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Impact of drying temperatures and air mass flow rates on the drying performance of a Parabolic Trough Solar Collector (PTSC) used for dehydration of apricots

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Abstract

An efficient parabolic trough solar collector (PTSC) was developed from locally available materials and used for dehydration of apricots. The apricots were cut into two halves and dried after pre-treatment of 1% with sodium benzoate solution. Apricots were dried at temperatures of 40, 50 and 60°C under three different air mass flow rates of 1.57, 2.29 3.56 $kg.min^{-1}$ at less than 30% humidity Shortest apricots drying time was 16 hours at 60°C temperature and air flow rate of 3.56 $Kg.min^{-1}$ with an average drying rate of 0.035 $g.hr^{-1}.cm^{-2}$.. It was followed by drying time of 19 hours at 55°C. The air mass flow rate was 2.29 $Kg.min^{-1}$with an average drying rate of 0.29 $g.hr^{-1}.cm^{-2}$. Initial moisture content of the apricots was 86% which reduced to less than 10% after drying. Results showed that both air mass flow rates and drying temperatures significantly ($P< 0.000$) affected efficiency, moisture lost, drying rate and drying time. The PTSCs must be operated at high temperatures and high air mass flow rates to achieve maximum performance. Apricots must be dried at high temperature and high air mass flow rates to get minimum time for getting valuable dried apricots.

Key words: Solar Energy, Parabolic trough, concentrating collector, Apricots, Moisture Loss, Drying Rate

Introduction

Apricot (*Prunus armeniaca*) is the sixth main fruit of Pakistan. Total area under apricot cultivation in Pakistan is about 28.8 thousand hectares with production of 210.9 thousand tons. The average production is 6.03 tons. ha^{-1} (MINFAL, 2011). Northern areas of Pakistan have the high production of apricots but almost 30-35% losses occur there as apricots cannot be stored for a longer period of time as they are perishable and spoil very quickly (Khalid et al., 2011). On-farm losses can greatly be reduced if apricots are dried with the help of solar dryers because they are one of the fruits best suited to drying (Henderson and Brenand, 2004). Dehydrators are the most efficient way to dehydrate apricots because they have a controlled heat source and a fan to circulate and remove the moist air. They are also able to dehydrate products more quickly and safely as pathogen attacks are minimized under control drying environment (Henderson and Charlotte, 2004; Istvan, 2011).

Hussain et al. (2008) studied dehydration of fruits by solar energy using thermo-convectional dehydrators of direct and indirect type made from indigenously available material. They concluded that agricultural products like apricots must be dried using solar thermal collectors as they dried the products under hygienic environment. The cost of dehydration was nominal, whilst the quality of the dried products was of marketable standards. The findings suggested the large scale use of such dehydrators as an economic means of drying fruits and vegetables. Yadollahinia et al. (2008) worked on experimental dryer and studied the effect of moisture and velocity of air on the product. They concluded that high velocities and low humidity accelerated the drying process. Rafiee et al. (2007) studied the effect of low humidity and high temperatures on drying. They concluded that there

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was significant effect of both temperature and humidity on the drying process. Drying occurs more quickly at high temperature and low humidity using a solar dehydrator. Hashemi and Shimizu, (2008) and Seiiedlo et al. (2010) studied the effect of temperature and air velocity on drying time of perishable fruits like apricots. Both of them concluded that increase in temperature and air velocity reduced drying time significantly. High temperatures effects the proteins present in the products and causes browning. They also concluded that temperatures higher than 60°C have a more negative effect on products to be dried.

Pakistan receives solar energy with intensity about 750 $w.m^{-2}$ throughout the year except for the monsoon. The prospect of utilizing solar energy is very bright (Ahmad, 2011). Like the rest of Pakistan, Peshawar and FATA receives about 1 $cal.cm^{-2}.min^{-1}$ which is almost 750 $w.m^{-2}$ (Khattak et al., 2010). The use of dehydrators in the form of solar collectors is increasing day by day in Pakistan. There is a good market of these technologies which is developed further in the future. The specific demand is of efficient solar drier that could dry more fruits in less time (ASF, 2011). The objective of this research was to develop a parabolic trough solar concentrating collector use to dry apricots in the Northern Areas of Pakistan. This research might enable us to develop processes and procedures to enhance performance of parabolic trough solar collector (PTSC) for valuable drying of apricots.

