The Application of Solar Energy in the Crops Drying Process

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Abstract

In the present study two convective types of solar dryers were investigated and tested under the Iraqi climate conditions. The first is called indirect type which consists of solar collector and drying chamber and the second type is a direct solar dryers. A drying equation based on a thin layer-drying function has been introduced to simulate the change of moisture content of crops with time taking into account the effect of flow rate of air, drying temperature, humidity ratio, initial and final moisture contents, and crops distribution on the drying rate and can be used for different crops. The dryers were tested using potato, fruit, any vegetables and other kinds of green leaves under typical condition of Iraqi weather. Good agreement has been obtained between the present results and the available published measurements. The study indicates that the indirect solar dryer gives definite performance advantage compared with the direct solar dryer.

Keywords: Solar energy, preserved foods

استخدامات الطاقة الشمسية في تجفيف المحاصيل الزراعية

الخلاصة

يقدم البحث دراسة لنوعين من المجففات الشمسية بحثث واختبرت تحت نفس الظروف المناخية للعراق، النوع الأول عبارة عن غرفة تجفيف مزودة بمجمع شمسي والثاني يعمل بامتصاص أشعة الشمس مباشرة . تم تقديم تفصيل كامل لتصميم وعمل هذين النوعين من المجففات. كما طبقت المعادلة التي تصف تغير محتوى الرطوبة للمحاصيل مع زمن التجفيف بإدخال العوامل التي تؤثر على معدل التجفيف مثل معدل سريان الهواء، حرارة التجفيف، معدل الرطوبة للمنتج وتوزيع المحاصيل داخل المجفف. ويمكن تطبيق هذه المعادلة لمحاكاة معدل التجفيف لمحاصيل مختلفة. تم الاختبار لمحاصيل مختلفة مثل البطاطا وبعض الفواكه والخضر تحت نفس الظروف المناخية للعراق. وأثبتت الدراسة دقة المعادلة المقترحة وتقارب النتائج مع العديد من النتائج المنشورة سابقا وأظهرت الدراسة أن المجفف المزود بمجمع شمسي يعطي أداء أفضل مقارنة مع المجفف المباشر الذي يعمل بامتصاص أشعة الشمس.

الكلمات الدالة : الطاقة الشمسية ، الأغذية المجففة

Nomenclature:

A_c	projected surface area of the absorber or solar collection area in direct dryer (m^2)
A_d	effective area of the dryer trays(m^2)
C_P	mean specific heat of air at constant pressure (kJ/kg K)
d.b	dry basis (-)
I	intensity of horizontal global solar radiation (W/m^2)
K	average drying coefficient, or the drying constant (h^{-1})
L	mean latent heat of vaporization of water (kJ/kg)
m	total mass of the sample (kg)
m_a	mass flow rate of air (kg/s)
m_o	mass of dry matter in the sample (kg)
m_w	mass of water vapor (kg)
P	atmospheric pressure (Pa)
P_v	saturation pressure (Pa)
T_a	ambient air temperature (^{o}C)
T_{av}	average air temperature in the dryer (^{o}C)
T_f	mean absorber air temperature or mean air temperature inside the direct dryer (^{o}C)
T_1,T_2	inlet and exit temperature of the collector (^{o}C)
T_{in},T_{out}	inlet and outlet temperature of the dryer (^{o}C)
$\overline{T}$	absolute temperature (K)
t	time (s)
U	the collector overall heat loss factor (W/m^{2}K)
V_a	volume flow rate of air (m^3/s)
$\overline{W}$	humidity ratio (kg/kg)
$\overline{W}_e$	humidity ratio at exit of the dryer (kg/kg)
$\overline{W}_a$	humidity ratio of the ambient air (kg/kg)
α	absorber absorpitivity (^{o}C)
ΔT	T_f -T_a (^{o}C)
η_c	collector thermal efficiency
η_d	heat collection thermal efficiency of direct dryer
θ	$\overline{W}_e - \overline{W}_a$ (kg/kg)
ρ_a	mean density of air (kg/m^3)
τ	glass cover transmitivity
ϕ	average percentage relative humidity at exit of the dryer
ϕ_a	average percentage relative humidity of ambient air
ω	percentage mean moisture content
ω_c	percentage equilibrium moisture content
ω_o	percentage initial mean moisture content

