

## Development of an Efficient Flat Plate Solar Air Heater for Drying and Water Heating Purposes

(Pembangunan Sebuah Pemanas Udara Suria Plat Rata yang Cepak bagi Tujuan Pengeringan dan Pemanasan Air)

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### ABSTRACT

*A 1.7 m<sup>2</sup> flat plate solar air heater was designed and developed in the Department of Agricultural Mechanization, The University of Agriculture Peshawar, Pakistan in collaboration with the Department of Environmental Sciences, University of Peshawar, Pakistan. It was operated under an average solar irradiance of 0.9 kJ.m<sup>-2</sup>.h<sup>-1</sup> in the month of September, 2013. It worked under an efficiency of 7.5 to 21%. The heat collected by the air heater was given to air flowing as a medium inside it. This hot air was given to a drying section and water heating tank for drying and water heating purposes. The drying section provided a temperature in the range of 40-50°C and humidity of 10-30% from 10:00 am to 3:00 pm. The water heating tank provides hot water with a temperature of 35- 45°C from 10:00 am to 5:00 pm. Furthermore, the drying section was used to dry apples, onions and persimmons. All the products showed a consistent moisture loss from them with an optimum drying rate. The two term exponential model showed that all the three products dried have a good correlation with drying time with R<sup>2</sup> values higher than 0.90. It was concluded that flat plate solar air heaters is the best technology for water heating and drying purposes and is a good alternative of conventional energy sources.*

*Keywords: Efficiency; drying; flat plate solar air heater; solar energy; water heating*

### ABSTRAK

*Sebuah pemanas udara suria plat rata berukuran 1.7 m<sup>2</sup> direka dan dibangunkan di Jabatan Pertanian Pemesinkan, Universiti Pertanian Peshawar, Pakistan dengan kerjasama Jabatan Sains Alam Sekitar, Universiti Peshawar, Pakistan. Ia telah beroperasi menggunakan purata sinaran suria sebanyak 0.9 kJ.m<sup>-2</sup>.jam<sup>-1</sup> pada bulan September 2013. Ia menggunakan kecekapan 7.5 hingga 21%. Haba yang dikumpul oleh pemanas udara telah diberikan kepada udara yang mengalir sebagai medium di dalamnya. Udara panas ini telah diberikan kepada bahagian pengeringan dan tangki pemanas air untuk tujuan pengeringan dan pemanasan air. Bahagian pengeringan menyediakan suhu dalam lingkungan 40-50°C dan kelembapan 10-30% dari 10:00 pagi hingga 3:00 petang. Tangki pemanas air menyediakan air panas dengan suhu 35-45°C dari 10:00 pagi hingga 5:00 petang. Selain itu bahagian pengeringan juga digunakan untuk mengeringkan epal, bawang dan pisang kaki. Semua produk menunjukkan kehilangan lembapan yang konsisten dengan kadar pengeringan optimum. Model eksponen dua istilah menunjukkan bahawa tiga produk kering tersebut mempunyai kolerasi yang baik dengan masa pengeringan dengan nilai R<sup>2</sup> lebih tinggi daripada 0.90. Kesimpulannya, pemanas udara suria plat rata adalah teknologi terbaik untuk tujuan pemanasan air dan pengeringan dan adalah alternatif yang baik sebagai sumber tenaga konvensional.*

*Kata kunci: Kecekapan; pemanas air; pemanas udara suria plat rata; pengeringan; tenaga solar*

### INTRODUCTION

Energy is the base of development of a nation. A nation rich with energy resources is said to be the leading nation of the world. Countries are trying to increase their energy resources due to increase in the demand which is increasing day by day. Due to huge consumption of conventional energy resources like coal, natural gas and petroleum fuel, which were becoming scarce, therefore nations of the world were trying to rely on non conventional energy resources like solar, wind, hydro and bio (Hanif et al. 2012a).

Non conventional energy resources also known as renewable energy sources are the best alternative choice to overcome the scarcity of conventional energy resources and to overcome the energy crises all over the world.

Developed countries have almost achieved this goal but developing and underdeveloped countries are still far behind in adopting these technologies. These countries are still relying on using conventional energy resources for heating and cooking purposes. The utilization is on unsustainable way causing damaged to the environment. The emission of harmful gases are not only a threat to life but also a cause of global warming (Yeh & Lin 1996).

