Journal of Agricultural Biotechnology and Sustainable Development Vol. 3(4) pp. 65-71, April 2011
Available online http://www.academicjournals.org/JABSD


*Full Length Research Paper*

# Performance evaluation of a mixed-mode solar dryer for evaporating moisture in beans

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Accepted February 9, 2011

**This research includes the design and manufacture of a solar dryer and its performance test on bean. Solar dryer consists of three parts; 1) the air heating section (solar collector), 2) two fins and 3) the drying chamber section with four trays. The drying test was conducted after setting the drying air speed at 1.5 m/s at the drying chamber. The drying process continued until the total beans weight was (100 kg). The highest and the lowest solar collector efficiencies of 61.82 and 45.40% were obtained at 11.00 and 9.00 h, respectively. Higher moisture evaporating from the beans was achieved in the first tray, as moisture content was reduced from 60 to 8% during the 6 h compared with the other three trays.**

**Key words:** Solar dryer, broad–bean, performance, temperature distribution.

## INTRODUCTION

Drying crops by solar energy is of great economic importance the world over, especially in Iraq where most of the crops and grain harvests are lost to fungal and microbial attacks. These wastages could be easily prevented by proper drying, which enhances storage of crops and grains over long periods of time. Iraq lies within the equator and is blessed with abundant solar energy all the year round. This solar energy can easily be harnessed by a proper design of solar dryers for crop drying. This method of drying requires the transfer of both heat and water vapour (Forson et al., 2007). Most of our crops and grain are harvested during the peak period of rainy season and so preservation proves difficult and most of these grains and crops get spoilt. This results in the crops not lasting the year, resulting in subsequent hunger and malnutrition. Solar drying may be classified into direct, indirect and mixed-modes. In direct solar dryers, the air heater contains the grains and solar energy passes through a transparent cover and is absorbed by the grains. Essentially, the heat required for drying is provided by radiation to the upper layers and subsequent conduction into the grain bed. In indirect dryers, solar energy is collected in a separate solar collector (air heater) and the heated air then passes through the grain bed, while in the mixed mode type of dryer, the heated air from a separate solar collector is passed through a grain bed and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls or roof (Gatea, 2010). These crops can be preserved and stored, so that they can be of economic importance both to the farmers and the entire populace. Rural farmers do this by open-air drying. This practice in the rural areas has some obvious disadvantages (Henry et al., 1999). This method is unhygienic since the crops are easily contaminated by animal droppings and consequent infestation by fungi and bacteria. Human health is thus endangered as a result of food poisoning. This method also prolongs drying and may result in the deterioration of the quality of the crops. Moreover, more labour is involved as the crops are being moved frequently in and out during the day and night and from rain. They are also watched in order to prevent physical attacks birds and other animals. It is a well known fact that in rural areas, conventional sources of energy like petrol and electricity are either totally absent or are not readily available to develop active dryers, which have higher rate of performance. A low temperature passive solar dryer has therefore been developed, which will be appropriate for crops and grains during the low temperature and high relative humidity periods of the year. The obvious advantage of low temperature drying is that, it enables crops to be dried without cracking and hence minimizes the exposure of the crops to fungal and bacterial infestation and wastage, this is also suitable for bulk drying for long-term storage (Forson et al., 2007). The objective of this research was to fabricate the solar dryer using indigenous materials to assess their efficacy in drying beans. The fabricated driers utilized no chimney and both direct and indirect modes in the same unit.

## DESIGN CALCULATIONS

### Declination (δ)

This is the angle between the sun's direction and the equatorial plane and is given by Forson et al. (2007) as,

$$\delta = 23.45 \sin [0.9863 (284 + n)] \quad (1)$$

Where (n) is the day in the year which varies from n = 1 to n = 365.

### Optimum collector slope (β)

The optimum collector slope, β, is determined from

$$\beta = \delta + \varphi \quad (2)$$

Where (δ) is the angle of declination for Baghdad, Iraq and (φ) is the latitude of the location.

### Collector efficiency (η)

This is computed from,

$$\eta = \frac{\rho V c_p \Delta T}{A I_c} \quad (3)$$

Where (ρ) is the density of air (kg/m$^3$), ($I_c$) is the insolation on the collector, (ΔT) is the temperature elevation, ($c_p$) is the specific heat capacity of air at constant pressure (J/kg K), (V) is the volumetric flow rate (m$^3$/s), and (A) is the effective area of the collector facing the sun (m$^3$).