Subscripts

c	collector
d	dryer

Introduction

Iraqi weather is favorable for the efficient operation of solar devices. Dehydration of vegetables and other food crops by traditional method of open air sun-drying is not satisfactory as the products become infected with bacteria and insects. Controlled dehydration in closed sun drying chambers or tunnels reduces drying time and avoids any contamination by dusts, insects, and rain or storm effects.

Currently the needs for preserved foods are increasing in particular dried ones. Dehydration offers the most efficient method for preserving agricultural crops, providing a good mean to meet the temporary food shortage and giving higher quality products. Dehydration as a method of preserving farm products involves the removal of moisture to prevent the development of environment for the growth of bacteria and insects. The crops and food dehydration offers essentially the advantages of reducing package and transportation costs and elimination of refrigeration requirements, long term storage, validity of seed grains and production of foods of greater economic value.

In the present study two convective types of solar dryers, direct (without solar collector) and indirect (with solar collector), were constructed and tested under same conditions. The indirect type consists of a flat plate solar collector integrated with a drying chamber while the direct dryer is a box provided with a glass cover without collector. The hot air is directed over the crops, which were spread in a thin layer, in order to reduce air resistance significantly, and hence decreasing the power consumed by the fan. The variables and the design parameters involved in the dehydration processes will be discussed.

Literature Survey

Several studies of the drying process have been found in many of the existing literature. Various investigators have proposed different physical mechanisms of the drying process. The use of greenhouses that utilize solar collector has been early conducted by Walker [1]. Misrat et al [2] reported that adopting solar energy system for high temperature drying has proven to be of low cost. A computer model was developed by Radajewski et al. [3] to demonstrate how the cost of drying can be minimized based on optimum drying parameters. An economic analysis showed that an annual increase in profit of dried hay could be attained under specific operating conditions. Sharma et al. [4] presented the design and performance of a cabinet type solar dryer for various agricultural products. The dryer consists of a quadrilateral shaped cabinet, trays for tile product and single layer of transparent glass at the top. An experimental investigation was conducted by Tiris et al. [5] to test a solar dryer consisting of a solar air heater and a drying chamber. The solar dryer with integrated collector showed better quality and shorter drying periods in comparison with natural sun dried products.

Theoretical Treatment and Analysis

Thermal Analysis of the Solar Collector

The collector thermal efficiency, η_c.is calculated from the following equation.

[6]: $$\eta_c = \left[\alpha\tau - U \frac{T_f - T_a}{I} \right] \quad \ldots\ldots\; (1)$$

The thermal efficiency can be determined experimentally by using energy balance of the airflow through the collector between the roof cover and the collector absorber plate as:

Useful energy intercepted by solar air heater = Useful energy gained by flowing air.[7]:

$$\int_t^{t+\Delta t} I \eta_c A_c dt = \int_t^{t+\Delta t} m_a C_p \Delta T dt \quad \text{or}$$

$$\eta_c = \frac{\int_t^{t+\Delta t} m_a C_p \, \Delta T dt}{\int_t^{t+\Delta t} A_c \, I dt} \quad \ldots\ldots\ldots\ldots \; (2)$$

Here, the collection efficiency of the direct solar dryer or collector absorber efficiency in indirect solar dryer is based on the same area collecting the solar radiation.

