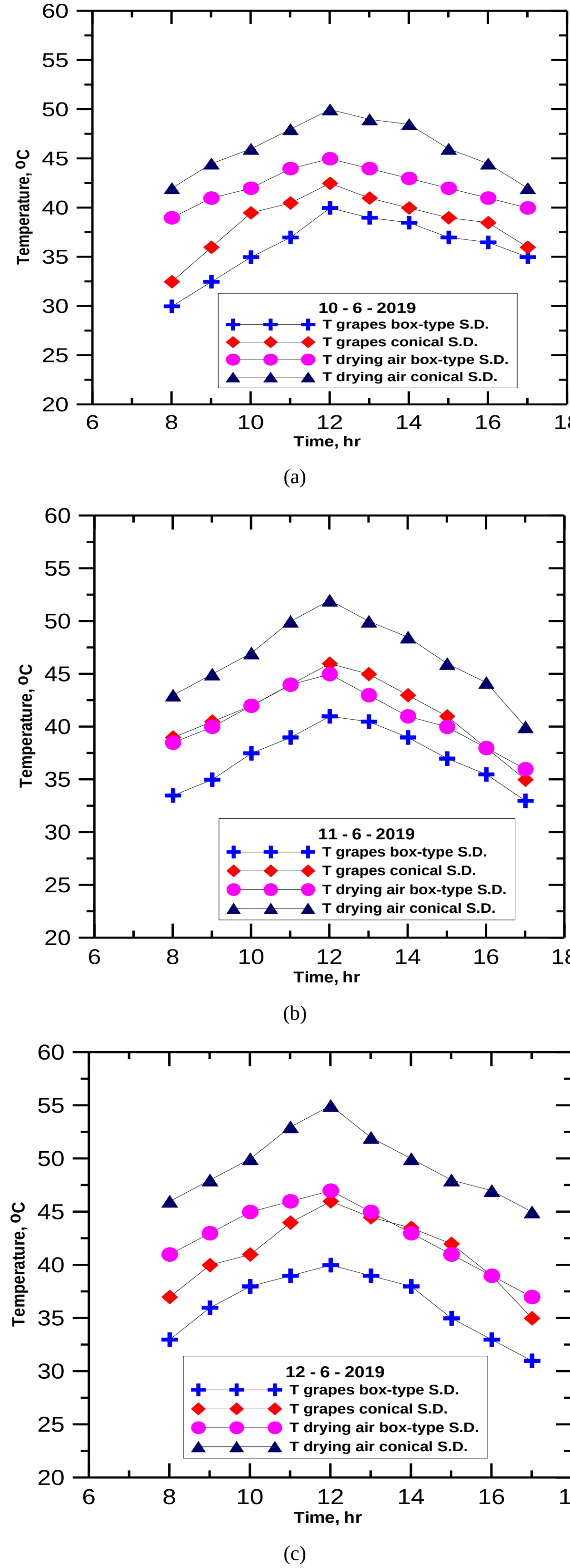


Fig. 6. Hourly variations of grapes surface and drying air temperature for box-type and conical solar dryer during the three working days.

Fig. 7 shows the moisture content variation with drying time in box-type, open sun drying and conical solar dryer. As shown in this figure, the grapes has an initial moisture content of 625% (d.b.) and the natural convection conical solar dryer has a shorter drying time compared to the box-type solar dryer. Depending on the mode of drying, the conical solar dryer developed shorter moisture content during the three days of the drying time. The decrease in the drying time occurred due to the values of high drying air temperature and low relative humidity obtained in the solar dryer. On the other hand, due to the moisture diffusion process, the drying rate decreases with time. Similar results for grapes have been obtained and reported by Fadhel [2].