### Dryer efficiency ($\eta_d$)

This is given by Henry et al. (1999) as,

$$\eta_d = \frac{ML}{I_c A t} \quad (4)$$

where (L) is the latent heat of vaporization of water, (M) is the mass of the crop, and (t) is the time of drying.

### Heat energy Q needed for crop drying at moderate temperature

This is given by

$$Q = M_w L = \rho c_p V (T_a - T_b) \quad (5)$$

where L = latent heat of vaporization of water, $M_w$ = mass of crop before drying, ρ = density of water, $T_a$ = ambient temperature, $T_b$ = dryer temperature.

### Moisture content (M.C.)

The moisture content is given as:

$$MC(\%) = \left( \frac{M_i - M_f}{M_i} \right) \times 100\% \quad (6)$$

where $M_i$ = mass of sample before drying and $M_f$ = mass of sample after drying.

### Moisture loss (ML)

The moisture loss is given as:

$$ML = (M_i - M_f) \text{ (g)} \quad (7)$$

Here, $M_i$ is the mass of the sample before drying and $M_f$ is the mass of the sample after.

### Length of the day

The length of the day is given by Henry et al. (1999) as:

$$N = (2/15) \cos^{-1} (-\tan\varphi \tan\delta) \quad (8)$$

## THE EXPERIMENTAL SET-UP

The solar dryer with box-type absorber collector was constructed using the materials that are easily obtainable from the local market. Figure 1 shows a section of the solar crop dryer. The dryer has four main features namely: the box-type absorber solar air collector, the drying chamber, the drying rack and two fines electric. The

