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Design and Evaluation of Forced Convection Solar Dryer Equipped with a Heat Exchanger for Crop Drying

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ABSTRACT

In this study, a pilot solar thin-layer dryer was designed and constructed. This dryer was equipped with an air-to-air cross-flow plate heat exchanger. An aluminum plate with a different design was used instead of holes in its surface. The collector, the airflow hitting the absorbent plate and passing through the surface of the pipes embedded on the absorbent plate received thermal energy and transferred it to the dryer chamber. Using the randomize complete design, influence of thickness of product in three levels of 3, 5 and 8 mm, three levels of air velocity of 0.5, 1 and 1.5 m/s and 2 modes with and without the use of heat exchanger on drying time of onion slices was studied. The crop thickness and airflow velocity had a significant effect on reducing the drying time of onion slices and the effect of crop thickness was greater than airflow velocity. However, the heat exchanger did not have a significant effect on drying time and collector efficiency.

INTRODUCTION

In the traditional sun drying method, some agricultural products such as banana, apple and tomato are spread out on mats and directly exposed to solar radiation. Although solar drying is the cheapest method, products dried with this method are not hygienic and contamination due to insects, dust and microorganism are usually present. Moreover, the drying processes cannot be controlled, and a relatively low quality of dried product, far below the international market standard, is usually obtain. These drying problems are most serious particularly during the rainy season, when products are rewetted by rain, which induces the growth of molds. To overcome these problems, more efficient drying equipment is needed to replace the traditional sun drying method (Schirmer *et al.*, 1996).

Mechanical drying is an energy consuming operation in the post-harvest technology of agricultural products, so more emphasis is given on using solar energy sources due to the high prices and shortages of fossil fuels. Solar dryers are now being increasingly used since they are a better and more energy efficient option other than fossil fuels (Pangavhane *et al.*, 2002).

A new specific prototype of an indirect active hybrid solar–electrical dryer for agricultural products was constructed and investigated. The fraction of electrical and solar energy contribution versus air mass flow rate was investigated. Sliced tomato was studied in different temperatures and velocities of drying air in order to study the effect of these parameters on moisture content removal from the product and kinetics of drying and also to determine their suitable values (Boughali *et al.*, 2009). In a study, an indirect active solar dryer was used to dry Nopal (*Opuntia Lasiacanta*). The results show that drying rate decreases linearly from the beginning without presenting clearly somewhere critical moisture that separate the area of constant speed from the rest and the drying time of greater amounts of product can be estimated by using the calculation of the average speed of the entire process (Finck-Pastrana, 2014).

In another study, a cabinet solar dryer was used to dry grapes. In this research, the experiments were conducted in two mixed and indirect methods and the effect of air flow rates and different modes of drying were investigated on moisture reduction trend for grapes. Statistical analysis showed that both airflow rate and mode of drying application were significantly affecting the rate of moisture removal from the products (Dadashzadeh *et al.*, 2008).

Six different types of natural circulation air heating solar collectors were designed, constructed and analyzed for their performance. Each collector mainly consisted of a frame constructed from hardboard, vent holes, hardboard insulation, absorbing surface made of black coated aluminum sheet and clear plastic glazing. The researchers conclude that if we decide to fabricate an air heater by using local materials, the collector must be single covered and front-pass type to get the highest efficiency (Koyuncu, 2006).

In the solar air flat plate collector, the insufficiency of the thermal exchange between the fluid and the absorber obliges the user to enhance their optimization. The researchers sought to improve the efficiency–temperature rise couple of the flat plate solar collector by considering several types of obstacles disposed in rows in the dynamic air vein of the flat collector. By comparing with the collector without obstacles, the thermal transfers and, consequently, the output

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temperature and the collector efficiency are clearly improved (Abene *et al.*, 2004).

The thermodynamic performance analysis of a solar dryer with an evacuated tube collector were investigated. The results showed that the warm outlet air of the collector attains temperature levels suitable for drying of agricultural products without the need of preheating. Thus, this collector was used as the heat source for a drying chamber in the frame of a novel, convective, indirect solar dryer (Lamnatou *et al.*, 2012). In this research a flat plate solar air collector was investigated under direct solar radiation consisted of a slatted glass cover, perforated absorber aluminum sheets. The experimental results show that thermal efficiency of collector increases by an increase in the porosity of the absorber. The absorber with lower porosity shows a better thermal efficiency at lower air mass flux because the air flows in the shorter path through the outlet air channel and may not able to cool the absorber effectively (Zamanian and Zomorodian, 2014). Habibi and Kavoosi Balootaki (2019) constructed an indirect cabinet solar dryer with three trays and grooved collector to use solar energy. This cabinet solar dryer had two different solar dryer types of collectors, simple grooved collector and grooved filled by turnery iron chaff collector.

