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Modelling of a Modular Indirect Natural Convection Solar Dryer

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Abstract

Nowadays, solar drying is becoming more important than ever before around the world. If more people use solar energy to dry agriculture and others products, our environment would be cleaner and the drying process will be more efficient. This paper discusses the performance and energy analysis of natural convection indirect solar drying system. The study rig that used consists from three main parts; flat plate air solar collector, dryer cabin and chimney. This system has been instilled in the laboratory of Szent IstvánUniversity in Gödöllő city in Hungary with collector tilt angle is 45° to the south according Budapest region, to get on the maximum amount of solar radiation. MATLAB software program has been developed to model the parts of this system, according the basic heat energy balance equations. The equations have been validated with many experimental results for different agricultural products. The experimental results showed the temperature and *RH* during drying period and the losses of water and moisture of the products.

Keywords: *solar collector, dryer, energy balance, performance*

1. Introduction

The use of the solar energy is getting a greater importance especially in the agriculture products drying. At the same time, the quality control and quality preservation technology becomes also very important technologies for processing of agricultural products than before. The Traditional application and very widely used product preservation is the drying process. Solar drying technology has many features upon the traditional dry technologies, it is low cost process and clean. In the past, the Agricultural and other products have been dried by the direct sun and wind in the open air for thousands of years. A typical solar dryer improves upon the simple open-air sun system, many main features:

- Products can be dried in a shorter period of time than the simple systems. Solar dryers improve drying process time by two methods. The first, by enhancing the translucent cover (the glass cover over the heat collection area inside the solar collector to raising the temperature of the air) and enhancing absorber plate area by increasing heat transfer area. Secondly, the flexibility of improving the solar collection area allows for greater amount of the solar radiation energy.
- Solar dryers more efficient than open-air sun system. The products can be dried faster, less possibility will be lost to spoilage immediately after harvest. This is especially for products that require immediate drying such as fresh grain with high moisture content.
- Control features, the control on the drying process parameters such as air temperatures, product and air moisture content, air velocity, etc. are better than the open-air sun dryers.

According to the brief review for many literatures the performance of drying process depend mainly on the performance of solar collector. So, the improvement of solar collector will improve the dryer work also (Mahendra et al., 1987). At the same time, some products do not need for high air temperature because it will damage such as fish, meats, etc. So, the control on the process parameters, air temperature, moisture content for air and product and air speed are very important.

Othieno (1986) explained solar cabinet dryer, it was very simple structure, and consists basically from small box has been made from wood. A transparent glass sheet was used as cover at upper edges surface. The box sides and bottom surfaces can be constructed from metal sheet (Aluminium) or wood. To circulate air through

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the system, holes has been made on the sides of the drier for this purpose. Indirect solar dryers also made of wood and plywood as presented by Amouzou et al. (1986). 10–15 kg of product can dried by drying chamber in 3 days. The absorber plate for solar collector is made galvanized sheet metal painted black to get selective surface.

Madhlopa et al. (2002) studied a solar dryer system had composite absorber plate systems on the principles of psychometric. The dryer consists of a flat plate solar collector, absorber plate approved with wire mesh, glass cover, chimney and insulated drying chamber. The drying chamber and solar collector box were made from wood sheets. The solar collector was connected to a drying chamber for product dehumidification.

Simate (2003) presented a comparison of optimized mixed-mode dryer and indirect-mode with natural convection solar dryers for maize. The two solar drying simulation models were validated against results from a laboratory solar dryer with experiments carried out under a solar simulator at the University of Newcastle, UK. They reported that, in both types, the collector and dryer width are the same. Airflow in the system is driven by buoyancy force. The drying cost with the mixed-mode dryer system using was 12.76 $/ton which was about 26% less than the indirect-mode system using; the quantity of dry grain obtained from the mixed-mode dryer for the one year was approximately 2.81 tones and was less than that from the indirect mode dryer by 15%.