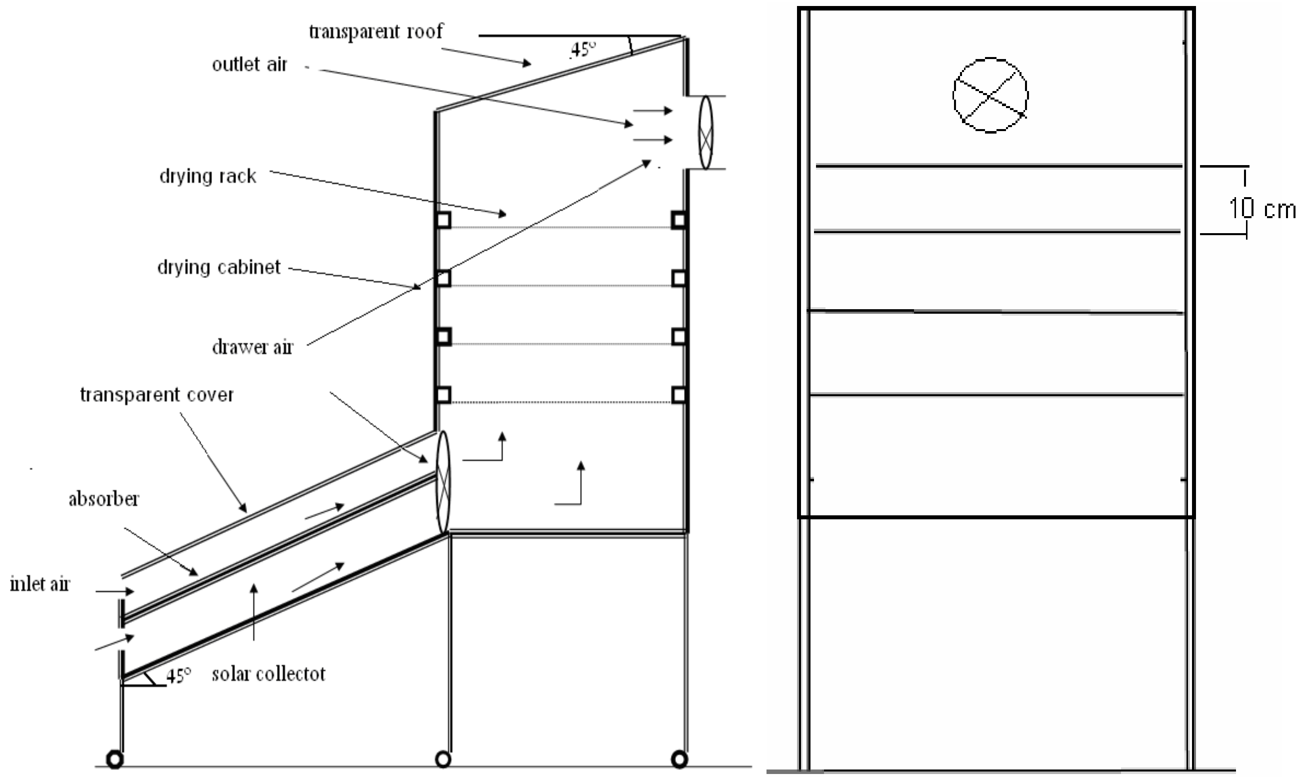


**Figure 1.** Shows section of the mixed-mode solar dryer.

parameters involved in the design of the solar crop-drying systems are shown in Figure 2.

### Collector (solar air heater)

The heat absorber (inner box) of the solar air heater was constructed using 1 mm thick galvanized plate, painted black, the surface facing sunlight was painted with black paint containing (5%) black chromium powder to increase its absorbing capability (Duffie and Beckman, 1974). The solar collector was insulated with rock wool of about 5 cm thickness and thermal conductivity of 0.04 $Wm^{-1}K^{-1}$ on all sides. The solar collector assembly consists of air flow channel enclosed by transparent cover (glazing). The glazing is a single layer of 4 mm thick transparent glass sheet. It has a surface area of 0.82 by 1.20 cm and of transmittance above 0.86 (Figure 3).

### The drying cabinet and drying racks

The designing of the drying chamber depends on many factors such as the product to be dried, the required temperature and velocity of the air to dry food material, the quantity of the dried product and the relative humidity of the air passing over the food material. The drying chamber houses four drying racks, between a tray and another tray is 10 cm as shown in Figure 1. Four trays of dimension (0.75 x 0.30 x 0.08 m) were fabricated and stacked uniformly/evenly at distances (0.02 m) apart, for placing of material to be dried. The tray was made from an aluminum wire mesh (0.003 X 0.003 m in size) attached to it. Metal handles (0.076 m) were attached on each tray for ease of handling and sliding the trays inside the chamber through the produce to be dried. The drying chamber was also lined with foam insulation material 5 cm thick to prevent loss of heat (Figure 4).

### Drying mechanism

In the process of drying, heat is necessary to evaporate moisture from the material and a flow of air helps in carrying away the evaporated moisture. There are two basic mechanisms involved in the drying process: 1) the migration of moisture from the interior of an individual material to the surface, and 2) the evaporation of moisture from the surface to the surrounding air (Youcef-Ali et al., 2001). The drying of a product is a complex heat and mass transfer process which depends on external variables such as temperature, humidity and velocity of the air stream and internal variables which depend on parameters like surface characteristics (rough or smooth surface), chemical composition (sugars, starches, etc.), physical structure (porosity, density, etc.), and size and shape of product.

### The experimental measurements

Two thermocouples have been positioned to measure the air temperature at the inlet and outlet portion of the air heater with accuracy of ±1. Another four thermocouples have been placed at trays 1, 2, 3 and 4 in order to measure the temperature of trays. Ambient temperature was also recorded during the course of experiments with the help of mercury thermometer. The experiment was conducted at Baghdad / AL.Zafaranya (latitude 33.27° northwards) and the orientation of the solar collector has been fixed towards the south direction, inclined at an angle of 45°. The solar radiation on a horizontal and inclined surface has been recorded