According to the conducted studies, various types of solar dryers have been designed and built, but the use of air-to-air heat exchangers has been less studied in these dryers, so in this research, the effect of this type of exchanger on the dryer has also been studied.

MATERIALS AND METHODS

In this research, an active cabinet solar dryer with perforated absorber plate was build. In the structure of the solar collector, an aluminum plate with a novel design was used instead of holes in its surface. In this collector, the air flow hitting the absorbent plate and passing through the surface of the pipes embedded on the absorbent plate received thermal energy and transferred it to the dryer chamber (Fig.1).

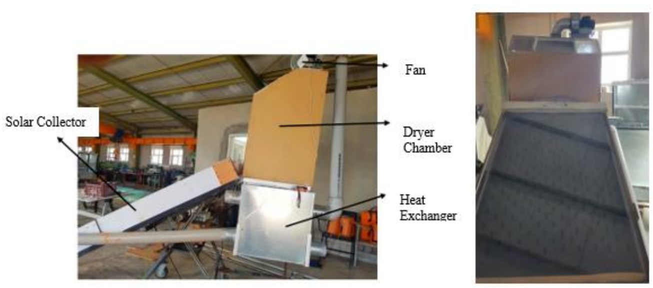

Fig 1. Fabricated dryer (Left) and absorbent plate (Right)

A 0.25 kW centrifugal fan was used to provide the required airflow rate for drying. This fan has the ability to change the amount of air entering the dryer chamber to regulate the air velocity at the outlet. The fan was installed at the top of the dryer chamber (outlet channel). In order to increase the thermal energy of the dryer, an air-to-air heat exchanger was used. In this research, a thermal energy recovery system was built by indirect contact. The working principle of this heat exchanger is in such a way that the outlet air from the drying chamber passed through it and caused the heat of the exchanger and also the air entering the solar collector passed through the exchanger and absorbed the thermal energy of the exchanger. A solar meter (TES 1333 R model, TES company, Taiwan) was used to measure the intensity of sunlight on the surface of the collector and in order to measure, record and control the temperature of the dryer and the temperature of the parts of the absorbent plate in the air inlet and outlet of the collector in the dryer chamber, 6 pt100 sensors were used. A SHT15 sensor was used to measure relative humidity and air temperature, and a Sky Watch model vane flow meter was used to measure air velocity. To record the temperatures of different parts of the dryer, a data logger device connected to the computer was used, which could be viewed online using the Labview software interface.

An A&D digital scale with an accuracy of 0.01 g was used for accurate weighing of the samples. In order to carry out the tests, the device was placed in a sunny area so that the collectors and the dryer chamber were exposed to the sun's rays at a suitable angle (equal to the latitude of the region). To prepare the samples, before being cut the onion rings, they were thoroughly cleaned and the two outer layers were removed. Then the onions were cut into 3, 5 and 8mm thick slices by a sharp knife. The moisture content and temperature of the drying air were measured every 30 seconds and recorded by Datalogger. Finally, the samples were placed inside the oven with a temperature of 70 °C for 24 hours. The dry weight of the samples was obtained after complete drying. The moisture ratio during the drying of the mass was used to compare the drying rate in different test conditions. Based on the conducted researches, in products that have high moisture content, the equation of moisture ratio during drying is obtained from the following equation (Hedayat *et al.*, 2015):

$$MR = \frac{M_d}{M_0} \qquad (1)$$

Where MR is the moisture ratio, M_d is the mass moisture at the current moment dry basis (kg water/kg dry mater) and M_o is the initial moisture of the product mass (kg water/kg dry mater). In this research, the tests were performed at three levels of sample thickness of 3, 5, and 8 mm and three levels of inlet air velocity of 0.5, 1, and 1.5 m/s and in two cases with and without heat exchanger. The statistical evaluation of the results was done using a factorial test in the form of a complete randomized design. Analysis of variance was performed to evaluate the effects of temperature, air velocity and sample thickness and heat exchanger on drying kinetics. Mean comparison tests were performed using Duncan's test at 95% confidence level and all statistical results were analyzed using SAS 9.2 software.