Halewadimath et al. (2015) studied and fabricated an indirect forced- natural convection solar air dryer to estimate its performance under dry and hot weather conditions of Hubli, Karnataka, India. The system has been tested experimentally for both natural and forced convection. The performances of natural and forced convection systems are compared. The system consists of solar flat plate collector, drying chamber and a chimney. There are six baffles (fins) attached to the absorber plate to increases the turbulence of flow and increase heat transfer area for heated air in the collector which. Also, a mathematical model was developed by Ramos et al. (2015) to simulate solar drying of grapes, the heat and mass transfer models are solved by an explicit finite differences method, by considering changing boundary conditions. Many experiments were performed on a mixed mode solar dryer located in the North of Portugal, with amount pre-blanched grapes. Simulations showed with the developed model can be good to estimate accurate drying times and then to design, control and optimize the production of foods.

Then, according to the above brief review for many literatures, the performance of drying process depend mainly on the performance of solar collector. And the improvement of solar collector will improve the dryer work also. But, some products do not need for high air temperature because it will damage such as fish, meats, etc. So, the control on the process parameters, air temperature, moister content for air and product and air speed very important. In the recent paper, mathematical analysis of passive indirect solar drying system, consists from main parts: flat plate air solar collector, dryer chamber and chimney.

2. Description of the dryer

The study represented the performance of simple convective solar dryer (distributed solar dryer with natural convection), shown in Fig. 1. The test rig is constituted of two main parts; a flat plate air solar collector. It is composed of the flat aluminium plate used as an absorber surface, covered from the above by a glass sheet was fixed on the upper edges of collector box, and collector box that insulated from all sides to decrease heat losses. There is a space between the absorber surface and the glass sheet cover. This narrow space used as an air flow duct through the solar collector and integrated with the second part.

The second part is the drying chamber made with support many trays where the product is placed. Drying chamber has been insulated and painted with black paint to decrease the losses by radiation to the surrounding. As mentioned, the study was by free convection, the movement of air was by bouncy force with using a long chimney, which permits to have a good air speed by free convection and homogeneous distribution of the heated air inside the drying chamber, it allows also having better control of the drying process.

Fig. 1: Solar dryer test unit

The drying system is energized by the sun's rays (solar radiation energy) passing through the collector glazing cover. The trapping of the solar radiation (short waves) is enhanced by the inside surfaces of the solar collector that were painted black to change it to heat energy (long waves). Then, the heat energy will transfer from the black absorber plate to the air which passing inside the collector by convection. The last energy collection method is called the greenhouse. The air current will flow through the drying chamber by the effect of green house in the solar collector. Energy exchange (heat and mass transfer) between products items and hot air inside the dryer chamber. Then, the moist and hot air rises and escapes from the upper vent in the drying chamber (chimney) while cooler air at ambient temperature enters through the lower vent in the solar collector. Therefore, an air current movement is maintained, as cooler air at a temperature ($T_{collector,in}$) enters through the lower suction vent and hot air at a temperature ($T_{chimney,out}$) leaves through the upper chimney vent.

When the dryer is empty (no products in it), the entering air at a temperature T_{in} with relative humidity X_{air} and the discharged air at a temperature T_{exit}, has a relative humidity X_{exit}. With the dryer contains no item, the inlet relative humidity X_{in} higher than exit X_{exit} because T_{exit} higher than T_{in}. As referred before, there is tendency for the hot exit air to get more moisture within the dryer, as a result of the moisture difference occurs between X_{air} and X_{exit}.

For flat-plate solar collector, it is always tilted in such a way that it receives maximum solar radiation during the day and to be perpendicular with solar radiation rays at noon. Based on Duffie and Beckman (2013), the best stationary orientation is due south in the northern hemisphere and due north in southern hemisphere. Therefore, solar collector in this work is oriented facing south and tilted at 45° to the horizontal according to the solar chart for Budapest region (Budapest 47.5° N, 19.05° E).

3. Modelling assumptions

According to the classical way to modelling, the physical base with many assumptions are used the performance for every thermal system generally and drying systems especially. To simplify physical model, there are many assumptions have been taken before modelling, as following:

1. Drying system performance works with steady state condition.
2. Air flow distribution through system components is assumed homogeneous.
3. Mass and heat transfer are one-dimensional inside system components (always with air flow direction).
4. There is one-dimensional heat flow through back insulation for solar collector.
5. Dust and dirt effects on the flat plate solar collector are negligible.
6. Wind speed is approximately constant.
7. Connecting air channels is assumed to be with no leakages and without heat losses.
8. Products items initial moisture is uniform throughout the mass of the product.