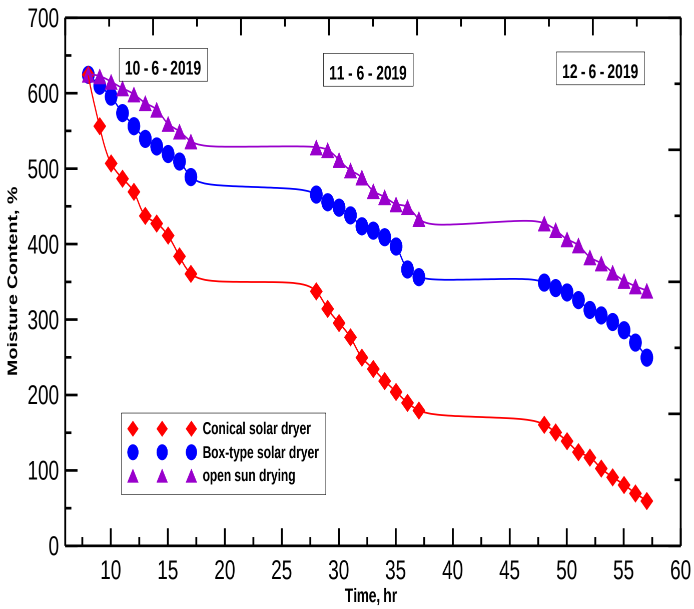
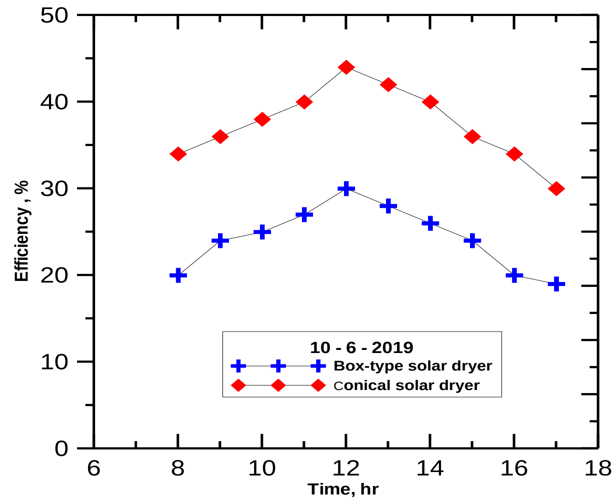


Fig. 7. Moisture content variation with the drying time for box-type, open sun drying and conical solar dryer

Fig. 8 shows the variation of the drying system efficiency with the drying time for box-type and conical solar dryer for grapes. It can be seen that the drying system efficiency increases significantly with time to reach the maximum value at the mid-day and it begins to decrease at the day end. This is occurs due to the presence of moisture content on the product surface. Also it can be noticed that the drying system efficiency at the first drying day is greater than the second day and the third day. However, the drying system efficiency decreased continuously at the second and third day because the grapes moisture content is also reduced and more energy power s required to drive out the same amount of moisture from the grapes. Similar results were reported by Boughali et al. [23]. The maximum recorded drying system efficiency was 30% and 44% for box-type solar dryer and conical solar dryer respectively depending on the drying air temperature and drying mode.



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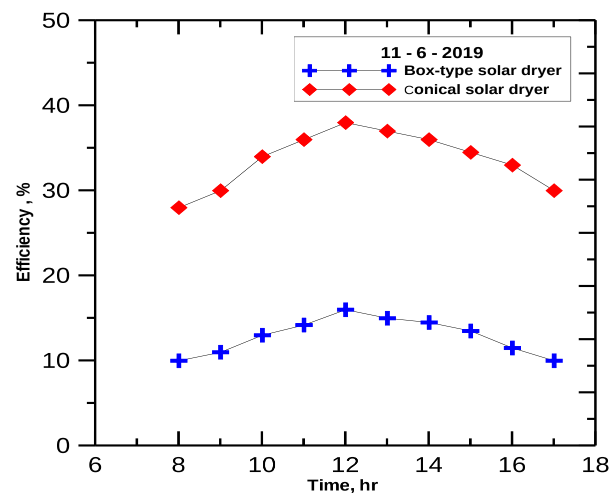