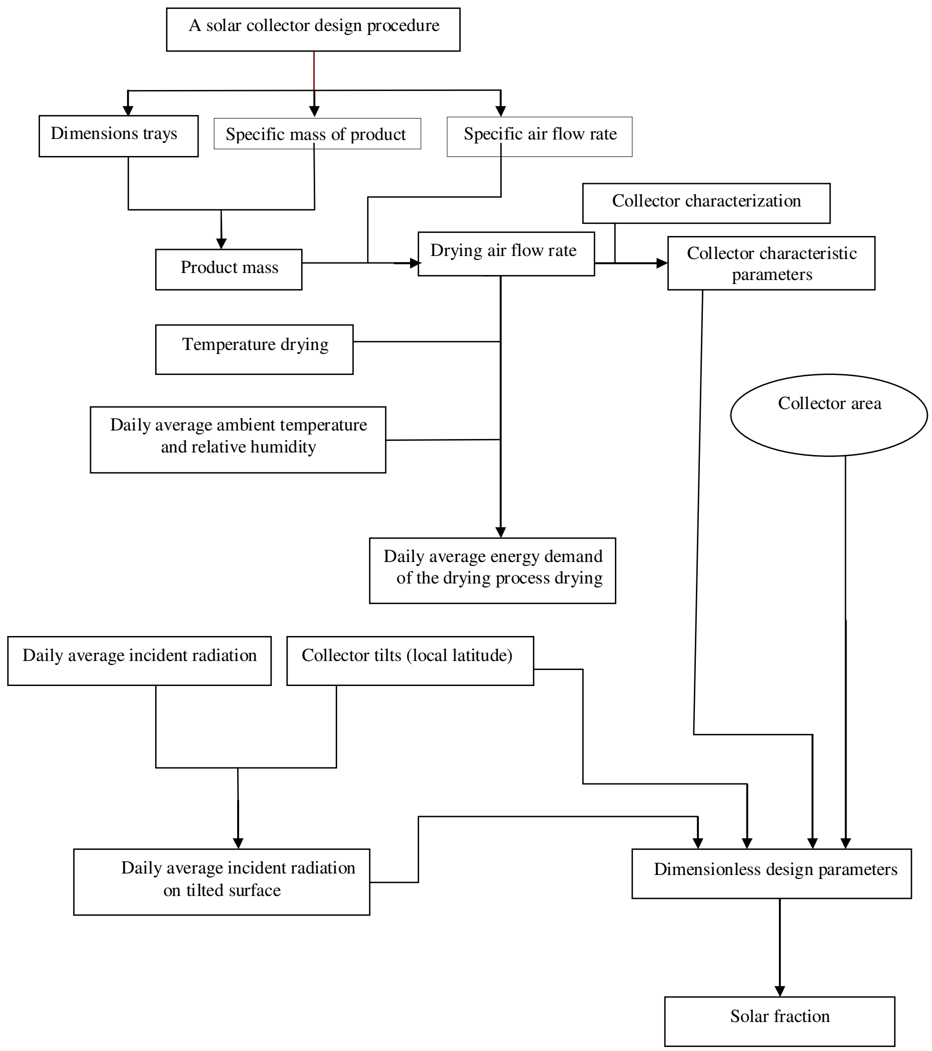


**Figure 2.** Schematic diagram of a mixed-mode solar crop drying system.

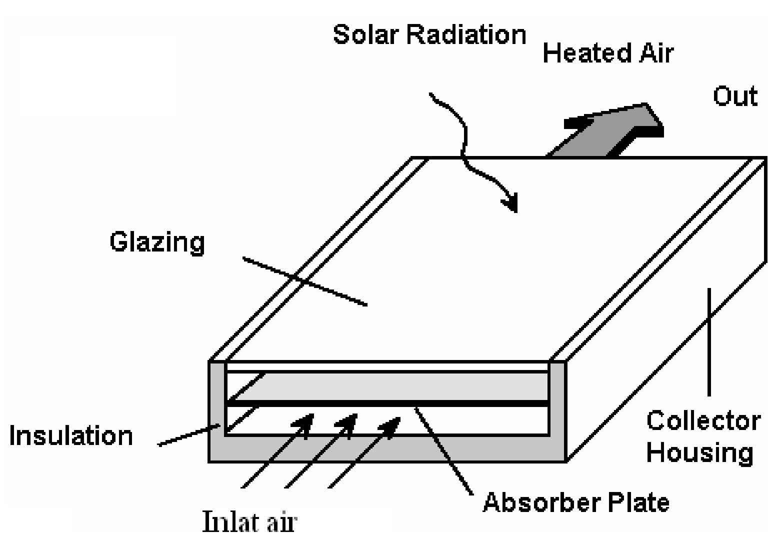


**Figure 3.** Typical solar collector for air heating.

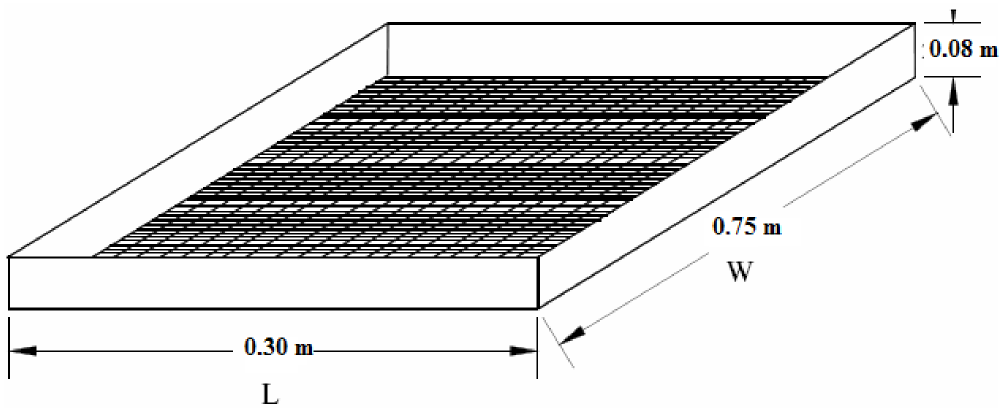


**Figure 4.** Dimension of trays used in the drying chamber.

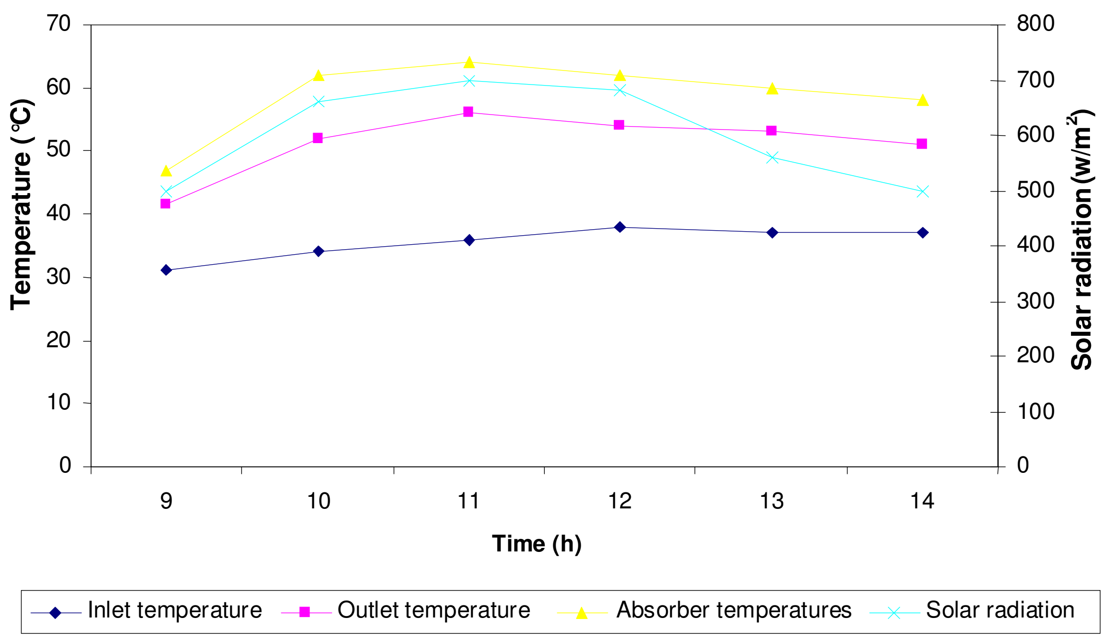


**Figure 5.** Variation of and temperatures of outlet air of collector, absorber, ambient, and radiation during test on June 26, 2009.

during the course of experiments with the help of solar meter. Air velocity or flow rate of air at the inlet position of the drying chamber was measured by anemometer.

## RESULTS AND DISCUSSION

### Solar collector performance

From results of the experiments, the diurnal variation of temperatures of the solar collector outlet air, absorber, ambient, and solar radiation were plotted. One typical day of June is shown in Figure 5. It is observed that the rise in air temperature due to the generated air flow rate in the collector is sufficient for the purpose of most agricultural products drying. The daily solar radiation was relatively high with an average of 600 W/m$^2$. For the inlet air temperature of 38°C, the maximum air temperature at the dryer inlet was recorded as 56°C at a solar irradiance level of 700 W/m$^2$. The mass flow rate of the drying air in the thermo-sphere mode of the collector depends on the prevailing wind conditions, ambient air temperature, incident solar radiation and the collector design. It was observed that, when the wind velocity was more or less uniform throughout the day, the air velocity in the collector shows definite dependence on the stack temperature difference between ambient and collector outlet air.