RESULTS AND DISCUSSION

The results of variance analysis are shown in table 1. According to the table, the effect of air velocity and thickness of onion slices is significant at the probability level of 1%, and the interaction effect of thickness and air velocity on the duration of drying is significant at the probability level of 5%. However, the heat exchanger and its interaction effects did not have a significant effect on air velocity. As expected, increasing the air velocity has reduced the drying time of onion slices.

Table 1- The analysis of variance for the effect of test factors on drying time

Source of Variation	DF	Sum of Squares	Mean of squares	F Value
Heat Exchanger (A)	1	20211.36	20211.36	2.66 ns
Air Velocity (B)	2	189773.72	94886.86	12.49 **
Thickness (C)	2	540376.9	270188.44	35.55 **
A×B	2	721.055	360.53	0.05 ns
A×C	2	24902.89	12451.44	1.64 ns
B×C	4	125465.4	31366.36	4.13 *
A×B×C	4	29088.44	7272.11	0.96 ns
Error	16	121590.22	7599.39	
Total	35	1065006		

** Significant at 1% level, * Significant at 5% level, ns non-significant

Increasing the air velocity increases the heat transfer coefficient between the sample and the drying air at a constant temperature and increases the moisture transfer rate from the sample to the air. The results of the research showed that in the thickness of 3 mm, increasing the air velocity from 0.5 to 1 m/s and optimal ventilation of the sample reduces the drying time of the sample by about 19.1%, but with increasing the drying air velocity from 0.5 to 1.5 m/s increases the effect of the air velocity and decreases in this case 35% of the drying time (Table 2). This shows that at high air velocity, mass transfer potential is still high. Therefore, it can be concluded that increasing the air displacement velocity in this dryer is desirable and more research should be done. However, it should be taken into account the energy consumption due to the increase in airflow velocity (by the high-power fans). The proper application of these two issues is important in designing dryers and optimizing the drying process. These results are in accordance with the results of some previous researches (Hedayat *et al.*, 2015; Hu *et al.*, 2013).

Table 2- The effect of increasing the air velocity on the reduction percentage in the drying time of onion slices

Thickness (mm)	Air velocity variations (m/s)		
	0.5→ 1	1→1.5	0.5 →1.5
3	19.1	19.6	35.0
5	8.0	10.7	17.9
8	23.1	5.0	27.0

Fig. 2 shows the effect of velocity variations of the air in different thicknesses of onion slices on the drying time up to the moisture ratio of 0.2. It should be noted that due to not reaching the moisture ratio of 0.2 in some experiments (especially in high thicknesses), the drying time has been calculated using the experimental model.

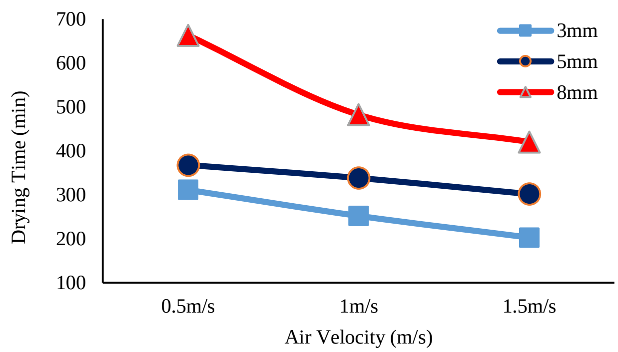

Fig 2. The effect of the drying air velocity variations in different thicknesses of onion slices on the drying time

According to the results of the variance analysis table (Table 1), the thickness of the product has a significant effect on the drying time of the onions at the probability level of 1%. With the increase in thickness, the drying time has increased because the moisture inside the product must travel a more distance. Figs. 3 to 5 show the changes in the moisture ratio of onion slices at different thicknesses without using a heat exchanger. From these Figs., it is clear that in high thicknesses, the drying rate is low and during the day (9:00 am to 3:00 pm) some tests did not reach the moisture ratio of 0.2. In addition, the Figs. 6 to 8 shows the changes in the moisture ratio of onion slices at different thickness and without heat exchanger. In the case of using a heat exchanger, similar graphs have been obtained. According to the results of the tests, with the increase in the thickness of the samples from 3 to 5 mm, the drying time of the onion slices has increased by 24.5%, and by increasing the thickness from 5 to 8 mm, has increased by 34%. These results are consistent with the results of researchers (Bagheri *et al.*, 2013).

