A NATURAL CONVECTION SOLAR DRYER FOR ROUGH RICE

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ABSTRACT

A solar drying system was constructed and tested to dry rough rice grains for seeding under Zagazig city prevailing weather conditions. The system consists of two integrated units, a solar collector with total area of 1.8 m^2 attached to a drying chamber. The system is classified as a natural convection indirect passive cabinet type without any moving parts. The study parameters included varying the air inlet area from 244 to 732 cm^2, testing three levels of initial moisture contents (20, 22, and 25% w.b.), and two different grain layer thicknesses of 5 and 10 cm. The system was operated from 8 AM to 5 PM under Zagazig local conditions (Latitude 30.5° N) for 2 weeks during the rice harvesting season of 2009. The results showed that the smallest air inlet area of 244 cm^2 gave the highest collector thermal efficiency, the highest temperature difference between ambient air and heated air inside the collector, and highest drying rate. Also the initial moisture content of 20% w.b. gave the highest drying rate and fastest drying time. Same results were found using layer thickness of 5 cm. So the combination of 244 cm^2 air inlet area, 5 cm layer thickness, and 20% initial moisture content is recommended for the best thermal performance and highest drying rate.

Keywords: solar energy, indirect passive cabinet, rough rice, natural convection, drying rate, thermal efficiency.

INTRODUCTION

Rice is the second largest produced cereal crop in the world. The crop can be harvested after reaching physiological maturity at moisture content of 20-25%, and then artificially or naturally dried to the storing moisture content without significant loss of quality. By doing this, the scarce agricultural land can be cleared 2-3 weeks ahead of time to be prepared for the consecutive crop. In Egypt, rice is

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dried naturally in farms. After harvesting, the crop is bundled and left in farm to be dried naturally before threshing. This process keeps the farm occupied for the drying period. Furthermore, the crop is lost by rodents, insects, grazing animals, and fungal infestation. Also crop can be destroyed by an unexpected rain during harvesting season. From this point, assisted drying is necessary for rice to maintain quality and minimize losses. Solar drying can be considered as an elaboration of sun drying and is an efficient system of utilizing solar energy. Solar drying systems may be classified into direct, indirect, and mixed modes. In direct solar dryers the air heater contains the product and solar energy passes through a transparent cover and is absorbed by the product. Essentially, the heat required for drying is provided by radiation to the upper layers and then conducted to the product bed. In indirect drying system, solar energy is collected in separate equipment, called solar air heater, and the heated air then passes through the product bed. In the mixed mode type of drying system, the heated air from a separate solar air heater is passed through a drying bed, and at the same time, the top surface of the bed absorbs solar energy directly through a transparent cover. The product is dried simultaneously by both radiation with downward conduction of heat and the convection of a heat from the solar air heater (**Simate, 2001**). **Zaman and Ball (1989)** reported the results of thin layer drying of rough rice in open floor, cabinet type and mixed mode dryers. The mixed mode type was found to be superior to either open floor or cabinet type dryers. On the other hand solar dryers can be further classified into two basic categories namely: natural convection (passive) and forced convection (active) dryers. The natural operation principle is based on the temperature difference and consequently the difference in the density of the air inside and outside the drying chamber. This difference provides driving force (buoyant force) for the air to flow through the drying bed. Passive drying systems do not require any mechanical or electrical power to run a fan. In general, the construction is simple, easy to maintain and inexpensive but working mechanisms is strongly dependent on the temperature difference and pressure drop across the product bed (**Miramare, 1997**).The objective of most drying processes is to reduce the moisture content of the product to a specified value. Moisture content (wet basis) is expressed as the weight of water as a proportion of total weight. The moisture content of rice has typically to be reduced from 24% to 14%. So to dry one ton of rice, 100 kg of water must be removed. If the heated air has an "absorption capacity" of 8 g/m^3 then 100/0.008 = 12,500/m^3 of air are required to dry one ton of rice. The heat required to evaporate water is 2.26 kJ/kg. Hence, approximately 250 MJ (70 kWh) of energy are required to vaporize the 100 kg water. There is no fixed requirement for solar heat input to the drier. This is because the incoming ambient air can give up some of its internal energy to vaporize the water (becoming colder in the process). Indeed, if the ambient air is dry enough, no heat input is essential (**Green and Schwarz, 2001**).Nevertheless, extra heat is useful for two reasons. First, if the air is warmer then less of it is needed. Second, the temperature in the rice grains themselves may be an important factor, especially in the later stages of drying, when moisture has to be "drawn" from the centers of the grains to their surfaces. This temperature will itself depend mainly on the air temperature but also on the amount of solar radiation received directly by the rice. Rapidly drying rough rice using such high temperatures may lead to kernel fissuring and eventual breakage during milling (**Inprasit and Noomhorm, 2001**).In a natural convection system, the flow of air is caused by the fact that the warm air inside the drier is lighter than the cooler air outside. This difference in density creates a small pressure difference across the bed of grain, which forces the air through it. The objective of this work is to construct a simple passive indirect natural convective cabinet solar dryer suitable for small farmers and test it under the prevailing weather conditions of Zagazig city. The design and operation of the dryer should be maintained simple to suit the simple illiterate farmers. This dryer is intended many to prepare rice seeds for long storage at 14% moisture content as recommended by most literature.