Every energy generation and transmission method affects the environment. As it is obvious conventional generating options can damage air, climate, water, land and wildlife, landscape, as well as raise the levels of harmful radiation. Renewable technologies are substantially safer offering a solution to many environmental and social

problems associated with fossil and nuclear fuels. Solar energy technologies provide obvious environmental advantages in comparison to the conventional energy sources, thus contributing to the sustainable development of human activities. Not counting the depletion of the exhausted natural resources, their main advantage was related to the reduced CO<sub>2</sub> emissions and normally absence of any air emissions or waste products during their operations (Mohanraj & Chandrasekar 2009).

Among the renewable energy resources, solar energy has an enormous tendency to meet the energy demand of the underdeveloped world. Solar technologies are safe and environmental friendly. This is a good choice if used instead of coal, gas and petroleum oil for heating, drying and cooking purposes. Solar energy technologies in the form of solar collectors are widely used in the Europe and American regions for various purposes like electricity generation, drying, building and water heating. In regard to the socio-economic view point the benefits of the exploitation of solar energy comprises increase the national energy independency, provision of significant work opportunities, diversification and security of energy supply, support of the deregulation of energy markets and acceleration of the rural electrocution in developing countries (Munir 1985; Sozen et al. 2008). The aim of the study was to develop a flat plate solar air heater for drying and water heating purposes and to make institutional awareness of its applications.

## MATERIALS AND METHODS

### SITE

The experiment was conducted at the Department of Environmental Sciences, University of Peshawar, Pakistan located between the longitudes 71.0.15° and 72.0.45° East and Latitudes 33.0.45° and 34.0.01°. The site was perfect to receive sunlight from dawn to dusk. There were no shading of any structure on the collector which can block the sunlight from reaching the collector. The collector will be oriented facing south at a tilt angle of 40° with horizontal. The tilt is 6° more than the latitude of Peshawar due to the fact that Peshawar receives more solar energy at this angle (Hanif et al. 2012a).

### COLLECTOR

The collector assembly consisting of the following parts:- The flat plate solar collector consists of an insulation box. The insulation box was 1.83 m long, 0.91 m wide and 0.18 m broad having an inside volume of 0.30 m<sup>3</sup>. The material for building the insulation box was wood of poplar and deodar. It was fully insulated on the inside with the help of polyurethane foam locally called as packing material. It was done to minimize heat loss from the collector. Wood of poplar and deodar was used for the manufacture of the insulation box because wood is a good insulator, cheap, easily available, having a high

melting point and have low weight. The box was painted in black and made fully air tight to minimize heat loss from its walls as heat loss from the collector decreased the overall efficiency of the collector. The absorber, which was (1.8 × 0.9 m) 0.32 mm thick v-corrugated black painted steel sheet, fixed in the middle of the wooden box with a total area of 1.62 m<sup>2</sup>. The absorber was assumed to be a perfect black body which absorbs maximum heat. The v-corrugation decreases the reflection of light from the absorber. Steel sheet has a high absorption of 80% of light, but black paint helps to increase the absorbance of the steel sheet up to 8%. So when black was painted then the total absorbance of the steel sheet becomes 88%. It also has 30% emissivity which higher than any other material. Steel sheet is low in cost, has high melting point and easily available in the local market as compared to other metal sheets. The cover material or glazing was 1.83 × 0.91 m and 8 mm thick glass sheet placed at the top of the insulation box to shield the absorber from air currents so that less heat was lost from the absorber and permit maximum solar radiation to reach the absorber. Glass was used as glazing because it was easily available, low cost, has a high melting point and 88% transmittance which is higher than any other covering. It also transmits long and short wave radiations from itself while reflecting 12% of the incident light.

The inlet is 0.10 m in diameter made up of P.V.C (polyvinyl-chloride) pipe fixed at the bottom of the collector due to the fact that air enters from lower side at lower temperature. The outlet has the same diameter of 0.10 m and provided at the top of the collector due to the fact that hot air goes up and colder air comes from lower side to replace the hot air. Both inlet and outlet have a cross sectional area of 0.0152 m<sup>2</sup>. There was a 0.15 m exhaust fan fixed on the inlet of the collector for pushing the air into the collector. The fan was provided with a regulator which regulates air mass flow rates at 1.5, 2.8, 5.8, 8.5, 11.7, 14.2, and 17.5 kg.min<sup>-1</sup>. The collector was supported and tilted with the help of a frame made up of angle iron. The frame was built with four legs in such a way that the front two legs have a height of 0.35 m and the rear two are 1.0 m high making the collector tilted at 40° with the horizontal towards south. A water heating tank was connected beside the solar air heater. The tank was 0.9 m high and 0.3 m in diameter having a total volume of 0.27 m<sup>3</sup>. A pipe extended from the tank pass over the absorber from where it receives heat and give it to the water in the tank (Figure 1).