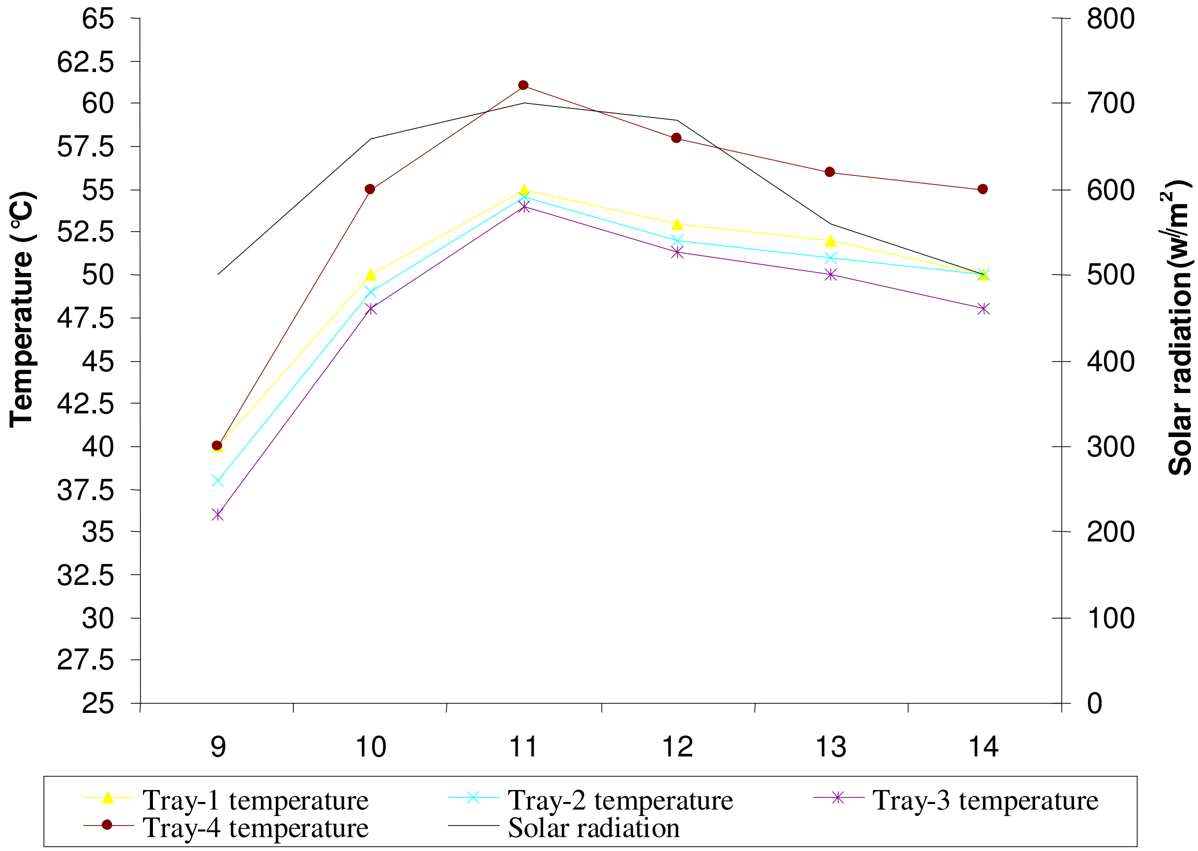


**Figure 6.** Variation of drying air temperatures on each tray, ambient temperature, and radiation during the unloaded experiment with variation of heat sources (June 27, 2009).

## Performance of solar dryer

The performance of the solar dryer depends on several factors, the solar radiation, inlet air temperature of solar dryer and the dryer design factors (Figure 6) note that access to the highest temperature required for drying when tray 4 is from 61°C and is at the highest intensity of the radiation 700 W/m$^2$ at 11. There were no significant differences in temperature at the trays (1, 2 and 3) with the differences ranging from (2 to 5°C).