MATERIALS AND METHODS

In this study, a simple solar dryer was fabricated and assembled at the workshop of Agricultural Engineering Department, Faculty of Agriculture, Zagazig University. The practical experiments were carried out from 29 Sep. to 13 Oct. 2009 at Zagazig city (Latitude of 30.50º N), Egypt, to utilize the natural convection mode of a simple dryer for drying the rough grains of local variety (*Giza 177)* of rice crop.

Description of the solar drying system

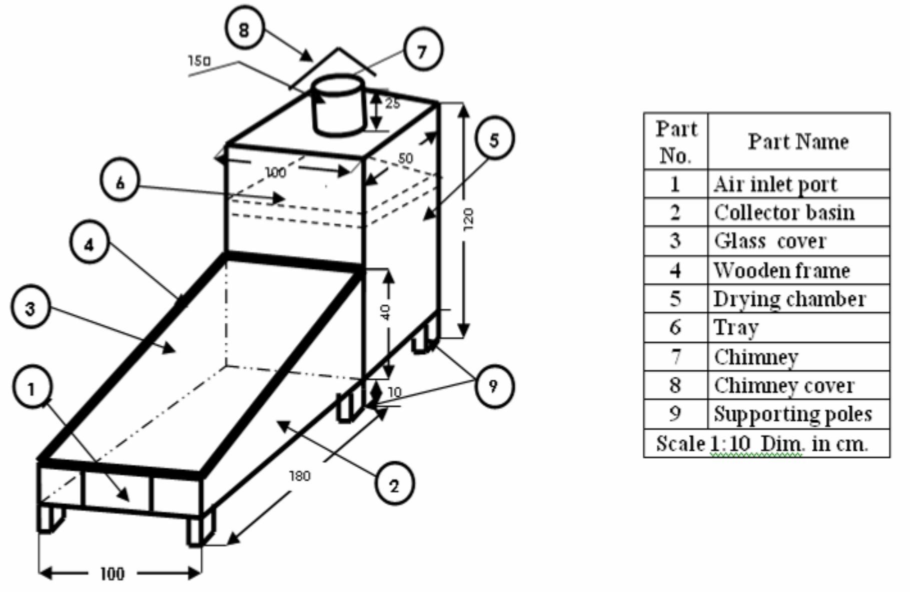
The drying system mainly consists of a solar collector attached directly to the drying chamber. The construction features and main components are shown schematically in Fig. (1). All components of the dryer were fabricated from locally obtainable materials. The construction of these components can be described as follows:

1-Solar collector

The solar collector is a shallow rectangular wooden box with 1.80 m length, 1.0 m width and 0.30 m depth, where the collector surfaces were painted from inside and outside using a black matt paint. The bottom and the sides of the wooden box were covered with a flat-steel sheets (1.20 mm thickness) and painted with a matt black materials used to maximize the absorption of solar energy. A thick layer, 3 cm thick of glass wool placed in space between the internal surface of the wooden box and the steel sheets at the bottom and sides of the collector as an insulated material. A clear single- sheet of glass with 3 mm thickness and transmittance of 0.90 was used as a cover for the collector. The cover was installed steeply with inclination angle 30º with the top edge of the collector and the air spaces are enclosed by the clear cover. The solar collector was supported with square poles at height of 0.10 m above the ground as shown in Fig. (1).

2-Drying chamber

The drying chamber attached directly with the collector and its frame was constructed as a rectangle wooden box painted with a black color with dimensions of 1 m length, 0.50 m width, and 1.10 m height. The drying box was supported at height of 1.20 m from the ground using four square wooden poles. The chamber has a door at the back with dimensions of 0.80 and 0.5 m to allow loading and unloading of the product. The chamber has a wooden frame to hold the drying tray as shelf. The drying chamber was insulated using glass wool with thickness of 0.30 m from the outer surfaces to avoid the heat leakage especially when the ambient temperature start to decrease to collect the maximum amount of heat energy. The air speed was controlled by means of a wooden gate at the entrance.