### HEAT AVAILABLE TO THE COLLECTOR IN THE FORM OF SOLAR ENERGY

Solar energy (kJ.m<sup>-2</sup>.hr<sup>-1</sup>) available per unit time per unit area was measured with the help of pyranometer. The solar intensity was calculated using (1) (Hanif et al. 2012a)

$$E_a = P_c \times C_v, \quad (1)$$



FIGURE 1. General view of the flat plate solar air heater

where,  $E_a$  is the heat energy available to the solar collector in the form of solar irradiance ( $\text{kJ.m}^{-2}.\text{hr}^{-1}$ );  $P_c$  is the pyranometer constant (0.88); and  $C_v$  is the chart value of pyranometer ( $\text{kJ.m}^{-2}.\text{hr}^{-1}$ ).

#### HEAT CONSUMED/LOADED BY THE COLLECTOR TO THE WATER TANK AND DRYING CHAMBER

The solar energy was converted into heat energy by the absorber and was in the form of heat energy consumed (kJ) by the water used for heating and drier in unit time. This energy is the product of the total energy consumed by water and air used as mediums inside the drier is given by (2) (Karim & Hawlader 2003).

$$E_h = (Fr \times CA \times \Delta T) \times (m \times C_w \times \Delta T), \quad (2)$$

where,  $E_h$  is the heat energy loaded by the collector ( $\text{kJ.m}^{-2}.\text{hr}^{-1}$ );  $Fr$  is the mass flow rate ( $\text{kg}.\text{hr}^{-1}$ );  $CA$  is the specific heat of air ( $1.006 \text{ kJ}.\text{Kg}^{-1}.\text{oC}^{-1}$ ); is the change in inlet and outlet temperature ( $^{\circ}\text{C}$ );  $m$  is the mass of water (kg); and  $C_w$  is the specific heat of air ( $1.006 \text{ kJ}.\text{Kg}^{-1}.\text{oC}^{-1}$ ).

#### EFFICIENCY OF THE COLLECTOR

Efficiency  $\eta$  (%) is the ratio of heat consumed by the water and drier to heat available to the collector in the form of solar radiation in unit time. Efficiency was calculated using (3) (Ahmed 2011),

$$\eta = \frac{E_h}{E_a} \times 100, \quad (3)$$

where,  $\eta$  (eta) is the efficiency of the solar collector (%);  $E_a$  is the heat energy available to the solar collector in the form of solar irradiance ( $\text{kJ.m}^{-2}.\text{hr}^{-1}$ ); and  $E_h$  is the heat energy loaded by the collector ( $\text{kJ.m}^{-2}.\text{hr}^{-1}$ ).

## RESULTS AND DISCUSSIONS

### DRYING ENVIRONMENT PROVIDED BY THE SOLAR AIR HEATER TO ONIONS

Drying environment provided by the flat plate solar air heater to the onions is given in Figures 2 and 3. Figure 2 shows the temperature data of the solar air heater assembly. The temperature of the absorber fitted in solar air heater start rising from  $40^{\circ}\text{C}$  at 9:00 am and reached to almost  $100^{\circ}\text{C}$  at noon. It begins to decrease from noon to 4:00 pm and reaches to  $45^{\circ}\text{C}$ . Due to the temperature of the absorber the temperature of the drier changes as absorber helps to make the air hotter which is then given to the drier. In the drier the temperature reaches to  $20^{\circ}\text{C}$  at 9:00 am which begun to rise and reaches to almost  $50^{\circ}\text{C}$  at Noon. It again starts decreasing and reaches to  $25^{\circ}\text{C}$  at the end of the drying period of the day. The drier provide a temperature in the range of  $40\text{-}50^{\circ}\text{C}$  from 10:00 am to 3:00 pm. Figure 3 shows the humidity inside the drier and of outside environment. The humidity of the drier start decreasing at 9:00 am from 65% and reached to almost 10% at noon. It begin to increase from noon to 4:00 pm and reaches to 55%. This change was due to the change in the driers temperature. The drier provide humidity in the range of 10-30% from 10:00 am to 3:00 pm. The results of temperature and humidity shows that there were 6 h of drying available in the day for suitable drying of onions. These results were in accordance with the findings of Hanif et al. (2013, 2012a, 2012b) who dried grapes using a dish type solar air heater and with the findings of Altfeld et al. (1988).