9. Product size and distribution of product items assumed uniform inside the drying chamber.
10. Product surface moisture content of the sample items instantaneously reaches to the equilibrium state with the surrounding air.
11. Surface resistance to the mass transfer at the product surface is negligible compared to internal resistance of the sample.

4. Energy balance calculations

In this section, the energy balance relations are described for the main components of drying unit as solar collector and drying chamber.

4.1. Solar collector

The solar collector has the size of 2 m x 0.5 m x 0.2 m. The solar collector with about 1 m^2 absorber plate area integrated to the dryer chamber to heat air flow that will enter the chamber. It has a transparent glass cover fixed on the top edges of the collector box and thermal insulation at the bottom base side of the metal box. For the better energy collection a black absorber plate was put on the half height of the collector body box. As mentioned, the solar collector in this work is oriented facing south line and tilted at 45° to the horizontal according to the solar chart for Budapest region. To get more absorption of solar radiation and radiation reflection reduction, absorber plate painted with matt black colour.

The energy balance on the absorber plate is obtained by equating the total radiation gained from the sun rays through the glass cover with transmittance (τ) to the total heat loosed from the absorber plate of the solar collector. Therefore:

Solar radiation per unit area = useful heat +heat losses+ reflected losses.

If τ is the transmittance of the top glazing cover sheet, I is the total solar radiation incident on the top surface of the solar collector and A_c is the area of absorber plate, then mathematically the solar radiation per unit area will be:

$$\text{Solar radiation per unit area} = \tau\, I\, A_c.$$

The solar radiation represented the total solar radiation, beam, diffuse and ground reflected radiation. Experimentally, it can be measuring by simple calibrated solar measurement device. Theoretically, according the position (Gödöllő) and the time, MATLAB software program has been developed to estimate it. For beam (direct) radiation component on the collector surface, calculated according ASHREA 2005 standard. For the diffuse (indirect) and ground reflected solar radiations, depending on Al-Joboory (2012) has been estimated.

The same for the reflected radiation from the collector, the mathematical expression reflected energy from the absorber surface is given by the following expression:

$$\text{Reflected losses} = \rho\, \tau\, I\, A_c,$$

where ρ is the reflection coefficient of the absorber surface plate. By the Substitution of solar radiation and reflected losses expressions in the general energy balance equation for the absorber plate, will get:

$$\tau\, I\, A_c = \text{useful heat} + \text{heat losses} + \rho\, \tau\, I\, A_c.$$

By rewriting the above relation:

$$\text{Useful heat} = \tau\, I\, A_c.\ (1\text{-}\rho) - \text{heat losses}.$$

For an absorber plate, according to Duffie and Beckman $(1\text{-}\rho) = \alpha$ and then:

$$\text{Useful heat} = (\alpha\tau)\, I\, A_c - \text{heat losses}.$$

The above expression represents the energy balance equation for the absorber plate surface. For this study, it is very important to estimate air temperature rise thorough the collector. The change of air temperature through it depend on how much energy that absorbed (collected) by the absorber plate. So the above energy balance is not enough useful to show the behaviour of air temperature.

In the direction of air stream, the inlet ambient air to the collector carried sensible heat energy also depend on its mass m^o and temperature $T_{c,i}$. The same for the outlet air, it will catch the heat from stored absorber plate energy by convection, then it will leave the solar collector with the same mass flow rate and new temperature equal to $T_{c,o}$. Then by considering the heat energy content for inlet and outlet air, the final energy balance for the air solar collector system will be:

Useful heat = ($\alpha\tau$) I A_c – heat losses+ inlet air heat content – outlet air heat content.