Materials and Methods

Experimental Site

The experiment was conducted at village Gundi, Khyber Agency (34° 0' 29" N / 71° 34' 22" E) of Federally Administrated Tribal Area (FATA), Pakistan. The collector was oriented facing south having a tilt angle of 34^o equal to the latitude of the experimental site to receive maximum solar radiation.

Description of the PTSC

A Parabolic Trough Solar Collector assembly (Figure. 1) consists of two units.

i. A Parabolic Trough used as Reflecting Unit

This composed of a parabolic trough solar reflector. The reflector was basically a steel sheet that concentrated the incoming solar radiation on the centrally located black painted steel pipe having a diameter of 5cm.. The pipe diameter was arbitrarily selected with the assumption that it will allow sufficient air flow under natural conditions as well. The pipe received ambient air that was heated inside it and then delivered to the drying unit for drying of apricots. Before constructing the parabolic structure, the desired focal length was by using the following equation (Price et al., 2002):

$$f = X^2 / 4Y$$

Where, f is focal length of the trough, X is radius and Y is the aperture of the trough.

ii. Drying Unit (Hanif et al., 2012)

This unit consisted of a steel box fully insulated on the inside with the help of polystyrene foam. The box was 1 m high, 0.55 m wide and 0.57 m long. There were three exhaust fans each having a diameter of 0.05 meters. The total volume of the drying box was 0.3135 m^3. The fans were used to suck hot air inside of the drying box through the absorber pipe. The flow rate of each fan was controlled by the help of dimmer fixed on the drying unit. There was an outlet fixed on the top of the drying unit having a diameter of 0.02 meters that removed humid air from the unit.

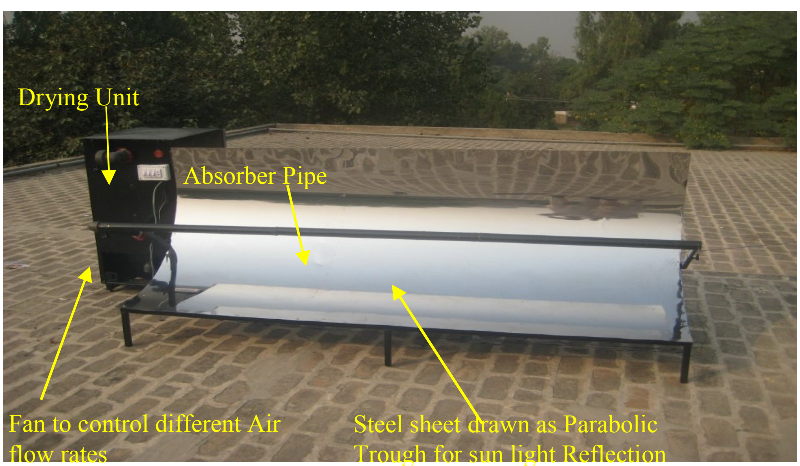

Figure 1. The Parabolic Trough Solar Collector showing its main parts.

Experimental design and treatment applications

The experiment was laid out as a randomized complete block design with a factorial arrangement of the treatments consisting of 3 levels of temperature and 3 levels of air mass flow rate, replicated 3 times and resulting in a total of 27 treatments. Factors and their treatment levels are given as below:

Factor #1 (Temperature)

T1 = 40°C, T2 = 50°C, T3 = 60°C

Factor#2 (Air mass Flow Rate)