Part No.	Part Name
1	Air inlet port
2	Collector basin
3	Glass cover
4	Wooden frame
5	Drying chamber
6	Tray
7	Chimney
8	Chimney cover
9	Supporting poles
Scale 1:10 Dim. in cm.	

Fig. (1): Schematic diagram of the solar dryer.

3-Drying tray

The drying system has one drying tray fabricated from steel sheet 0.90 m length, 0.45 m width, and 0.10 m depth. The drying tray was perforated to permit the hot air streaming through the layer contents.

4-Exhuast system

The exhaust system included a cylindrical shaped outlet chimney with 0.15 m diameter and 0.25 m length, installed vertically and attached directly to the drying chamber to expel the exhaust air from the drying chamber to the atmosphere.

The experiments and measurements:

Material under investigation of rice grains (*Giza 177*) for seeding was loaded into the drying chamber in two different layer thickness of 5 and 10 cm using air inlet areas of 244, 488 and 732 cm^2.The material was stirred several times during drying operation. Rice grains have to be dried with initial moisture contents of 20, 22 and 25% at temperature not exceeding 45° C as a recommended degree for seeding. The load was weighed before, each 4 hours, and after drying process to calculate moisture content. Also drying time required to reach desired moisture content as well as drying rate were recorded.

Measurement of temperature and air velocity:

The temperature (ºC) was measured in three different locations, outside the collector (ambient temperature), beneath drying tray and in the exhaust system (through chimney hole) using a Tri-sense Hygrometer/Anemometer/ Thermometer device (Model No. 37000-00) produced by Cole Parmer Instrument Company, Illinois, USA. Also, same instrument was used to measure air velocity (m/s) at the collector inlet to calculate the mass flow rate of air into the collector.

1-Measurement of the hourly total solar radiation (I_T):

A weather station (Watchdog, model 900 ET) was used to measure wind speed (0-175 mph) ± 5%, wind direction (2° increments) ± 7°, temperature (-30° : 100° c), relative humidity (20-100%) ± 3%, rainfall (0.01-0.25 cm) ± 2% and solar radiation (1- 1250 W/m^2). Data were recorded each 15 minutes and averaged for each hour.

2-Estimation of instantaneous efficiency of the solar collector

The useful gained energy (q_u) was calculated as a function of airflow rate and the difference in temperature at the inlet and outlet ports of collector, according to the equation of **(Awady, 1993)** as follows:

$$q_u = m \times c_p \times (T_o - T_i)\text{, (W)} \quad , \qquad m = A_a \times V_a \times \rho_a \quad \text{,(kg/s)}$$

Where: m is the airflow rate and A_a ,V_a and ρ_a are the air inlet area ,air velocity and air density respectively. Cp is the specific heat of air (kJ/Kg.ºC), T_o and T_i are the outlet and inlet temperatures of the solar collector (ºC) respectively. The instantaneous thermal efficiency can be calculated using the equation given by **(Awady, 2003)** as follows:

$$\eta_{th} = \frac{q_u}{A_C \times I_T} = \frac{m \times C_P \times (T_o - T_I)}{A_C \times I_T}$$

Where: A_C is the solar collector surface area (m^2).

3-Drying Rate (D_R):

Drying rate (D_R), is expressed as the amount of the evaporated moisture over time. (*dM/dt)*. The drying rate can be determined using the following equation of **Farhang *et al*. (2010):**

$$D_R = \frac{M_t - M_{t+dt}}{dt}$$

Where:

D_R .(dM/dt) : drying rate, kg_{water}/ h
M_t : initial moisture content, kg_{water}.
M_{t+dt} : moisture content at (t) time, kg_{water}
dt : drying time, h.

4-Moisture content determination:

Moisture content (M.C) was determined according to ASAE standards, 1994 by using samples about 10 g which dried at 105 °C for 24 h. Samples were taken from drying chamber every 4 h interval until the moisture content drops to the equilibrium moisture content. The following equation was used to calculate the moisture content on wet basis (**Brooker *et. al***, 1978):

$$MC = \frac{M_w - M_d}{M_w} \times 100$$

Where: M_w: wet mass of sample, g, and M_d: dry mass of sample, g.