Mathematically:

$$M\ C_p \frac{dT_{c,o}}{dt} = (\alpha\tau)\ I\ A_c - U\ A_c\ (T_c - T_a) + m^o\ C_p\ T_{c,i} - m^o\ C_p\ T_{c,o}. \qquad \text{(Eq. 1)}$$

Then by rewriting Eq. (1), get:

$$\frac{dT_{c,o}}{dt} = \frac{1}{M.C_p}\left[(\alpha\tau)\ I\ A_c - U\ A_c\ (T_c - T_a) + m^o\ C_p\ T_{c,i} - m^o\ C_p\ T_{c,o}\right], \qquad \text{(Eq. 2)}$$

where M is the mass of air inside collector duct in (kg), T_a is the temperature of ambient air in (K), T_c is the average temperature of the absorber plate in (K), C_p is an air specific heat at constant pressure in (J/kgK), $\tau\alpha$ is called transmittance-absorptance product for glazed collector, and it was for black colour absorber plate about 0.87 (considered for this study) according to Anderson et al. (2009) and U represents to the total energy losses from the flat plate solar collector: top U_t, back (bottom) U_b and side edges U_s heat losses. It means:

$$U = U_b + U_s + U_t. \qquad \text{(Eq. 3)}$$

The bottom heat loss coefficient and by the basic of conduction heat transfer resistance for the wall or material layer with thickness equal X_b and material thermal conductivity equal K_b, the back heat loss coefficient U_b will be as follow in Eq. (4):

$$U_b = \frac{K_b}{X_b}. \qquad \text{(Eq. 4)}$$

The same for collector edges heat loss coefficient U_s, but with multiplying by the area ratio between collector side edges area to the solar collector area as shown in Fig. 2. Then, U_s for collector length L, width W and depth X will when the side edges have K_s as a thermal conductivity and side thickness equal X_s, will be:

$$U_s = \frac{K_s}{X_s}\left[\frac{X.(L+W)}{L.W}\right]. \qquad \text{(Eq. 5)}$$

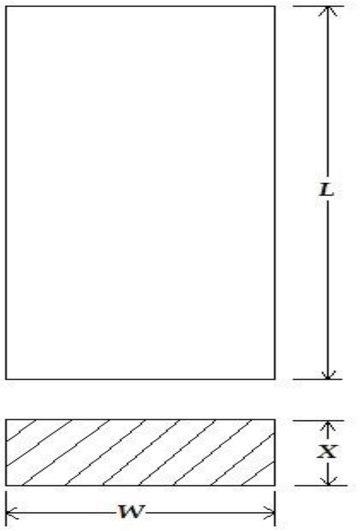


Fig. 2: Solar collector dimensions

The estimation of top energy loss coefficient for most solar collectors is complicated with using basic heat transfer relations. However, with good designed system, the collector loss should be low so that it is not necessary to predict it with great accuracy. To estimate the value of tope loss coefficient, as Kalogirou mentioned in his book an empirical useful formula is used by depending on number of covers, absorber plate temperature, and ambient temperature, etc. as follow:

$$U_t = \left[\frac{N}{\frac{C}{T_c}.\left[\frac{T_c - T_a}{N+f}\right]^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma(T_c+T_a)\left(T_c^2+T_a^2\right)}{\frac{1}{\varepsilon_p+0.0059N.h_w}+\frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g}-N}. \qquad \text{(Eq. 6)}$$

where N represents to the covers number, h_w is an wind heat transfer coefficient, σ is Stefan-Boltzmann constant, ε_p and ε_g are the absorber plate and glass cover emissivity, and each of C, f and e are constants and calculated from Eq. (7) as follow:

$$C = 520\ (1-0.000051\ \beta^2).$$

$$f = (1+0.089\ h_w - 0.1166\ h_w \varepsilon_p)\ (1+0.07866\ N). \qquad \text{(Eq. 7)}$$

$$e = 0.43\ (1-100/T_c).$$

$$h_w = 2.8+3V.$$

where β is a bulk coefficient of expansion of air in K^{-1} and V represents to the ambient wind velocity in m/s.

4.2. Dryer

The drying chamber (the dryer) with 7 trays for the different products items. The drying cabin dimensions are 0.8 m x 1 m x 0.65 m. The drying chamber is integrated with the solar collector by a small duct (indirect drying). The heated air exit from the collector will enter the chamber with high temperature and low moisture content. The total energy required for drying process for given quantity of any type of products items can be determined by using the basic energy balance equation for the evaporation of water. According to the schematic diagram for the dryer, the basic energy balance equation (mass + heat), as written below:

$$Q_{air,inlet} + Q_{product,inlet} = Q_{air,outlet} + Q_{product,outlet} + energy\ losses\ .$$