Analysis of Solar Dryer

When a crop is at equilibrium with its environment, there must be a direct relationship between the moisture content within the crop and the vapor in the drying air stream. The concept of equilibrium moisture content is important in drying crops in that it determinants. The minimum moisture content level to which material will dry. It is accepted that the general form of the drying equation would involve the rate of water mass loss as a function of the drying potential, represented by the difference between conditions in the crop layer and in the surrounding air stream. In the present work a thin layer-drying function has been introduced assuming that the initial moisture content of a crop sample on dry basis (d.b) is ω_o As soon as drying begins the moisture content changes until it reaches equilibrium moisture content "ω_e". The simple model analogous to Newton's law of cooling is often used to describe the moisture loss in thin layer of crop drying which is given by [8]:

$$\frac{\omega(t)-\omega_e}{\omega_o-\omega_e}=\exp(-kt) \qquad \text{...... (3)}$$

K can be determined from the experimental drying data, and

$$\omega=\frac{m-m_o}{m_o} \qquad \text{.............. (4)}$$

For certain mean moisture content "ω" of the constituents and definite value of mean equilibrium moisture content "ω_t" after drying, the mass of water vapor "m_w" can be determined as:

$$m_w = m_o\,(\omega-\omega_e) \qquad \text{.............(5)}$$

In the present analysis the drying constant K in Eq. (3) is adjusted and modified to include the effect of the following parameters that have a direct effect on the change in the moisture content of the crop during the drying process:

1- the average temperature of the drying air (T_{av}).

2- the difference between the humidity ratio of the drying air at exit of the dryer $(\overline{W}e)$ and the ambient humidity ratio $(\overline{W}_a)$, $\theta=\overline{W}_e-\overline{W}_a$.

3- the air flow rate per unit surface area used to collect solar radiation (V_a/A_c).

4- the initial moisture content (ω_v) of the product.

5- the equilibrium moisture content (ω_e) of the product.

6- the loading density of the crop per unit area of the dryer trays (m/A_d)

To provide best fit to the measured data, the constant K in Eq. (3) takes the form:

$$K = C_1 + C_2T_{av} + C_3\,\theta + C_4(V_a/A_c) + C_5/(m/A_d) \qquad \text{.............(6)}$$

where, C_1, C_2, C_3, C_4 and C_5, are constants to be determined from the measured data.

The drying constant also depends on the type of the products as demonstrated later in the discussion of results.

As the relative humidity is measured in the present study instead of die humidity ratio at the average temperature of the drying air at exit, the humidity ratio is calculated from the following relation [9]:

$$\overline{W}=\frac{0.622\phi P_V}{P-\phi P_V} \qquad \text{.............. (7)}$$

where,

$$\ln P_V = A_1/\bar{T} + A_2 + A_3\bar{T} + A_4 T^{-2} + A_5 T^{-3} + A_6 \ln\bar{T}$$

with

A_1= -5800.2206,
A_2= 1.3914993,
A_3= -0.04860239,
A_4= $0.4176768\text{x}10^{-4}$,
A_5= $-0.14452093\text{x}10^{-7}$,
A_6= 6.5459673

When air of volume V_a is passing over a wet crop in the dryer its temperature would be cooled from T_{in} to T_{out} as a result of evaporation of mass m_w from the crop. The value of V_a can be evaluated from the following equation:

$$m_w L = \rho_a V_a C_P (T_{in} - T_{out}) \qquad \text{….(8)}$$

Description of the Solar Dryer

In the present study two different solar dryers of the convective type were investigated under the Iraqi climate conditions. The first is called indirect type, which consists of solar collector and drying chamber as shown in Fig.1. The second type is a direct solar dryer as indicated in Fig.2 . Each dryer has a solar collection area of 2 m^2 (2m length and 1m width). The air was sucked through the dryer by an electric fan of 15W. The solar collector consists of glass cover of thickness 3 mm, black-painted metal plate absorber and back cover. The absorber was made of galvanized steel sheet the space between the absorber plate and the glass cover was 7.5 cm provided by 4 lateral baffles of 80 cm length, 7.5 cm height and 70 cm pitch to enhance the but trawler rate of the absorber. The solar collector surface is titled 30' towards the south for maximum energy capture of the solar radiating according to Baghdad location. The drying chamber is a box of, triangular shape located just under the back of the collector fitted with 3 mesh trays as shown in Fig.1. The bottom of the chamber is made of wire mesh supported by expanded metal on steel rods. To reduce the conductive heat losses from the bottom and sides of the drying chamber, a glass wool insulation of 0.036 W/m.K thermal conductivity [10] and 5 cm thickness was used. The fan is located close to the roof of the drying chamber to pull air through the crop bed. The direct solar dryer has the same made of galvanized steel equally spaced upon which die crop is spread in a thin layer volume and geometry as that of the drying chamber in the indirect dryer as depicted in Fig. 2. It is a triangular shaped box consisting of a single layer of transparent glass at the top facing the south at an angle of 30°. It is provided with 27 holes, each of which has a diameter of 6 cm located close to the top of the dryer and distributed under the glass cover as shown in Fig. 2. The fan is located near the bottom of the dryer. During the experiments, the outside air was sucked inside the collector or directly to the direct dryer and discharged outside by the dryer fan.

Thermocouples were fixed in the layers of the crops in the dryers to measure the temperatures at the center of each tray as shown in Figs 1 and 2. Also temperatures of the ambient air, inlet and outlet of the dryers and collector absorber were recorded using Copper-Constantan, Type T, thermocouples. The air velocity and relative humidity was found to be 0.1 m/s and 0.1% respectively.

Results and Discussion

The dryers constructed here were tested using potato as an example of the green leaves. The data measured were solar radiation, ambient air relative humidity, ambient air temperature, temperatures inside the dryers, air velocities and temperatures at inlet and exit of the dryers and solar collector absorber. Calculations were made based on the measured data to find the air flow rate, the overall heat loss factor, the products of the absorbitivity and transmitivity for direct and indirect solar dryers. In case of indirect solar dryer the air velocity was measured at 20 locations in the inlet section of the solar collector, while in case of direct dryer the velocity of air is measured at the inlet of each hole using the velocity probe which is moved manually. The average values of the velocity measurements were used to calculate the air flow rate of both dryers. Also the drying constants in the proposed equation which was introduced to describe the change in moisture content of the crop were determined.

A series of experimental runs were performed during the month of April 2008 to examine both dryers simultaneously under the same conditions. The experimental measurements recorded in the day of 15th of April 2008 as recommended by Klein [10] were selected for the analysis. Figure 3 shows the variation of the solar radiation measured at a horizontal surface during this day, which shows a maximum value close to 1 p.m. For the same day, the change of the relative humidity of the ambient air is presented.

The minimum value of the relative humidity is observed at 11a.m.

Figure 4 shows the variation of the air temperature measured at the outlet of the solar collector absorber, exit of the drying chamber, outlet of the direct solar dryer and the ambient air. Generally the temperatures during the hours of the day increased from the morning hours and reached their maximum values after the noontime by one or two hours and then decrease. It is clear that the exit temperature from the drying chamber of the indirect solar dryer is higher than that of the direct solar dryer for all hours of the day. Also, it can be noticed that the rise in temperature of the direct solar dryer above the ambient was 8°C, while this value reaches 13°C in the drying chamber provided with solar collector in indirect solar dryer. Figure 5 indicates the changes in the average air temperatures inside the drying chamber and inside the direct solar dryer with the time of the day. It can be observed that the average air temperature inside the drying chamber of the indirect solar dyer is always higher than that of the direct solar dryer. This means that for the same drying conditions the indirect solar dryer gives higher heating rates to the crop than that given by the direct dryer. The experimental results of the collection efficiencies of both direct and indirect solar dryers are shown in Fig. 6. It is observed that for all values of temperature rise, the solar collector efficiency of the indirect dryer is significantly higher than heat collection efficiency of the direct solar dryer. This trend fits the following equations:

First, for indirect solar dryer,

$$\eta_c = A_1 B_1 \frac{\Delta T}{1} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

when Eq. (9) is compared with Eq. (1), it is found that:

$\alpha\tau)_c = A_1 = 0.75$

$U)_c = B_1 = 0.305$

Second, for direct solar dryer,

$$\eta_c = A_2 - B_2 \frac{\Delta T}{1} \qquad \ldots\ldots\ldots\ldots\ldots (10)$$

comparing Eq. (10) with Eq. (1) gives:

$\alpha\tau)_d = A_2 = 0.515.$

$U)_d = B_2 = 0.227$

where, $\Delta T = T_f - T_a$ and $\alpha\tau)_c$, $\alpha\tau)_d$ are the product of absorpitivity and transmitivity of solar collector in indirect and direct solar dryer respectively, while $U)_c$, $U)_d$ are the corresponding overall heat loss factors.

Drying experiments carried out here lasted 8 hours. The moisture content was determined by weighing. A digital weight indicator was used for weighing. A sample of the product was spread on a stainless steel wire dish (l0xl0 cm). The dish was fitted on the top tray behind the door. The weight of the sample was recorded every 30 min. The equilibrium moisture content is considered to be reached when the weight of the dryer in two successive weighing is almost unchanged. Fresh potato was loaded in a thin layer on the trays at a nominal density of 1.25 kg/m^2. The initial moisture content of potato when freshly harvested was 85% (d.b). The recommended moisture content for storage purposes, i.e. equilibrium moisture content is 5%.

Figure 7 shows a typical drying curve of the change in the measured moisture content of potato with the drying time for both direct and indirect dryers. The average experimental drying curve is used to determine the drying constant K which was found to fit the following equations: For indirect solar dryer:

$$K= -0.15 + 0.005T_{av} + 5.04\theta + 0.00477 (V_a/A_c)+0.251(m/A_d) \quad \ldots\ldots\ldots\ldots (11)$$

By substituting the measured data (T_{av}=45°C, ϕ=69%, ϕ_a=48%, V_a=320 m^3/h.

For direct solar dryer;

$$K= -0.65 + 0.005T_{av} + 6.8\theta + 0.00477(V_a/A_c) + 0.25/(m/A_d) \ldots\ldots.(12)$$

By substituting the measured data (T_{av}= 39°C, ϕ=65%, ϕ_a=48%, V_a=320 m^3/h. A_c= 2m^2, (m/A_d) =1.25) gives K= 0.56 h^{-1}.

The plots in Fig. 7 indicate that the rate of moisture loss decreases as the drying time increases until the crop reaches the equilibrium moisture content. The variation in the predicted moisture content of potato with the drying time for different air flow rates per unit area of the solar collector for indirect solar dryer is indicated in Fig.8. It is found that as the airflow rate increases the rate of moisture loss increases.

The corresponding values of the drying constant for the flow rates given in Fig. 8 are 0.72h^{-1}, 1.01h^{-1}, 1.4h^{-1}, 2.04 h^{-1} and 2.35 h^{-1} respectively.

The predictions obtained from the drying equation proposed here were validated by comparison with the published data obtained for different crops in indirect solar dryer. The variations of moisture content of green beans of initial and equilibrium moisture contents of 85% and 5% respectively and tomatoes of initial and equilibrium moisture contents of 95% and 7% respectively as a function of the drying time are shown in Fig. 9. The corresponding drying constants which fit the measured data are given as: for green beans:

$$K=-0.116+0.005T_{av} + 5.04\phi+0.00477 (V_d/A_c)+ 0.25/(m/A_d) \quad \ldots\ldots\ldots\ldots\ldots \quad (13)$$

and for tomatoes:

$$K = -0.271 + 0.005T_{av} + 5.04\theta + 0.00477(V_a/A_c)+0.25/(m/A_d) \quad \ldots\ldots\ldots(14)$$

For the data of Fig. 9 the corresponding drying constants are 0.705 h^{-1} for green beans and 0.55 h^{-1} for tomatoes respectively.