RESULTS AND DISCUSSION

The obtained data was tabulated, analyzed, and graphed to visualize the effect of meteorological data and dryer parameters on collector thermal efficiency and drying rate.

1-Distribution of total solar radiation and useful energy:

The total hourly solar radiation incidence on the collector aperture, W/m^2, and useful energy gain, W, were plotted against the hour of the day as displayed in Fig. (2) for the day Sep. 29, 2009 and air inlet area of 244 cm^2. It is visible that the maximum solar radiation and hence solar useful gain are attainable around noon hours. It is also clear that the useful energy gain is a direct function of the total hourly solar radiation. Similar trends were found for different dates and air inlet areas. The useful energy gain is low at the beginning and the end of the day . Also the ambient air temperature and collector outlet temperature are displayed in Fig. (3) for the same day and inlet area. It can be concluded that the highest values are directly related to total solar radiation and collector outlet temperature directly proportional to ambient temperature. One can expect that operating the system in such high temperature and radiation hours would improve its performance.

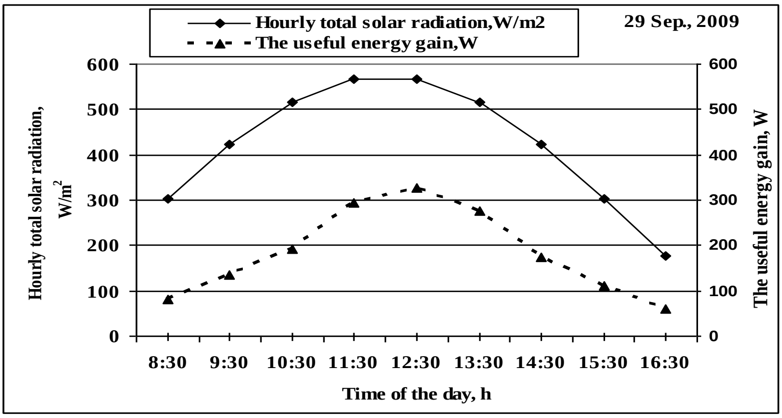


Fig. (2): Hourly solar radiation and useful energy distribution.

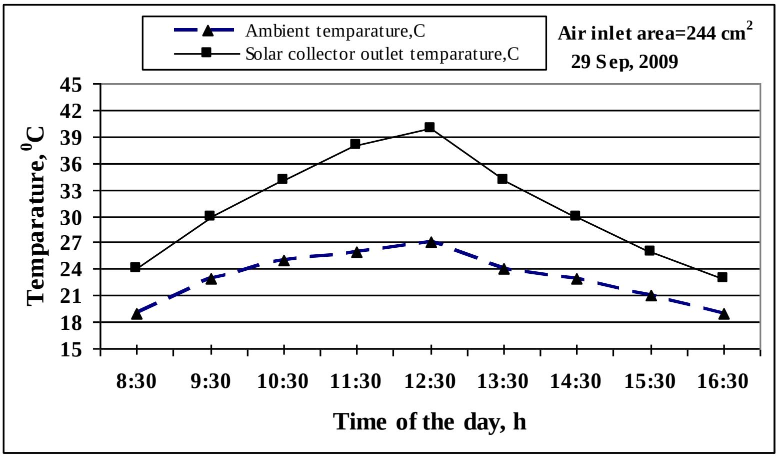


Fig. (3) Distribution of ambient and collector outlet air temperature during the day.

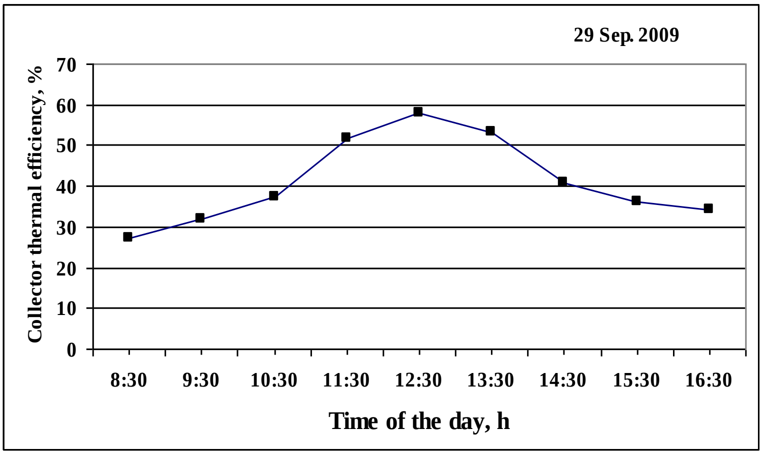


Fig. (4) Collector thermal efficiency.