For perfect system insulated, the value of energy losses from the dryer will be very small, so it can be neglected. Then, the latent energy of the evaporated water from the product with mass W_v and latent heat of vaporization equal L_v will equal the heat lost from the air which flowed through the dryer. Mathematically:

$$W_v\ L_v = m^o\ C_p\ (T_{d,i} - T_{d,o}), \qquad \text{(Eq. 8)}$$

where $T_{d,i}$ and $T_{d,o}$ are inlet and outlet temperatures through the dryer. The inlet dryer temperature $T_{d,i}$ equal to the outlet temperature of the solar collector $T_{c,o}$ by assuming that is no heat losses through connection small duct between the solar collector and dryer. Where the mass of water evaporated from the product W_v calculated from Eq. (9):

$$W_v = m_i \frac{w_i - w_f}{100 - w_f}, \qquad \text{(Eq. 9)}$$

where m_i is the initial mass of product in (kg), w_i is the initial moisture content and w_f is the final moisture content. During drying process, water at the surface layer of the product evaporates and water in the inner part transfer gradually to the surface to get evaporated. The ability of this water movement depends on the porosity of the product item material and the surface area available.

The basic theory of drying process was described by Lewis (1921) based on the partial similarity with Newton's law of cooling and is often used to mass transfer in thin-layer drying as follow in Mahedra et al. (1987):

$$\frac{dw}{dt} = -k\ (w - w_e), \qquad \text{(Eq. 10)}$$

where k represents drying process constant, w_e is an equilibrium mass, by solving the above differential Eq. (10) for these conditions, (at $t = 0$, $w = w_o$) and (at $t = \infty$, $w = w_e$), get:

$$\frac{w_t - w_e}{w_o - w_e} = -e^{-kt}. \qquad \text{(Eq. 11)}$$

The above term in Eq. (11) called moisture ratio (MR), then:

$$\frac{w_t - w_e}{w_o - w_e} = MR\ . \qquad \text{(Eq. 12)}$$

A product material stills for a long time at a fixed temperature and relative humidity then will eventually gradually reach a moisture content that is in equilibrium with the moist air. The equilibrium state does not mean that the product item and the air have the same moisture content. It simply means that an equilibrium condition exists such that there is no net exchange of moisture (latent heat) between the product material and the heated air. This equilibrium moisture content (w_e) is a function of the temperature, the relative humidity, and the type of the product.

Finally, to estimate the efficiency for all the system (solar collector and dryer chamber), the following relation represent the ratio between input energy and output energy to the totally system has been calculated. The system efficiency indicates the overall thermal performance of a drying system including the efficiency of a solar collector, the drying chamber and any other supplement add to the system:

$$Totalefficiency\ = \frac{W_v\ L_v}{I\ A_c}. \qquad \text{(Eq. 13)}$$

As known to increase heat transfer by convection, turbulence of air should increase. So, the effects of free convection will be enhanced by adding a long chimney in which exiting air is heated even more by friction and enhance the buoyant flow of air. Some studies showed that the installation of three small fans and a photovoltaic cell is equivalent to the effect of chimney with 12 m length.

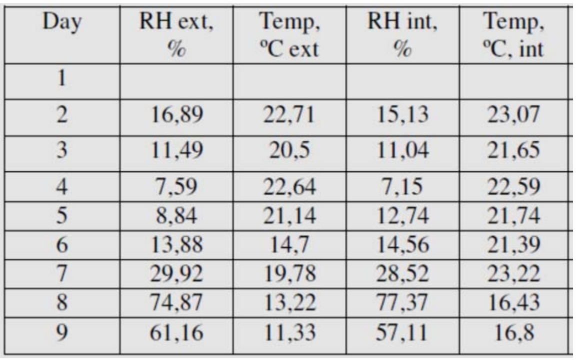
5. Results for validation

In this section a validation of the energy relation are performed based on the measured results for different products drying and environmental variables. The solar drying experiments were carried out between April and May 2006 at Gödöllő, Hungary (Farkas et al., 2006).

5.1. Environmental variables during the experiments results

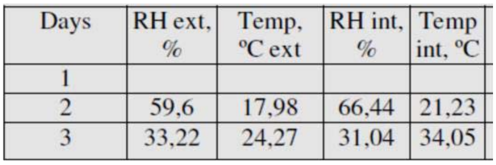
This section shows the conditions of temperature and relative humidity during the drying period for different products as carrot, apple and potato (Tables 1-3 and Figs 3-4).