Figure 10 presents a comparison between the predicted results and the corresponding measured data for drying sunflower seed [11] under the same operating conditions. The variation of the moisture ratio $\left(\frac{\omega(t)-\omega_e}{\omega_o-\omega_e}\right)$ with the drying time for different drying temperatures is shown. The best fit of the drying constant K for the measured data is given by:

$$K= -1.168 + 0.025T_{av} + 9.0\theta + 0.001(V_a/A_c) + 0.25 (m/A_d) \quad \ldots\ldots\ldots (15)$$

And for the data given in Fig. 11, $K=0.85h^{-1}$ for $T_{av} = 27^oC$, $K=1.4h^{-1}$ for $T_{av} =49^oC$ and $K=1.95\ h^{-1}$ for $T_{av}=71^oC$ respectively.

From the above analysis and comparison of the predicted results, of the proposed drying equations, it is found that the fit of these equations agrees well with the corresponding published measured data.

Conclusions

Based on the local weather of Baghdad two different types of solar dryers were constructed and tested for dehydration of crops. An empirical drying equation was introduced and tested to simulate the drying process taking into account the effect of drying temperature, humidity ratio, and initial and final moisture contents of the crop. Also the effect of crop distribution per unit area of the trays and the flow rate of air per unit area used for solar collection were included. From the analysis and discussion of the experimental measurements presented here it can be concluded that the proposed drying function shows its ability to describe well the drying process and can be used to simulate many agricultural crops. Also, the analysis indicated that the indirect solar dryer performs well compared with the direct one of the same geometry and operating conditions. The superiority of the indirect solar dryer is referred to:

1) it takes less time for drying crops

2) has a higher collection efficiency due to the presence of the solar collector.

This means that the type of dryer affects the rate of drying. The analysis showed that the introduced equation can form a basis for prediction of moisture change of many farm products. It may also be helpful for selecting operating parameters depending on the state of the crop such as flow rate and loading density on trays of the dryer.

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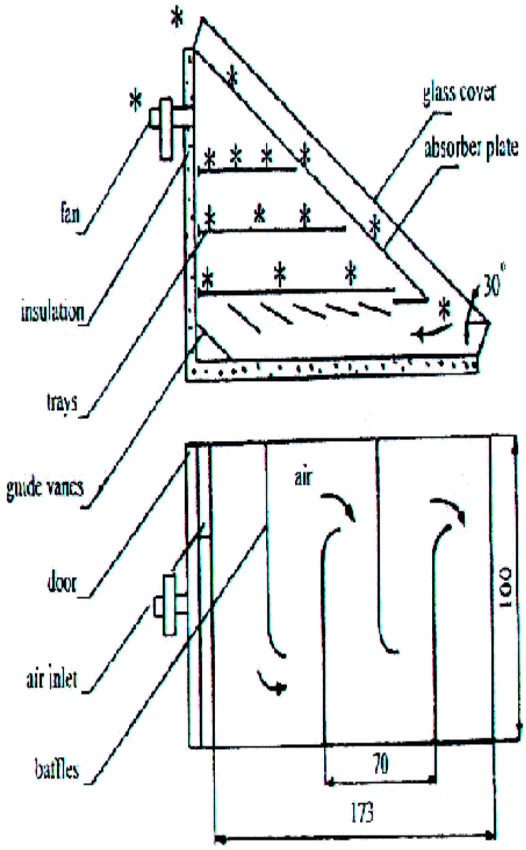
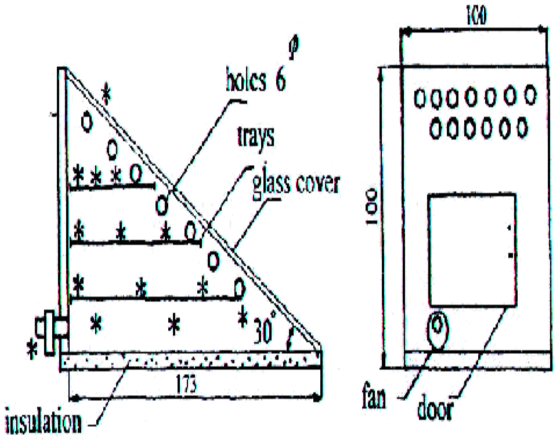