F1 = 1.57 $Kg.min^{-1}$, F2 = 2.29 $Kg.min^{-1}$, F3 = 3.56 $Kg.min^{-1}$

Solar energy and its conversion to heat

Solar energy ($kJ.m^{-2}.Sec^{-1}$) available per unit time per unit area was measured with the help of mechanical pyranometer. The solar intensity was calculated using the equation (Hanif et al., 2012):

$$Ea = Pc \times Cv \qquad (1)$$

Where, Ea is the solar irradiance ($kJ.Sec^{-1}$), Pc is the pyranometer constant (367.78) for the one used in the experiment) and Cv is the chart value of pyranometer. This solar energy was converted into heat energy by the absorber pipe and was in the form of heat energy consumed ($kJ.Sec^{-1}$) by the drier in unit time. This energy is the product of the the total energy consumed by the air (medium) inside the dryer is given by equation (Karim and Hawlader, 2003):

$$E_h = Fr \times C_p\,(\Delta T) \qquad (2)$$

Difference between inlet and outlet temperatures of the collector (ΔT) was determined by the help of thermometers.

Air Mass Flow Rate

Air mass flow rate ($kg.s^{-1}$) is the mass of air flowing from the collector to the drying box in unit time. It is the product of velocity V ($m.sec^{-1}$) of air at the outlet area A (m^2) of the outlet and density ($kg.m^{-3}$) of air. Air mass flow rate determined using equation (Ahmed, 2011). The air mass flow rate was changed by changing the speed of the fan fixed at the outlet.

$$Fr = V \times \quad \times A \qquad (3)$$

Efficiency of PTSC

Efficiency η (%) is the ratio of heat consumed by the drier unit Eh to heat available to the collector Ea in the form of solar radiation. Efficiency was calculated using the equation (Ahmed, 2011).

$$\eta = \frac{Eh}{Ea} \times 100 \qquad (4)$$

Moisture Loss and Drying Rate

Moisture loss (%) by apricots after each hour of drying was determined. The products were dried to less than 10% moisture content to minimize mold, insects and bacterial attack. The initial moisture content was determined by taking 3 samples in an oven and dried for 48 hours at a temperature of 105°C to completely remove the moisture present in them (Ehiem, 2009). After determining the total moisture, the moisture loss after each hour in drying was determined by using equation (Mohanraj and Chandrasekar, 2009).

$$MC = \frac{W_l}{Wi} \times 100 \qquad (5)$$

Also drying rate D_r ($g_w.gdm^{-1}.cm^{-2}.hr^{-1}$) was calculated using the equation (Henderson and Perry, 1976).

$$D_r = \frac{(W_l)}{(D_m \times A_p \times Dt)} \qquad (6)$$

where W_l is the moisture loss during time interval D_t from product with surface of A_p. The apricots were dried till the moisture content becomes less than 10%. The drying time is noted from the beginning till the moisture becomes less than 10%.

Experimental procedure

Only good quality apricots were used in these experiments. About six (6) kg of apricots were cut into halves and blanched for 5 minutes in hot water at 80°C. After that pretreatment of 1% sodium benzoate solution was given for two minutes. Then the initial moisture content was determined by oven-drying method. The apricots were put on trays of drying unit having 80% perforation and dried until the consecutive weights of samples remained constant i.e. the moisture content of 10% wet basis was achieved (Santos et al., 2005). The fans were switched on and the air mass flow rate through the outlet was adjusted according to the design of the experiment (1.57, 2.29, 3.56 $kg.min^{-1}$). The velocity of air at the inlet of the tray was measured with the help of digital anemometer. Solar intensity was measured with the help of mechanical pyranometer. Temperature and humidity at the inlet and outlet of the PTSC and drying unit were recorded every hour with the help of a hygrometer (Mahmood et al., 2005). All the experimental observations were made after transient state when the drier attains the steady state condition (Wilcke, 1980). The experiments were repeated three times. The characteristics of the PTSC like drier thermal consumption, available solar irradiance and inlet and outlet temperatures were studied and also drying characteristics of apricots such as moisture content and drying rate were determined by using equations (1-6) respectively.

Statistical analysis

Analysis of variance (ANOVA) was used to evaluate the effect of temperatures and air mass flow rate on PTSC efficiency, drying time, drying rate and moisture loss by apricots. A two factorial Randomized Complete Block Design was used to find the main factor and the interaction effect of drying temperature and air mass flow rate on the performance of PTSC and drying mechanism of apricots. A software named SPSS version 17 was used for ANOVA. Comparison of means was performed with Duncan's Multiple Range Test.