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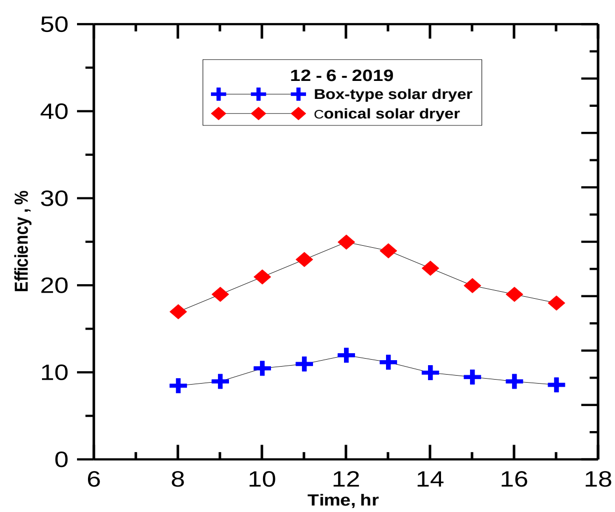
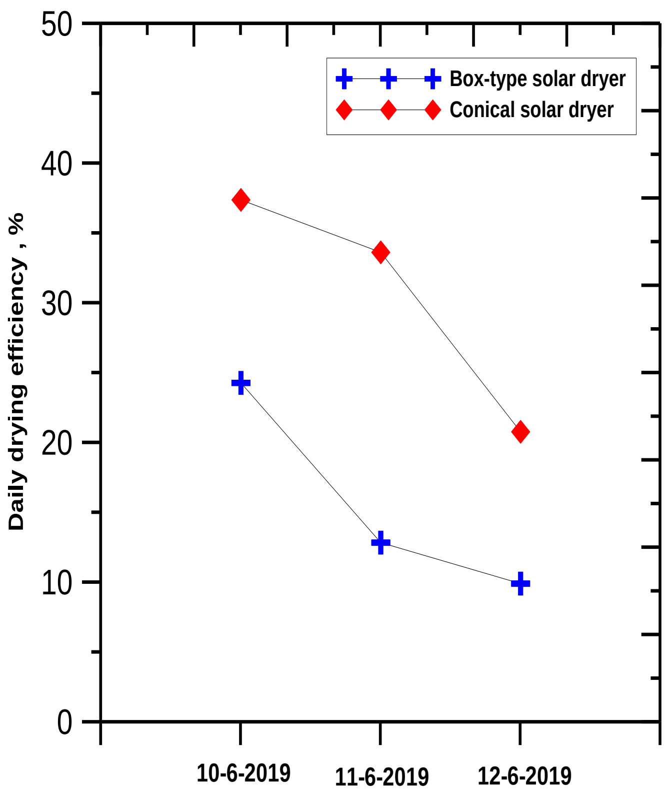


(c)

Fig. 8. Variation of the drying system efficiency with the drying time for box-type and conical solar dryer

The variation of daily drying efficiency during the three days for box-type and conical solar dryer for grapes is shown in Fig. 9. The daily dryer efficiency of the solar dryers decrease significantly with the drying time. The reason that makes the daily drying efficiency very low during the second and third drying days is the very low value of grapes moisture content and this means that the most captured energy was dissipated without any drying effect. The daily drying efficiency for box-type and conical solar dryer were 24.3%, 12.87% and 9.93% for the box-type solar dryer for days of 10, 11 and 12/6/2019 respectively and the corresponding values for conical solar dryer were 37.4%, 33.65% and 20.8% respectively. The maximum increasing in daily dryer efficiency compared to open sun drying-mode was 37.78% and 59.57% for the box-type and conical solar dryer respectively. The system efficiency also depends on the weather conditions of dryer, products to be dried and final moisture content. Bena and Fuller [24] report efficiency values of 22%, for a direct type solar dryer operated in the solar free-convection operation mode. Consequently, the performance of the present solar dryer is satisfactory. Table 2 shows the drying system and daily dryer efficiencies as well as the percentage increase in their efficiencies compared to open sun drying mode. The results of the present study indicates that the conical solar dryer is capable of drying grapes as well as agricultural products effectively.