The collector instantaneous thermal efficiency also showed a similar trend during the day hour. Maximum value of 58 % obtained at noon while as expected minimum values where found at the morning hours. Afternoon hours had thermal efficiency values higher than similar morning hours due to the accumulation of thermal energy during the day hours as shown in Fig. (4).

2-Effect of air inlet area on thermal efficiency and temperature difference:

The air inlet into the collector was controlled by means of a sliding gate to investigate the effect of its area on the collector thermal efficiency and the difference between ambient temperature and air temperature inside the drying chamber. The inlet area was adjusted to have values from 244 to 732 cm^2. Fig.(5) illustrates the relationship between collector air inlet area and maximum temperature difference at noon for five experimental days. It can be concluded that the maximum temperature difference attained at air inlet area of 244 cm^2 as a result of low air flow rate which tends to increase the temperature inside the dryer. Fig.(6)illustrates the relationship between collector air inlet area and thermal efficiency for the day Sep. 29, 2009. It is obvious that the smaller the inlet area the higher the thermal efficiency. This phenomenon can be attributed to the fact that the increase of inside air temperature with the decrease of air flow rate through the inlet area.

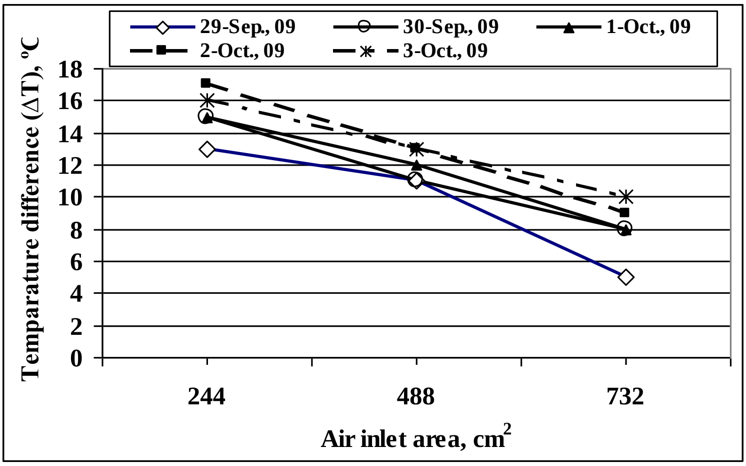


Fig. (5): Effect of air inlet area on maximum temperature difference at noon.