Results

Solar energy and its conversion to heat

The solar energy available to the collector during the drying period is given in Figure 2. The solar intensity graph recorded by pyranometer shows that a total of 12 hours (6:00 am to 6:00 pm) of solar energy in the form of sunlight was available. The intensity of solar energy was higher at noon (12:00) which is about 367 KJ. At this time the PTSC collected the maximum heat (Figure 2) because of high efficiency of the PTSC. The Chi-squared goodness of fit test shows that the distribution of solar energy available (Ea) is normal with chi square value of 0.998 and P value = 0.009. Similarly the distribution of solar energy consumed (Eh) is also normal with chi square value of 0.967 and P value = 0.007. The site receives a brilliant amount of solar radiation. The intensity was 260 KJ.min^{-1} which was far better for the purpose of solar drying. The intensity of sunlight was high at noon. The PTSC began to convert incident solar irradiance to heat from 9:00 am till 6:00 pm. Therefore, a total of 9 hours were available for apricots for drying under a temperature range of 40-60°C and humidity of less than 30%.

Efficiency of PTSC

The data regarding the efficiency of PTSC with different drying temperatures and air mass flow rates is shown in Figure 3. The variance analysis was done for finding the effect of temperature and the air mass flow rate of the efficiency of the PTSC. The significant difference (P < 0.000) was found by drying temperatures and mass flow rates as well as their interaction on the efficiency of PTSC (Table 1) while the replication effect was not significant. The mean values (Table 2) Shows that at T1 and T2 the efficiency was 44% which becomes higher at T3 with 49%. Efficiency on F1 was 45% which increase to 47% at F2. Similarly an increase in efficiency was recorded when air mass flow was increased to F3. Efficiency increased from 47% to 48%.

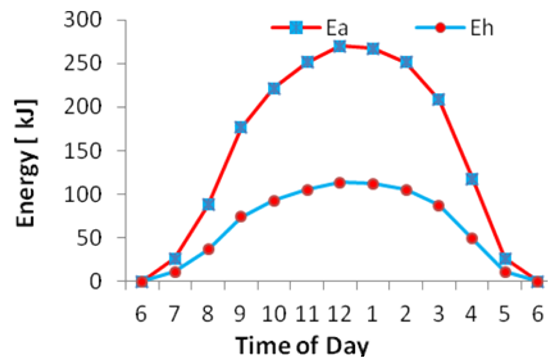

Figure 2. Energy available and consumed by the PTSC and drier.

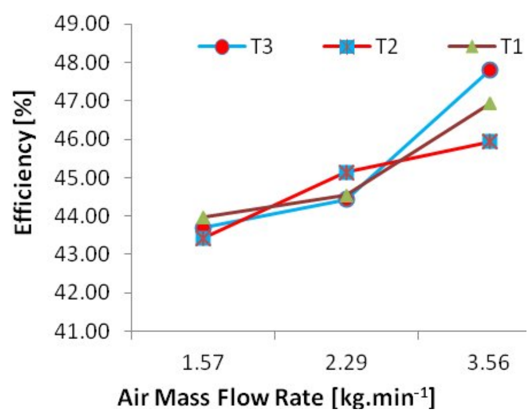

Figure 3. Efficiency of PTSC with different air mass flow rates under different temperatures.

Table 1. Analysis of variance for Efficiency.

Source	Degree of Freedom	Sum of Square	Mean Square	F- value	Prob
Replication	2	4.018	2.009	4.2799	0.0324^{Ns}
T	2	63.333	31.667	67.4556	0.0000 *
F	2	312.900	156.450	333.2659	0.0000 *
TxF	4	25.579	6.395	13.6219	0.0001*
Error	16	7.511	0.469		
Total	26	413.342			

The star (*) Indicates significance difference at 1% confidence level; Ns indicates non significant Effect

Table 2. Means Comparison of Efficiency @ 1% confidence interval by Duncan's Multiple Range Test.