### HEAT AVAILABLE TO THE COLLECTOR IN THE FORM OF SOLAR ENERGY

Heat available to the solar air heater was the solar energy falling on the collector area in unit time and is given in

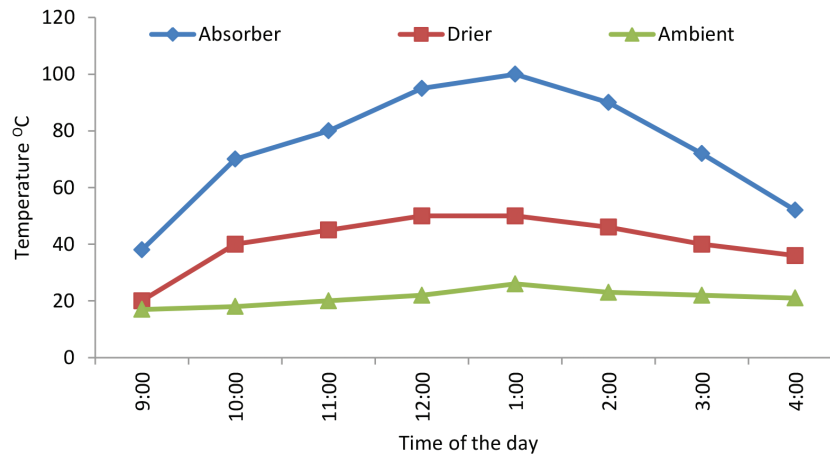


FIGURE 2. Temperature data of the solar air heater assembly

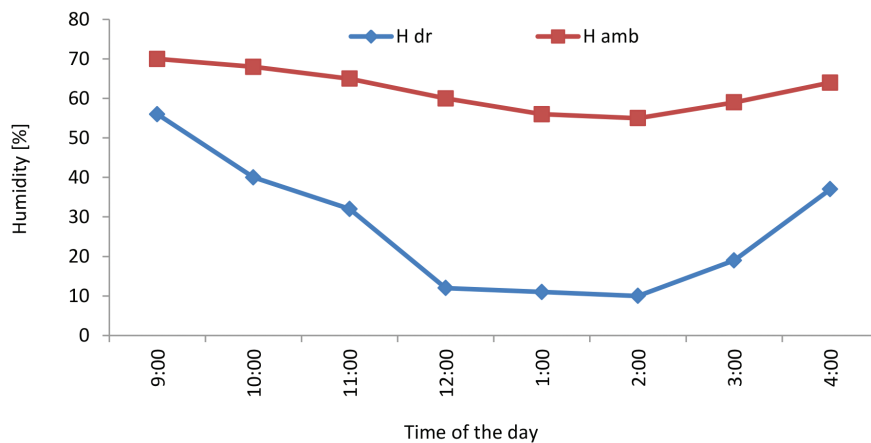


FIGURE 3. Humidity of the drier and ambient air

Figure 4. The solar irradiance starts falling on the solar air heater at 7:00 am and reaches to maximum of almost  $1200 \text{ kJ.m}^{-2}.\text{hr}^{-1}$  at noon. It again starts decreasing from 1:00 pm and comes to zero at 7:00 pm in the evening. The graph is bell shaped due to which chi square goodness of fit test was applied on the data which give the value of 0.931 showing a very good relationship of solar irradiance with time of day. These result were in accordance with the findings of Ayensu (1997), Eisenmann et al. (2003) and Hanif et al. (2013, 2012).

#### WATER HEATED BY THE SOLAR HEATER

Figure 5 shows the heat gained by the water tank at different day times. The data shows that more heat was gained by the water inside the water tank at noon due to high temperature of the absorber which transferred more heat to the water inside the pipes running from the absorber to the tank. Temperature data of the water tank and ambient air is shown in Figure 6.

The temperature remain from  $35\text{-}45^\circ\text{C}$  from 10:00 am to 3:00 pm. This suggested that we can use the water tank for using hot water for domestic use for 5 h daily. These

results were in accordance with the findings of Ertkin et al. (2008) and Munir (1985) who developed flat plate solar collectors for water heating purposes.

#### EFFICIENCY OF THE SOLAR AIR HEATER

Efficiency of the solar air heater is given in Figure 7. The collector starts giving out hot air at 8:00 am having efficiency of 7.5% and reaches to maximum of almost 21% at noon. Although the solar energy is available at 7:00 am but the solar air heater starts showing efficiency at 8:00 am. This was due to the fact that the collector first goes to the transit state and then go on to equilibrium state where it shows increase in its efficiency when solar irradiance increases. The efficiency again starts decreasing from 2:00 pm and comes to zero at 6:00 pm due to non availability of solar energy that is sunlight. The graph of efficiency was also bell shaped as that of solar irradiance and due to this chi square goodness of fit test was applied on the efficiency data which give the value of 0.897 showing a very good relationship of solar irradiance with time of day. These results were in accordance with the findings of Hanif et al. (2013, 2012b) and Ertekin et al. (2008).