## Moisture content variation

As shown in Figure 7, the moisture content was reduced from 60% on dry basis to 8% on dry basis through 6 h. Been delivering moisture content of the beans on (trays 1, 2, 3 and 4) to (8, 11, 14 and 18%) respectively.

## Solar collector efficiency

The efficiency of the solar collector depends on the air flow rate and the difference in temperature ($t_o$- $t_i$) and radiation intensity as in the Equation 3 of Figure 8, was obtained at the highest efficiency of the solar collector the amount of 61.82% at midday, and less efficient were obtained from 45.4% at 9 am.

## Conclusions

The study revealed the following conclusions:

1. The maximum drying temperature through the drying time was 61°C.
2. The amount of the moisture content was decreased to 11% in 6 h which depends on drying temperature and the time of exposure to sun radiation. This drying rate was an adequate rate of moisture extraction. The main factor in controlling the drying rate was found to be the drying air temperature and air velocity.
3. The drying time depends on the thermal and physical properties of the biogases pulp and also on the climatic conditions (solar radiation, relative humidity, ambient temperature and wind speed).
4. The highest efficiency solar collector was 61.82% at the 11 o'clock hour and the lowest efficiency was 45.40%

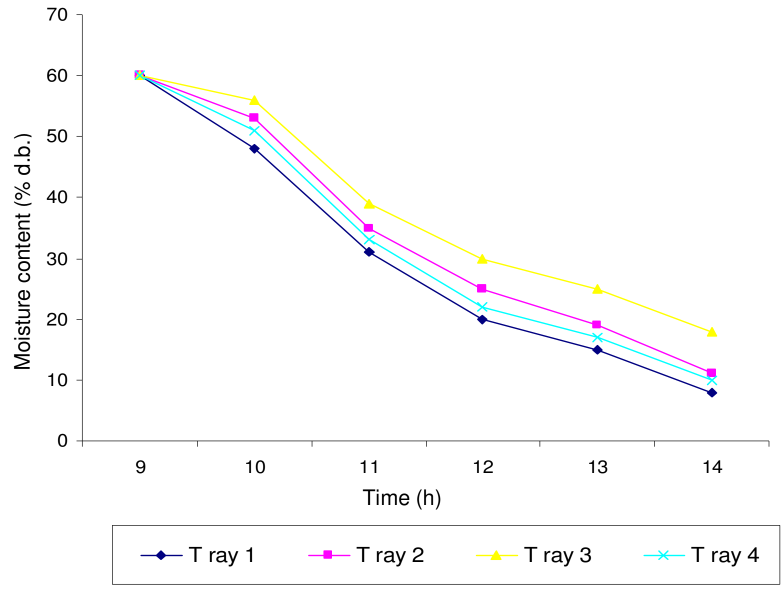


**Figure 7.** Decreasing of moisture content of broad –bean for each tray of the dryer.

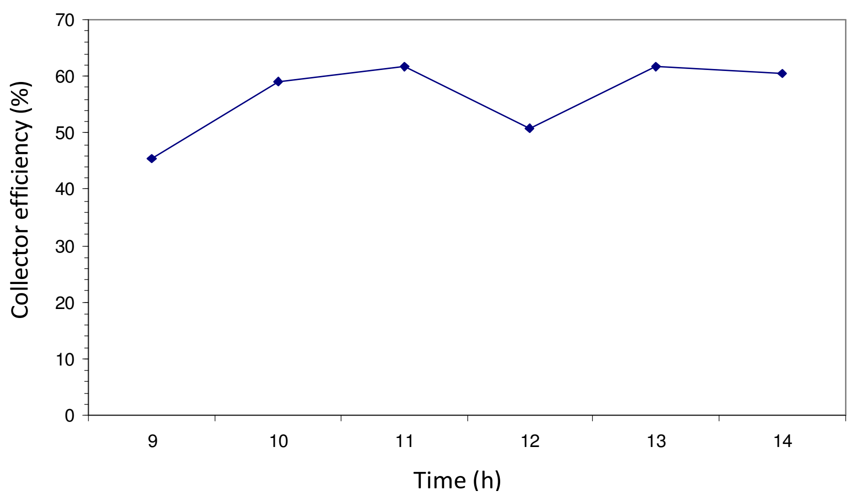


**Figure 8.** Variation of solar collector efficiency.

at the 9 o'clock hour.

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