Factor		Mean
Replication	R1	15.984a
	R2	16.231a
	R3	16.898a
Drying Temperature	T1	19.206a
	T2	17.498b
	T3	17.490b
Air Mass Flow Rate	F1	20.726a
	F2	15.972b
	F3	12.416c
LSD = 1.389		

Means followed by different alphabets are significantly (α = 0.01) different from each other

Moisture Loss and Drying Rate

The initial moisture content of apricots was 86% and apricots were dried until the final moisture content reached to less than 10%. It was due the fact that pathogen attack was minimized when dried fruits having a moisture content less than 10%. The statistical analysis (Table. 3) Showed that drying temperature, air mass flow rate and their interaction have significant ($P < 0.000$) effect on moisture loss (%) from apricots. The means comparison (Table 4) shows that moisture loss from apricots was more at T3. It was about 4.7% in each hour. T3 is followed by T2 with 4.5% followed by T1 with 4.4%. Also the data of air mass flow rates were affecting the moisture loss. At F3 moisture loss was 4.9% followed by F2 and F1 with 4.6 and 4.2%.

The statistical analysis (Table. 5) showed that drying rate was significant ($P < 0.000$) affected by drying temperature, air mass flow rate and their interaction. The means comparison (Table. 6) Shows that the drying rate of apricots was more at T3. It was about 0.139 $g_w.g_{dm}^{-1}.cm^{-2}.hr^{-1}$ in each hour. T3 is followed by T2 with 0.123 $g_w.g_{dm}^{-1}.cm^{-2}.hr^{-1}$ followed by T1 with 0.111 $g_w.g_{dm}^{-1}.cm^{-2}.hr^{-1}$. Also the data of air mass flow rates were affecting the moisture loss. At F3 drying rate was 0.149 $g_w.g_{dm}^{-1}.cm^{-2}.hr^{-1}$ followed by F2 and F1 with 0.127 and 0.104 $g_w.g_{dm}^{-1}.cm^{-2}.hr^{-1}$. Moisture loss from apricots as a function of time is given in Figure. 4. At F1T1 the apricots took 24 hours to be dried. At F2T2 the apricots took 20 hours to be dried and at F3T3 the apricots took 16 hours to be dried. So drying time decrease as we increase the temperature and Mass flow rate.

Table 3. Analysis of variance for Moisture loss by Apricots.

Source	Degree of Freedom	Sum of Square	Mean Square	F- value	Prob
Replication	2	0.059	0.029	0.8240	0.0624^{Ns}
T	2	0.387	0.194	5.4550	0.0156^{Ns}
F	2	1.476	0.738	20.7875	0.0000 *
TxF	4	0.086	0.021	0.6050	0.0051*
Error	16	0.568	0.036		
Total	26	2.576			

*Indicates significance at the 1% confidence level

Ns indicates non significant Factor

Table 4. Means Comparison of Moisture loss by Apricots @ 1% confidence interval by Duncan's Multiple Range Test.

Factor		Mean
Replication	R1	4.544a
	R2	4.467a
	R3	4.578 a
Drying Temperature	T1	4.400b
	T2	4.500ab
	T3	4.689 a
Air Mass Flow Rate	F1	4.222b
	F2	4.789a
	F3	4.578a
LSD = 0.318		

Means followed by different alphabets are significantly (α = 0.01) different from each other

Table 5. Analysis of variance for Drying rate of Apricots.

Source	Degree of freedom	Sum of Square	Mean Square	F- value	Prob
Replication	2	0.001	0	2.3846	0.0012*
T	2	0.003	0.002	12.0769	0.0000 *
F	2	0.007	0.003	23.6154	0.0000 *
TxF	4	0.001	0	2.3462	0.0091*
Error	16	0.002	0		
Total	26	0.015			

*Indicates significance at the 1% confidence level

Ns indicates non significant Factor

Table 6. Means Comparison of Drying rate of Apricots @ 1% confidence interval by Duncan's Multiple Range Test.