━ Thermocouple location

Dim. in cm

Fig.(1) Indirect solar dryer (solar collector and drying chamber)



━ Thermocouple location

Dim. in cm

Fig.(2)Direct solar dryer

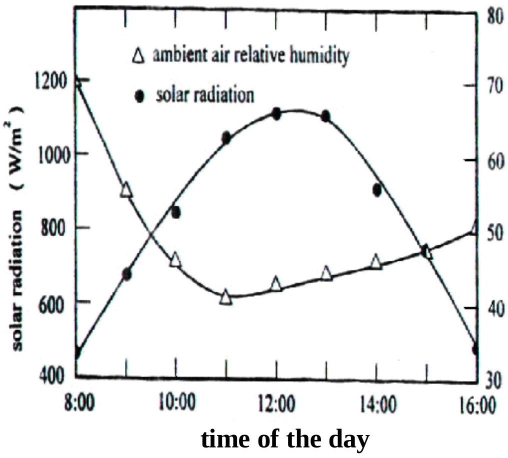


Fig. 3. Variation of the solar radiation and relative humidity of the ambient air with the time of the day.

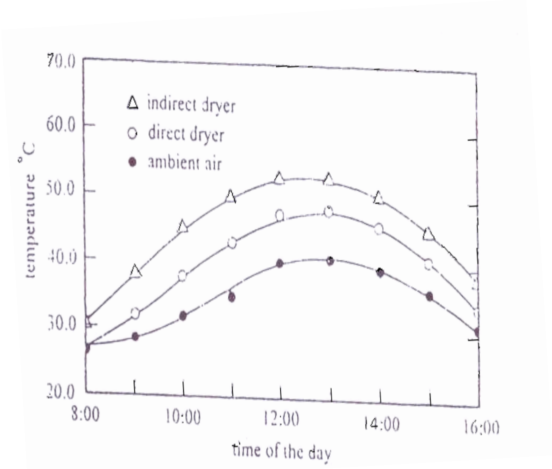


Fig. 5. Variation of the average air temperature inside the drying chamber and inside the direct solar dryer with the time of the day (V_d=320 m^3/h, m/A_d=1.25 kg/m^2).

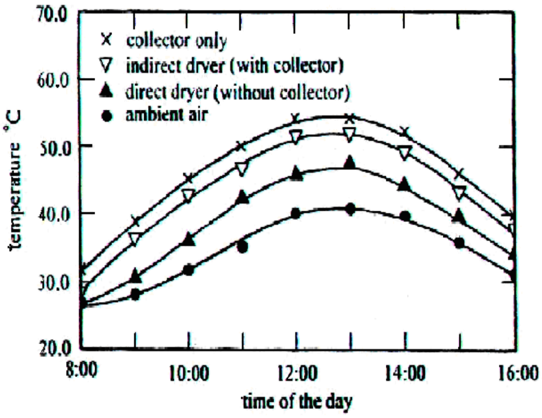


Fig. 4 Variation of air temperature at exit of solar collector, exit of drying chamber, exit of direct dryer and ambient air with the time of the day
(V_a=320m^3/h, m/A_d=1.25 kg/m^2).