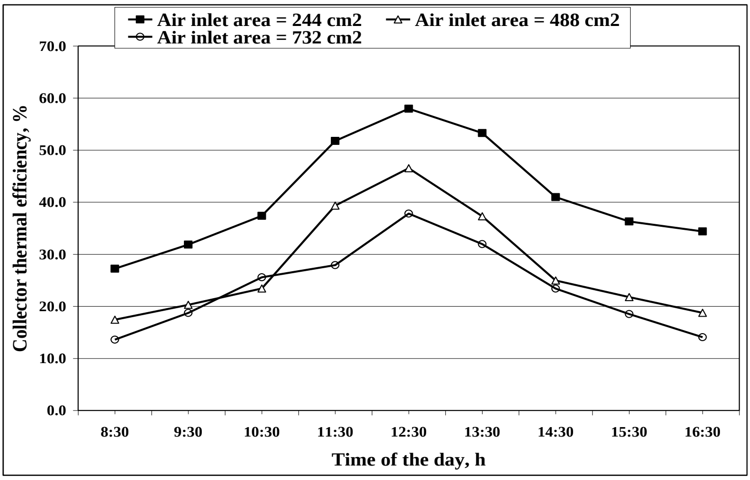


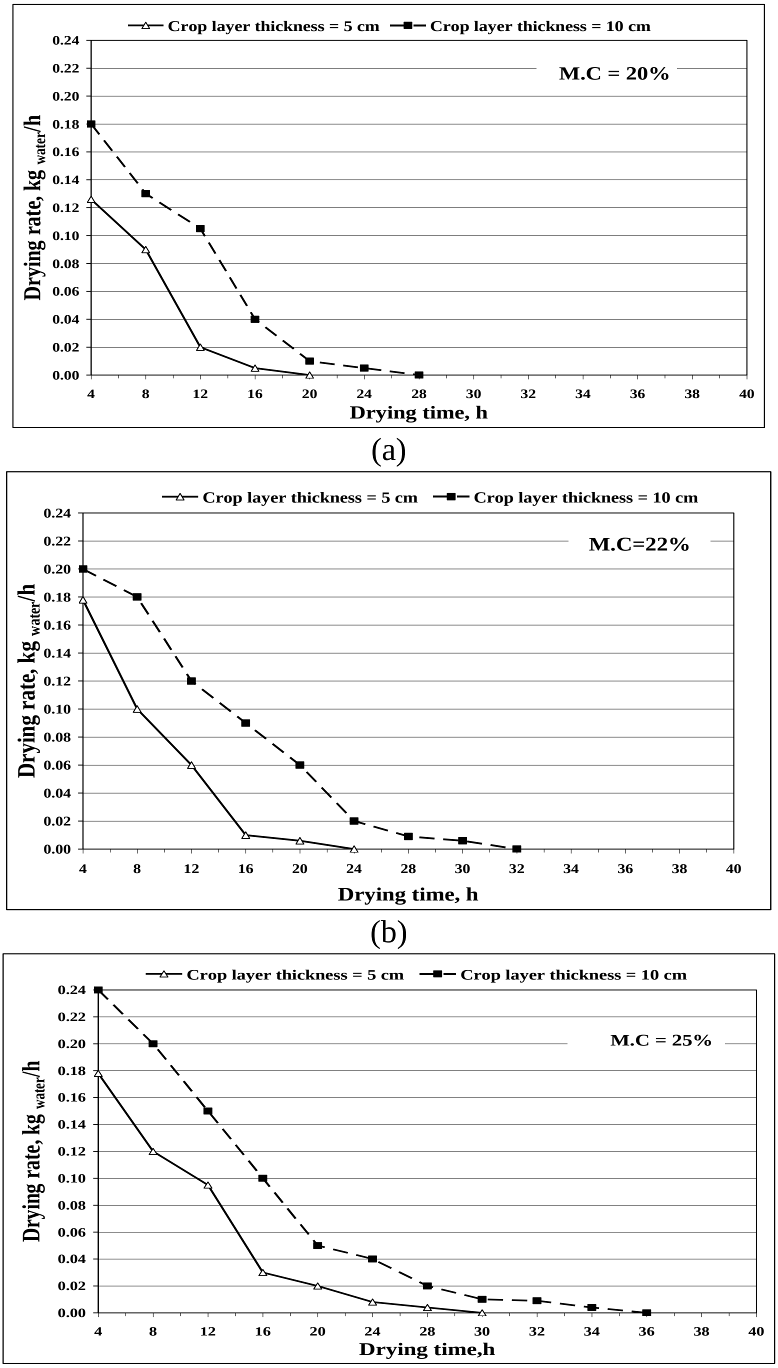
Fig. (6): Effect of air inlet area on thermal efficiency, Sep. 29, 2009.

3- Effect of layer thickness on drying rate

Rough rice samples were taken each 4 h and oven dried to calculate the amount of water removed during drying process. Fig. (7, a-c) depicts the drying rate under air inlet area of 244 cm^2, two different layer thicknesses, and three initial moisture contents (20, 22, and 25%). Under all conditions, drying rate was fast in the first 12-16 hours then dropped significantly until equilibrium moisture content was reached. This can be attributed to the fact that at the beginning of the drying process the moisture is lost from the grain surface but after a period the water had to be drawn from the center of the grain to the surface first. It is visible that drying rate for layer thickness of 10 cm is higher than that of 5 cm layer thickness due to the amount of water evaporated per hour. Also, layer thickness of 5 cm reached equilibrium moisture content 4-6 hours faster than 10 cm layer thickness due to less water content per load.

4-Effect of air inlet area on drying rate

Air inlet area was controlled by a sliding gate to investigate the inlet area size on the drying rate.Fig.(8) shows the relationship between different air inlet areas and drying rate using the layer thickness of 5 cm. It is evidence that increasing air inlet area tends to increase air mass flow rate into the dryer and consequently, decreasing the temperature difference between ambient air and hot air inside the dryer. As a result, using an inlet area of 244 cm^2 increased drying rate and required the least drying time.



(a)

(b)

(c)

Fig. (7): Effect of layer thickness on drying rate at different levels of grain moisture content at air inlet area of 244cm^2.