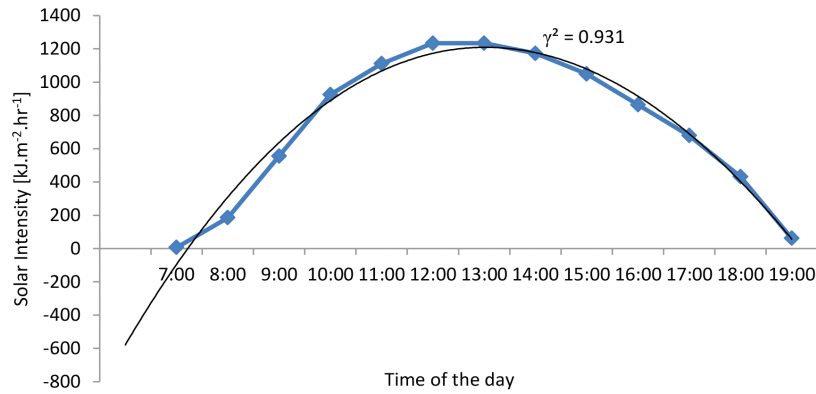


FIGURE 4. Solar energy available to the collector

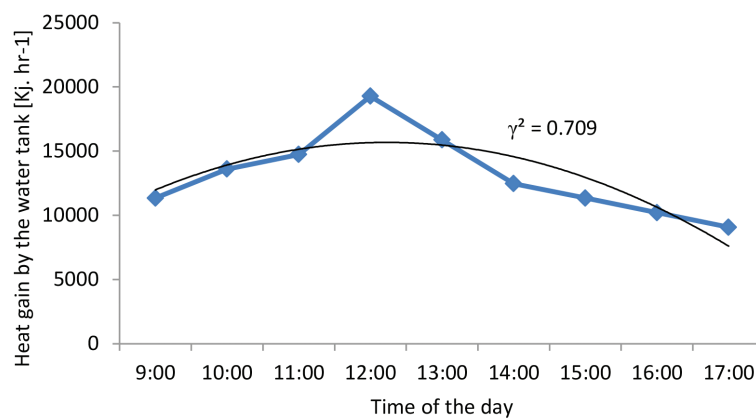


FIGURE 5. Heat gained by water tank vs time of day

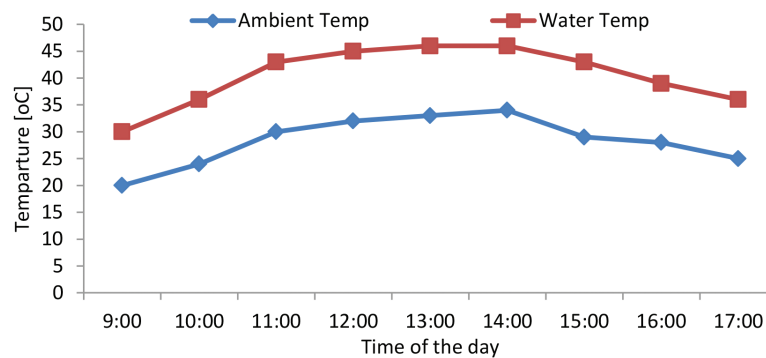


FIGURE 6. Temperature of ambient air and water inside the water tank

#### THE DRYING CURVES OF ONIONS

Moisture loss in each hour of drying by onions is shown in Figure 8. The initial moisture of onion flakes was 93% which reduced to 5% in 16 h of drying which was equal to two days of drying period in the drying section. At first day the onion flakes lost 30% moisture and on the second almost 55% of moisture was lost by onions. The two term exponential model shows that there is a good relationship between moisture loss and time of day with  $R^2$  value of 0.9924. These results were in accordance to

the finding of Kadam et al. (2008) and Kumar et al. (2005) who recorded moisture loss at the same drying conditions using a flat plate solar air heaters and a solar tunnel dryer. Drying rate of onion flakes at each hour of drying is shown in Figure 9. The initial drying rate of onion flakes was  $0.05 \text{ g}_{\text{H}_2\text{O}} \text{ g}_{\text{DM}}^{-1} \text{ hr}^{-1}$  which reduced to 0.01 after 16 h of drying. The first 4 h of drying shows the constant rate drying while the rest of 11 h was falling rate drying. The first day the drying rate starts at  $0.05 \text{ g}_{\text{H}_2\text{O}} \text{ g}_{\text{DM}}^{-1} \text{ hr}^{-1}$  and reaches to  $0.035 \text{ g}_{\text{H}_2\text{O}} \text{ g}_{\text{DM}}^{-1} \text{ hr}^{-1}$  at the end of the day