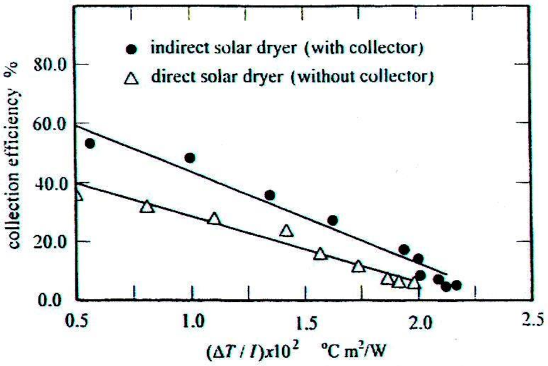


Fig. 6. Collection efficiencies in indirect and direct solar dryers.

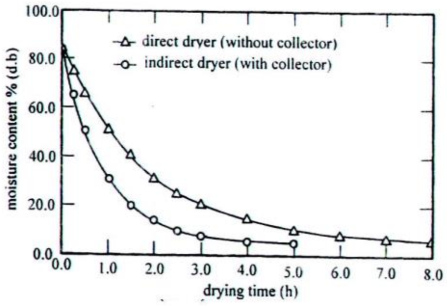


Fig.7. Variation of the moisture content of potato with the drying time for direct and in direct solar dryers (V_a=320 m^3/h, m/A_d=1.25 kg/m^2).

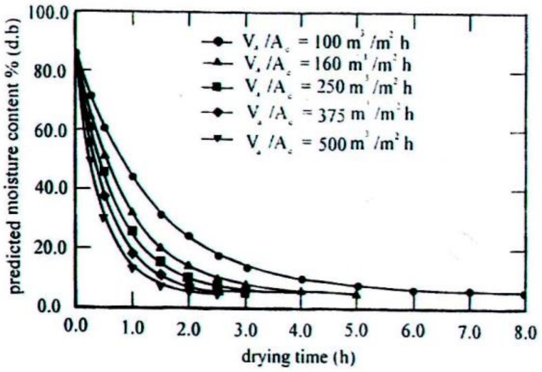
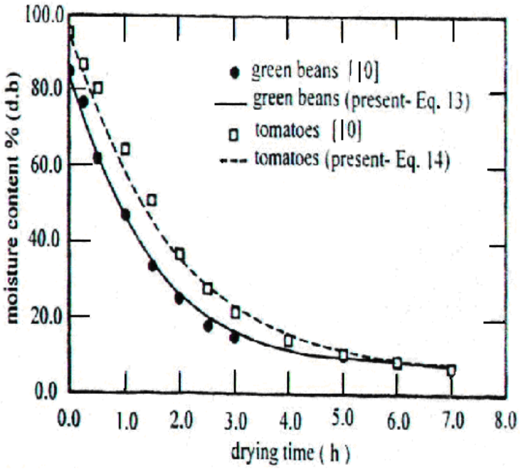


Fig. 8 Variation of the predicted moisture content with the drying time for different air flow rates in indirect solar dryer (T_{av}=25°C, ϕ=69%, $ϕ_a$=38%, m/A_d=l.25).



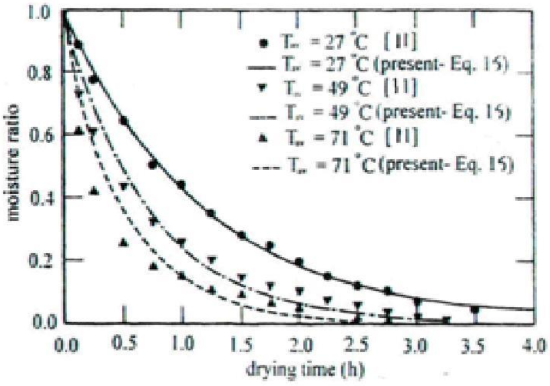


Fig. 9 Comparison between predicted results and the measured data of green beans and tomatoes (T_{av}=50°C, ϕ=70%, V_a/A_c=100 m^3/m^2 h,ϕa=47%,

Fig.10. Comparison between predicted results and the measured data of sunflower seed for different drying temperatures (ϕ=50%, $ϕ_d$=29%, V_a/A_c=1080 m^3/m^2 h).