Table 1: Relative humidity (RH) and average inlet and outlet temperatures for carrot



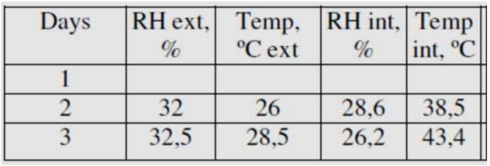
Day	RH ext, %	Temp, ºC ext	RH int, %	Temp, ºC, int
1				
2	16,89	22,71	15,13	23,07
3	11,49	20,5	11,04	21,65
4	7,59	22,64	7,15	22,59
5	8,84	21,14	12,74	21,74
6	13,88	14,7	14,56	21,39
7	29,92	19,78	28,52	23,22
8	74,87	13,22	77,37	16,43
9	61,16	11,33	57,11	16,8

Table 2: Relative humidity (RH) and average inlet and outlet temperature for apple



Days	RH ext, %	Temp, ºC ext	RH int, %	Temp int, ºC
1				
2	59,6	17,98	66,44	21,23
3	33,22	24,27	31,04	34,05

Table 3: Relative humidity (RH) and average inlet and outlet temperature for potatoes



Days	RH ext, %	Temp, ºC ext	RH int, %	Temp int, ºC
1				
2	32	26	28,6	38,5
3	32,5	28,5	26,2	43,4

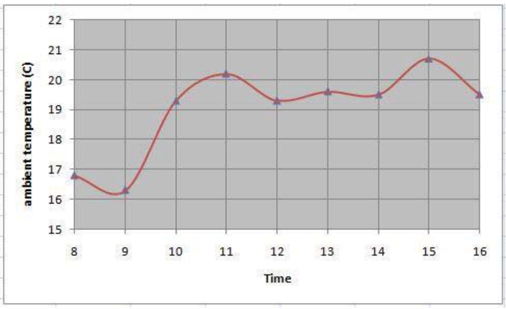


Fig. 3: Average daily ambient temperature during drying period of 8 days

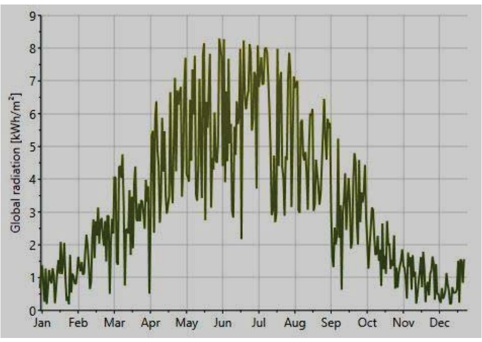


Fig. 4: The global solar radiation for 2006

5.2. Loss of water

In Figs 5-7 the changes in mass of the carrots, placed in different trays, are represented through the drying period. In Fig. 5 it can be seen that after 4 days the carrots lost 87% of the initial weight. In Fig. 6 it can be seen that after 24 hours the apples lost 84% of the initial weight. In Fig. 7 it can be seen that after 24 hours the apples lost 83,5% of the initial weight.