.Fig. 9. Variation of daily drying efficiency with drying day for box-type and conical solar dryer

Table 2: Minimum and maximum values of the drying system and daily dryer efficiencies as well as the percentage increase in efficiencies compared to the open sun drying mode.

Parameter	Open sun drying mode		Box-type solar dryer		Conical solar dryer	
	Min.	Max.	Min.	Max.	Min.	Max.
Drying System efficiency, %	7.1	22.0	8.5	33.0	17.00	44.0
Daily Dryer efficiency, %	5.5	15.12	9.93	24.3	20.8	37.4
Increasing in drying system efficiency compared to sun drying-mode, %	-	-	16.47	33.33	58.24	50.0
Increasing in daily dryer efficiency compared to sun drying-mode, %	-	-	44.61	37.78	73.56.	59.57

In order to ensure safe storage for the grapes, the acceptable quality of grapes is ranged between 13% and 18% moisture content dry basis [3, 8], while the commercial norm moisture content is evaluated by 16% (d.b.) [25]. So in this work, the drying process was continued until the moisture content reduced to final safe storage level of about 8% d.b, On the other hand, in order to compare between the tested two solar dryers we used a reference moisture content value of 10% dry basis. As shown in Fig. 7 the grapes initial moisture content of 625% (d.b.) was dried to the reference moisture content value of 10% dry basis. During the experiments, the time required to reach the moisture content of 10% (d.b.) for conical solar dryers were found to be 35 hr, while the drying time required for box-type and open sun drying mode were 49 and 64 hr respectively. Table 3 presents the drying characteristics for grapes in two tested solar dryers and in open sun drying mode as well as the reduction in drying time compared to sun drying-mode. From this table it is clear that conical solar dryer has a shorter drying time compared to other drying modes and the drying time was reduced to 23.4% and 45.3% compared to open sun drying for box-type and conical solar dryer respectively. Similar results have been reported by Fadhel [2] for grapes, and Bala, [26] for pineapple.

Table 3: Drying characteristics for grapes tested in solar dryers and open sun drying mode.

Drying mode	Initial moisture content, %	Final moisture content, %	Drying time, hr	Reduction in drying time compared with the open sun drying-mode,%
Box -type	625	10	49	23.4
Conical solar dryer			35	45.3
Open sun drying			64	-

IV. CONCLUSIONS

Drying is one of the most important applications of solar energy and it is the oldest processes used for drying agricultural products. In this study two solar dryers were designed and fabricated in Egypt. The first one is known as the box-type solar dryer and the second one is the conical solar dryer with cone height to diameter ratio of unity. The climate conditions was measured and recorded during the working days such as the global solar radiation, wind velocity and the ambient temperature. The results were compared with the box-type solar dryer and the open sun drying. The results showed that the conical solar drying presents a faster drying process and no addition running cost as that of mechanical dryer and the conical solar dryer was found satisfactory for drying grapes and various kinds of products. In addition it achieves higher drying rates compared to box-type and open-sun drying mode. Moreover, it gives both higher drying air temperatures and system drying efficiencies. The maximum recorded drying system efficiency was 30% and 44% for box-type solar dryer and conical solar dryer respectively. The daily drying efficiency for box-type and conical solar dryer were 24.3%, 12.87% and 9.93% for the box-type solar dryer for days of 10, 11 and 12/6/2019 respectively and the corresponding values for conical solar dryer were 37.4%, 33.65% and 20.8% respectively. The maximum increasing in daily dryer efficiency compared to open sun drying-mode was 37.78% and 59.57% for the box-type and conical solar dryer respectively. Finally at grapes moisture content of 10% dry basis the drying time was reduced to 23.4% and 45.3% compared to open sun drying for box-type and conical solar dryer respectively.

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