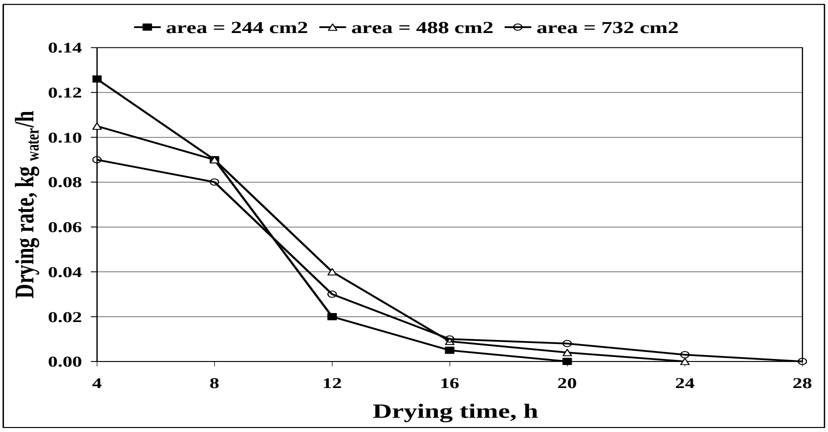


Fig. (8): Relationship between air inlet area and drying rate.

5-Effect of initial moisture content on drying rate

Fig. (9) depicts the drying rate under different initial moisture content at air inlet area of 244 cm^2. It can be concluded that drying rate dropped sharply in the first 16 hours under all moisture content then it steeply dropped until the equilibrium moisture content was reached. Furthermore, drying rate for samples containing higher initial moisture content was higher than that for samples containing lower moisture content but it took a longer time to reach the equilibrium moisture content. For example, samples of initial moisture content of 25% took up to 30 hours to reach equilibrium moisture content while samples of initial moisture content of 20% took 20 hours only to reach equilibrium moisture content. This is due to the amount of water to be removed from higher moisture content samples is greater than that to be removed from samples having less moisture content. Similar trends were found under other air inlet areas.

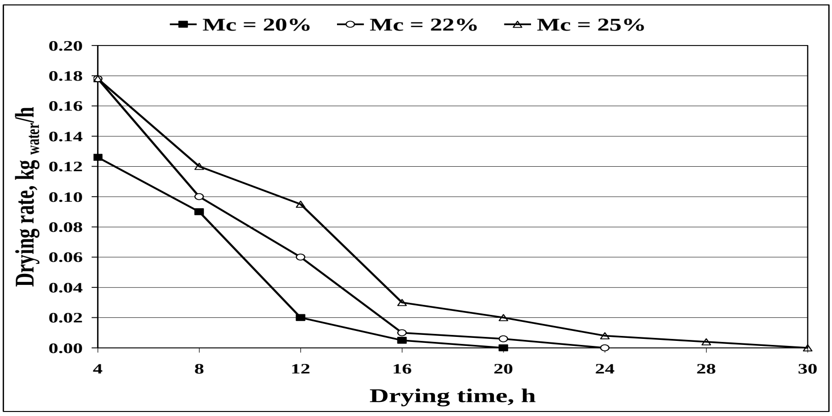


Fig. (9): Effect of initial moisture content on drying rate.

CONCLUSION

A simple indirect passive cabinet solar dryer was constructed and tested to dry rice grains for seeding at maximum temperature of 45° C. the experiments were conducted at the Dept. of Agric. Eng., Zagazig Univ., Zagazig, Egypt during the rice harvesting season of 2009. The construction and operation of the dryer were kept simple to the advantage of the simple farmer. From the results, it can be concluded that:

1-The maximum temperature difference attained at air inlet area of 244 cm^2.

2-The maximum solar radiation and hence solar useful gain are attainable around noon hours. So, operating the dryer around noon hours will improve its thermal performance.

3-Increasing layer thickness increased the drying rate but also increased the drying time required to reach equilibrium moisture content.

4-Decreasing the air inlet area increased the temperature difference between ambient air and inside hot air and consequently, increased the thermal performance of the dryer.

It is recommended that using the smallest air inlet area of 244 cm^2 with layer thickness of 5 cm(7.88 kg_{rice} at M.C of 20%) and operating the dryer around noon hours would improve its thermal performance and reduce the time required to reach the equilibrium moisture content. Solar drying units are experimental but can be recommended for using in small farms or can be scaled up to suit medium sized farms.