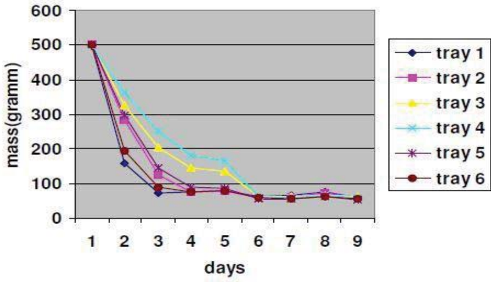


Fig. 5: Loss of water during the drying period for the carrot

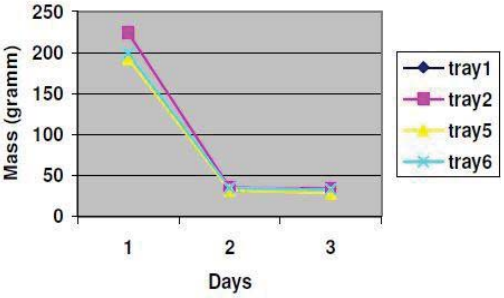


Fig. 6: Loss of water during the drying period for the potatoes

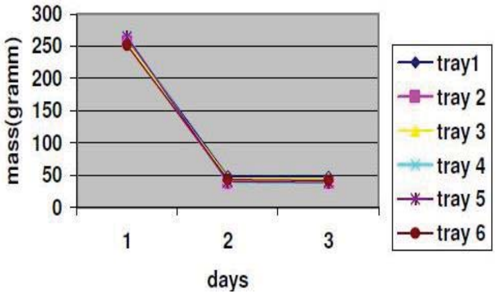


Fig. 7: Loss of water during the drying period for the apple

5.3. Temperature distribution

Figs 8-10 show for the products the distribution of the temperature outside and inside the dryer between 8 a.m. and 4 p.m. Fig. 8 shows that for the carrots there is no difference in temperature among the trays and inside the chamber is higher than outside in the second part of the day (12-16) hours. For the apples the temperature inside the chamber is always higher than that outside. This difference is more evident between 11-16 hours. The Fig. 10 shows, that for the case of potatoes there is difference in temperature among the trays in particular in the first tray where the temperature is higher than that other trays and the temperature inside the chamber is always higher than that outside.

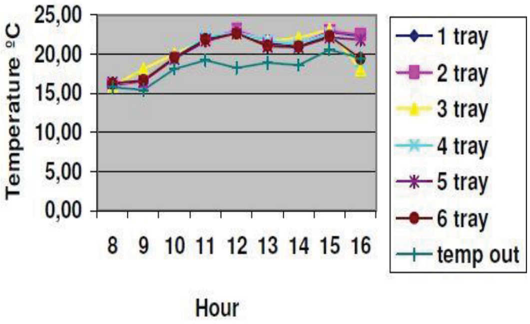


Fig. 8: Temperature distribution outside and inside the dryer for the carrots

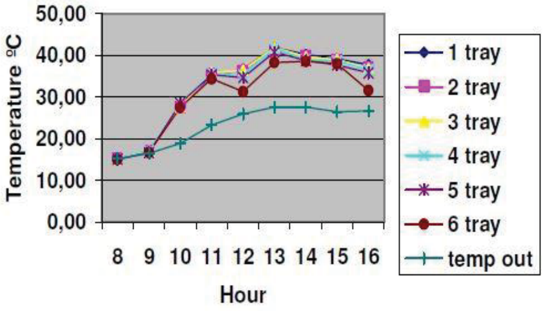


Fig. 9: Temperature distribution outside and inside the dryer for the apples

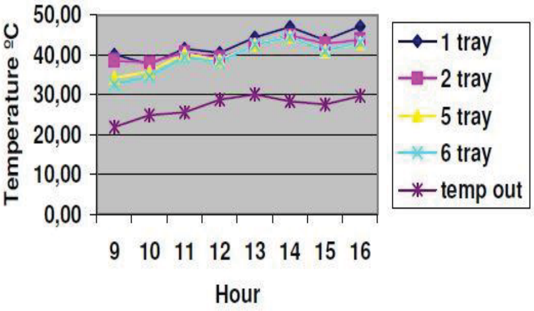


Fig. 10: Temperature distribution outside and inside the dryer for the potatoes

6. Conclusions

The temperature of air inside the system (drying chamber and solar collector) is much higher than the surrounding temperature during most times of day. That means, these systems better performance than open-air sun drying systems. The control on the drying parameters such as air velocity, temperatures, moisture contents, etc. are not complicated and not expensive.

Drying process with using solar heater, depends on the temperature and moisture content difference between an air stream and product items inside the insulated chamber. It is very important to know the type of product item, to estimate the temperature rang that is suitable to save it from damaging during drying process. With some drying products like fish, meat, yam chips, etc., over heating must be avoided to save the quality of the product.

Also that is many methods to enhance these types of dryers, such as heat transfer area is increasing, air turbulence increasing, and improvement the insulating of the system, etc. for this study, a long chimney is integrated with the drying chamber to increase air velocity during drying process. The increasing of air velocity will improve the rate of water evaporated from the product item. Also, the very important point in this dryer, it is very economic process (low costs of constructions), simple design and efficient control.

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