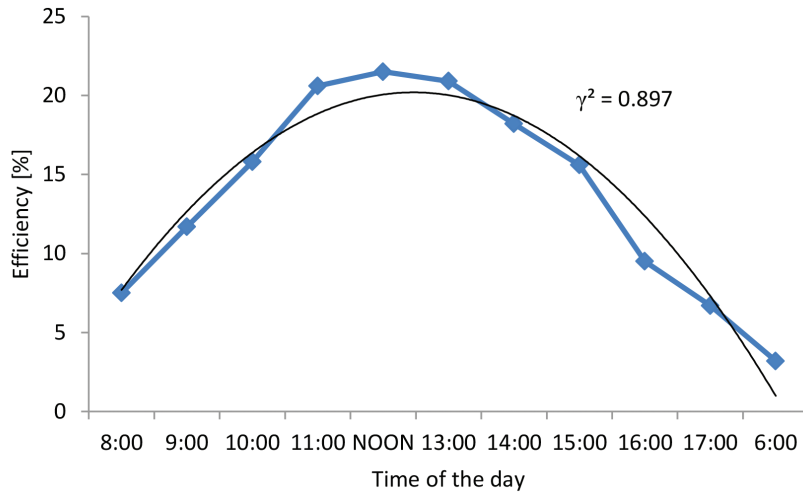


FIGURE 7. Efficiency of the solar air heater

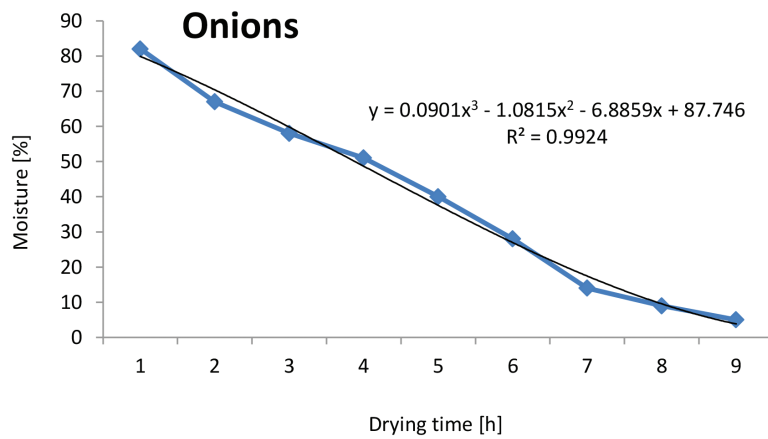


FIGURE 8. Moisture loss by onions with drying time

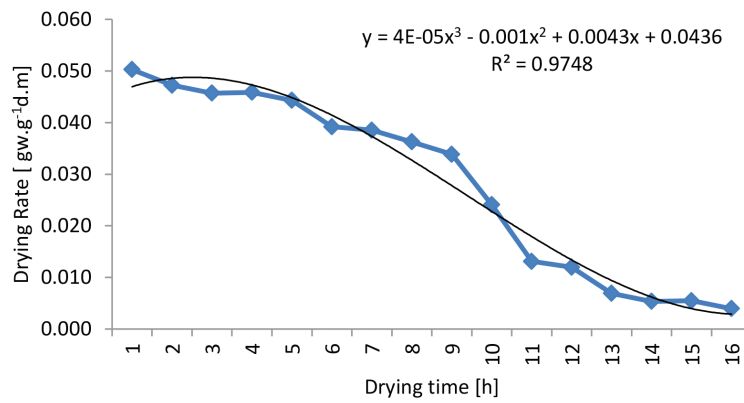


FIGURE 9. Drying rate of onions with drying time

which was again initiated at second day and reached to  $0.01 \text{ g}_{\text{H}_2\text{O}} \text{ g}_{\text{DM}}^{-1} \text{ hr}^{-1}$  at the end of the drying periods. The two term exponential model shows that there is a good relationship between drying rate and time of day with  $R^2$

value of 0.9748. These results were in accordance with the finding of Hanif et al. (2012b) and Strom (2011) who recorded moisture loss at the same drying conditions using flat plate solar air heaters.