Factor		Mean
Replication	R1	0.123b
	R2	0.119c
	R3	0.131a
Drying Temperature	T1	0.111c
	T2	0.123b
	T3	0.139a
Air Mass Flow Rate	F1	0.149a
	F2	0.127b
	F3	0.104c
LSD = 0.006		

Means followed by different alphabets are significantly (α = 0.01) different from each other

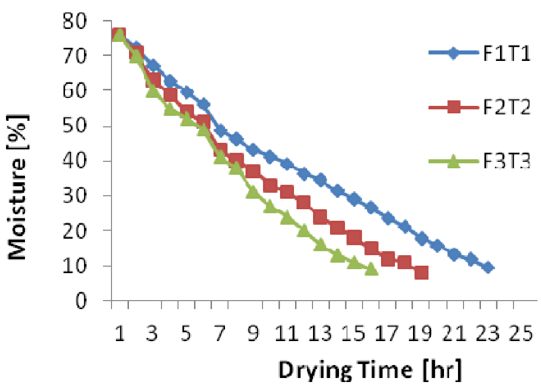

Figure 4. Interaction of Drying Temperature and Air mass flow ratee of Moisture loss from Apricots.

Discussions

The site received 260 KJ.min^{-1}, a brilliant amount of solar radiation, suitable for the purpose of solar drying. A total of 9 hours were available for apricots for drying under a temperature range of 40- 60°C and humidity of less than 30%. The PTSC performance results showed that efficiency was significantly affected by drying temperature, air mass flow rate and their interactions. The greater the difference between the collector and drying unit's temperature and the ambient temperature the greater was the heat loss. At high temperatures of 60°C, the collector has a high average efficiency at different flow rates as compared to 50°C and 40°C. The effect of drying temperature over increase in efficiency is significant having P value 0.000. The reason for this was that at low ambient temperature, difference between the outside environment and the collector temperature was more and thus the collector lost more heat to the surroundings. At a low ambient temperature the enthalpy of air was less and needed more heat to be warmed up. At high ambient temperatures the air had high enthalphy and needed less amount of heat to be warmed up. As a result the average efficiency of the collector at 60°C was greater than that at 50°C and 40°C. Also collector shows high efficiency at high air mass flow rate. This is because at a high mass flow rate, more air was pumped into the collector that resulted in more heat delivery to the drying unit. This ultimately increased efficiency of the collector. These results are in the agreement with the findings of Karim et al. (2003), Ehiem et al. (2009), Khattak et al. (2010) and Hashemi et al. (2008) who recorded a significant increase in efficiency with an increase in drying temperature and air mass flow rate. The performance of PTSC to dry apricots was significantly affected by drying temperature, air mass flow rates and their interactions. Both moisture loss and drying rate of apricots were higher at high temperature and high air mass flow rates. As moisture loss and drying rate both are directly related with temperature and air mass flow rate, high temperature of 60°C and high air mass flow rate of 3.56 kg. min^{-1} the moisture loss and drying rate were hgher. These results are also in the agreement with the findings of Ahmad (2011), Mahmood et al. (2005), Mohanraj and Chandrasekar (2009), Santos et al. (2005) and Wilcke (1980) who recorded a significant increase in moisture loss and drying rate with an increase in drying temperature and air mass flow rate. Acosta-Esquijarosa et al. (2011) also recorded that drying kinetics are affected by both drying temperature and air mass flow rates. They concluded that drying is faster when temperature and mass flow rate in increased.

Conclusion

Based on the findings obtained in this study, it is concluded that:

The Efficiency of the PTSC increased significantly with the increase in the air mass flow rate as well as drying temperature. It is recommended to operate PTSC with air as medium of heat transfer at a higher air mass flow rate and within a high range of drying temperature to get maximum performance.

PTSC gives maximum performance as a drier and work efficiently for 9 hours in a day from 9:00 am to 6:00 pm in summer. It is recommended to dry apricots by the PTSC's drying chamber from 9:00 am to 6:00 pm.

Moisture loss from apricots and drying rate was more rapid at high temperature and high air mass flow rate. It is therefore, recommended to dry apricots at high air mass flow rate and within a high range of drying temperature. They will be dried quickly and will be of good quality and taste.

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