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الملخص العربى

مجفف شمسى يعمل بالحمل الطبيعى لتجفيف حبوب الأرز

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تم بناء واختبار مجفف شمسى من النوع الغير مباشر يعمل بالحمل الطبيعى لتجفيف حبوب الأرز بغرض استخدامها كتقاوى على درجة حرارة لا تتعدى ٤٥° م والتى أوصت بها الأبحاث السابقة. تم تجميع أجزاء المجفف من خامات متوفرة محلياً ومراعاة البساطة فى التصميم والتشغيل ليناسب المزارع البسيط. يتكون المجفف من وحدتين أساسيتين هما المجمع الشمسى بمساحة تجميع كلية ١٨٠ سم^{٢} وصندوق التجفيف الذى يحتوى على صينية تجفيف واحدة ومزود بمدخنة من أعلى لخروج الهواء المحمل ببخار الماء ويوجد به باب من الخلف لتداول المواد. تم تزويد مدخل الهواء إلى المجمع ببوابة منزلقة للتحكم فى مساحة مدخل الهواء وبالتالى معدل مرور الهواء إلى المجمع وتم ضبط مساحة دخول الهواء لتصبح ٢٤٤، ٤٨٨ و٧٣٢ سم^{٢} وذلك لاختبار معدل مرور الهواء على الأداء الحرارى للمجمع. تم استخدام حبوب أرز على درجات رطوبة مختلفة ٢٠ ، ٢٢ ، ٢٥% وتم توزيعها فى طبقتين بسمك ٥ ، ١٠ سم مع تقليب الحبوب كل فترة وأخذت عينات لتقدير المحتوى الرطوبى كل ٤ ساعات وذلك لحساب معدل التجفيف.

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أجريت التجارب لمدة أسبوعين من موسم حصاد عام ٢٠٠٩م بورشة قسم الهندسة الزراعية بكلية الزراعة جامعة الزقازيق وذلك لدراسة تأثير العوامل السابقة على الأداء الحرارى للمجمع ومعدل التجفيف. تم قياس كلاً من الإشعاع الشمسى ودرجة حرارة الهواء الخارجى وكذلك درجة حرارة الهواء المسخن داخل المجفف ونسب الرطوبة وتم حساب الطاقة المستفادة والكفاءة الحرارية للمجمع وكذلك معدل التجفيف تحت كل احتمالات المتغيرات السابقة وتم أخذ المتوسطات وجدولة وعرض النتائج بيانياً لسهولة قراءتها.

أوضحت النتائج أن أعلى معدل إشعاع شمسى لوحدة المساحة وبالتالى أعلى طاقة مستفادة تركزت حول ساعات الظهيرة وذلك لسقوط الأشعة عمودية على سطح المجمع. كذلك وجد أن أعلى فرق فى درجات الحرارة بين الهواء الخارجى والهواء المسخن حدث باستخدام مساحة دخول الهواء ٢٤٤ سم^{٢} وذلك كنتيجة لقلة معدل مرور الهواء بالمجمع. كذلك وجد أن أعلى كفاءة حرارية لحظية للمجمع ٥٨% لوحظت عند ساعات الظهيرة باستخدام فتحة ٢٤٤ سم^{٢} لمرور الهواء وبزيادة مساحة الفتحة قلت الكفاءة الحرارية للمجمع. كذلك اتضح من الدراسة أن سمك طبقة الحبوب والمحتوى الرطوبى الابتدائى للحبوب لهما تأثير واضح على معدل التجفيف تحت كل التوليفات الممكنة، حيث كان معدل التجفيف سريعاً فى ١٢-١٦ ساعة الأولى ثم انخفض بشدة حتى وصلت الحبوب إلى رطوبة الاتزان فى نهاية التجفيف. ويمكن تفسير ذلك بأن الرطوبة تفقد من السطح الخارجى للحبوب بسهولة فى بداية التجفيف ولكن بعد فترة يجب سحب الرطوبة من مركز الحبة إلى سطحها قبل أن تتبخر. أيضاً وجد أن السمك الأقل ٥ سم

يحتاج إلى زمن تجفيف أقل من السمك الأكبر. وجد أيضاً أن مساحة مدخل الهواء لها تأثير مباشر على زمن ومعدل التجفيف حيث أعطت المساحة ٢٤٤ سم^{٢} أفضل النتائج مقارنة بمساحة الفتحات الأخرى. ووجد أيضاً أن محتوى الرطوبة الابتدائى للحبوب له تأثير مباشر على زمن ومعدل التجفيف حيث أعطى المحتوى الرطوبى الأقل أفضل النتائج.

نخلص من هذه الدراسة إلى التوصية باستخدام فتحة دخول الهواء بمساحة ٢٤٤ سم^{٢} مع سمك طبقة الحبوب ٥ سم وأن أفضل وقت لتشغيل المجفف هو الساعات حول وقت.