## THE DRYING CURVES OF APPLES

Moisture loss in each hour of drying by apples is shown in Figure 10. The initial moisture of apples chips was 85% which reduced to 5% in 9 h of drying which was equal to two days of drying period in the drying section. At first day the apples chips lost 35% moisture and on the second almost 50% of moisture was lost by apples. The two term exponential model shows that there is a good relationship between moisture loss and time of day with  $R^2$  value of 0.9924. These results are in accordance with the finding of Ahmed (2011) and Wang et al. (2007) who recorded moisture loss at the same drying conditions using a flat plate solar air heaters and a solar tunnel dryer. Drying rate of apples chips at each hour of drying is shown in Figure 11. The initial drying rate of apples chips was  $0.026 \text{ g}_{\text{H}_2\text{O}} \text{ g}_{\text{DM}}^{-1} \text{ hr}^{-1}$  which reduced to 0.001 after 9 h of drying. The first 3 h of drying shows the constant rate drying while the rest of 6 h was falling rate drying. The first day the drying rate starts at 0.025 and reaches to 0.05 at end of the day which was again initiated at second day

and reached to 0.002 at the end of the drying periods. The two term exponential model shows that there is a good relationship between drying rate and time of day with  $R^2$  value of 0.99814. These results are in accordance with the finding of Santos et al. (2005) and Wang et al. (2007) who recorded moisture loss at the same drying conditions using a flat plate solar air heater.

## THE DRYING CURVES OF PERSIMMONS

Moisture loss in each hour of drying by persimmon slices is indicated in Figure 12. The initial moisture of persimmon slices was 70% which reduced to 6% in 9 h of drying which was equal to two days of drying period in the drying section. At first day the persimmon slices lost 50% moisture and on the second almost 25% of moisture was lost by persimmon slices. The two term exponential model shows that there is a good relationship between moisture loss and time of day with  $R^2$  value of 0.992. These results are in accordance with the finding of Ehiem et al. (2009) and Karim and Hwaladar (2003) who recorded moisture loss

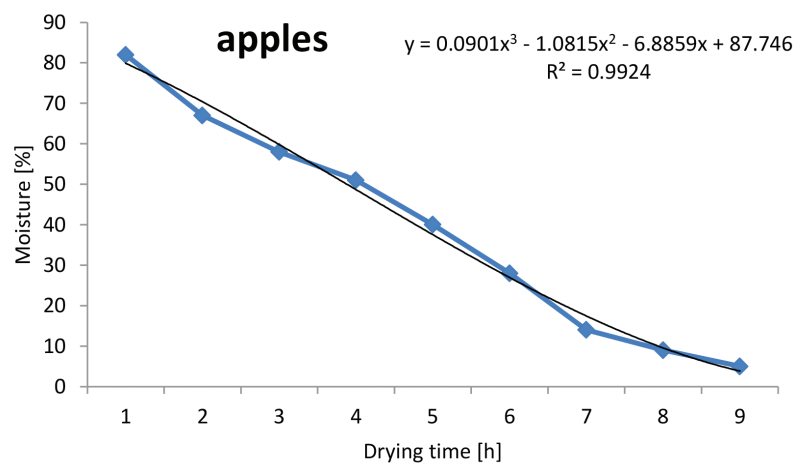


FIGURE 10. Moisture loss by apples with drying time

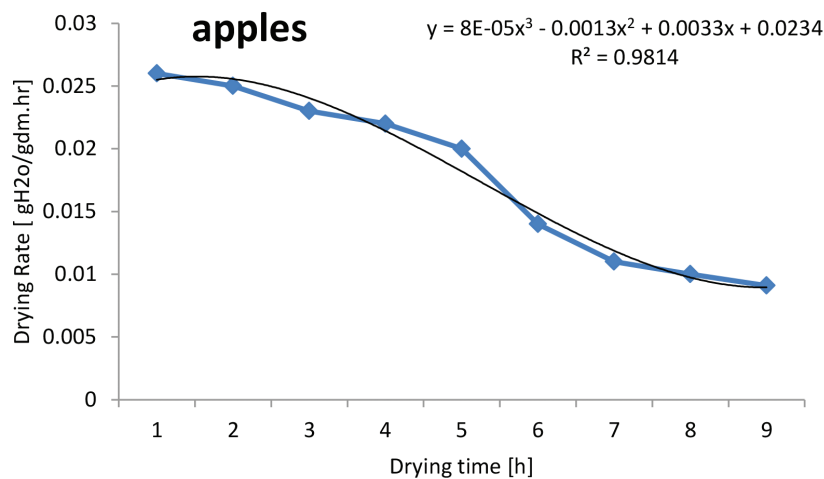


FIGURE 11. Drying rate of apples with drying time

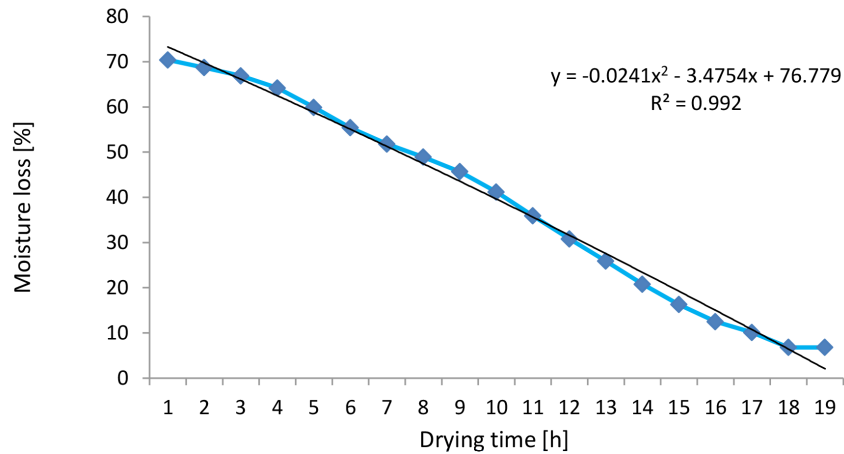


FIGURE 12. Moisture loss by persimmon

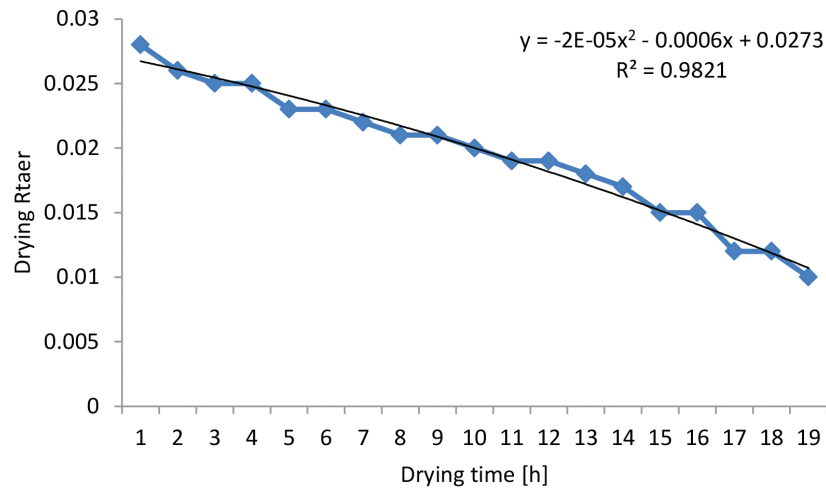


FIGURE 13. Drying rate of persimmons

at the same drying conditions using a flat plate solar air heaters and a solar tunnel dryer. Drying rate of persimmon slices at each hour of drying is shown in Figure 13. The initial drying rate of persimmon slices was  $0.028 \text{ g}_{\text{H}_2\text{O}} \text{ g}_{\text{DM}}^{-1} \text{ hr}^{-1}$  which reduced to 0.011 after 19 h of drying. The first 3 h of drying shows the constant rate drying while the rest of 16 h was falling rate drying. The first day the drying rate starts at  $0.028 \text{ g}_{\text{H}_2\text{O}} \text{ g}_{\text{DM}}^{-1} \text{ hr}^{-1}$  and reaches to  $0.023 \text{ g}_{\text{H}_2\text{O}} \text{ g}_{\text{DM}}^{-1} \text{ hr}^{-1}$  at end of the day which was again initiated at second day at the rate of 0.23 and reached to 0.015 at the end of the drying periods. The two term exponential model shows that there was a good relationship between drying rate and time of day with  $R^2$  value of 0.982. These results were in accordance with the finding of Ahmed (2011) and Ibrahim (2012) who recorded moisture loss at the same drying conditions using a flat plate solar air heaters.

#### CONCLUSION

Flat plate solar air heater worked efficiently to dry different products including apples, onions and persimmons and

heat up water up to  $45^\circ\text{C}$ . All the products showed a consistent moisture loss from them with an optimum drying rate. The two term exponential model showed that all the three products dried have a good correlation with drying time with  $R^2$  values higher than 0.90. Flat plate solar air heaters is the best technology for water heating and drying purposes and is a good alternative of conventional energy sources.

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