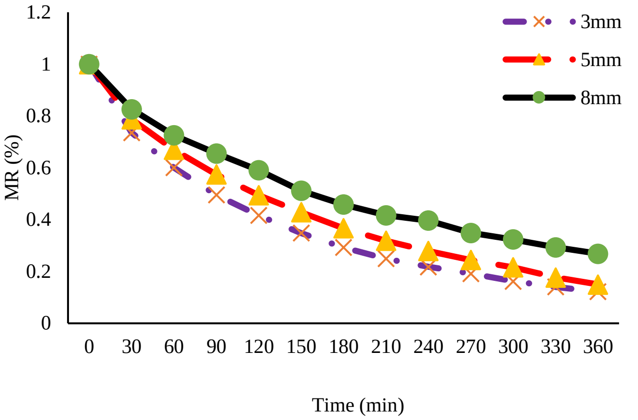

Fig 3. Moisture ratio variations of onion slices in different thicknesses at air velocity of 1.5 m/s and without the heat exchanger

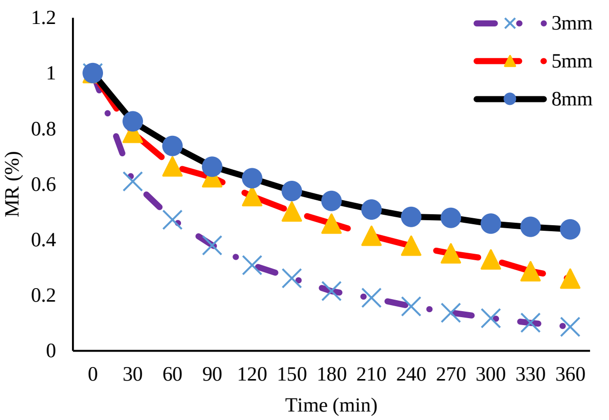

Fig 4. Moisture ratio variations of onion slices in different thicknesses at air velocity of 1 m/s and without the heat exchanger

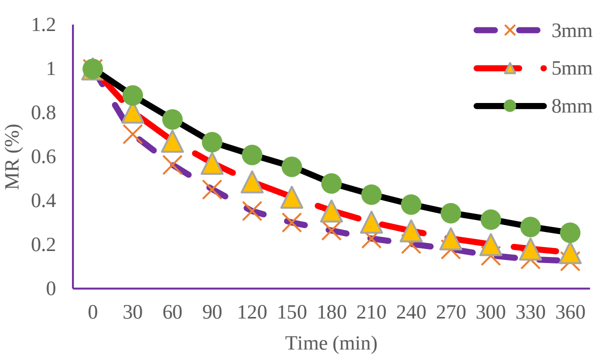

Fig 5. Moisture ratio variations of onion slices in different thicknesses at air velocity of 0.5 m/s and without the heat exchanger

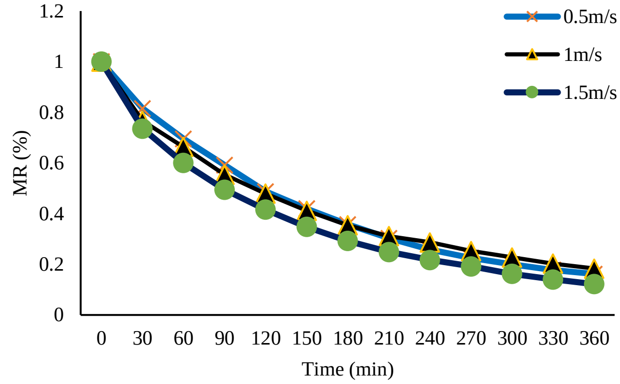

Fig 6. Moisture ratio variations of onion slices at different air velocity in a thickness 3 mm and without the heat exchanger

From the Fig. 8, in high thicknesses of the product, the air velocity did not have a significant effect on the drying of the onion slices. In other words, the effect of sample thickness on reducing the drying time is greater than the effect of increasing the drying air velocity.

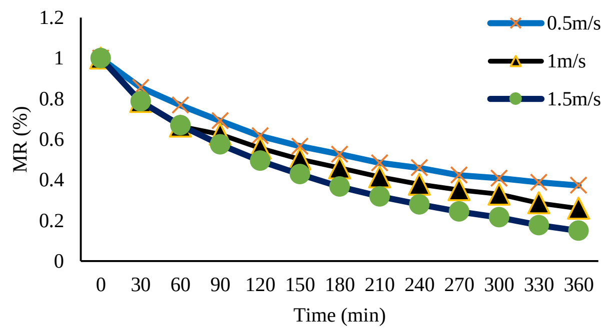

Fig 7. Moisture ratio variations of onion slices at different air velocity in a thickness 5 mm and without the heat exchanger

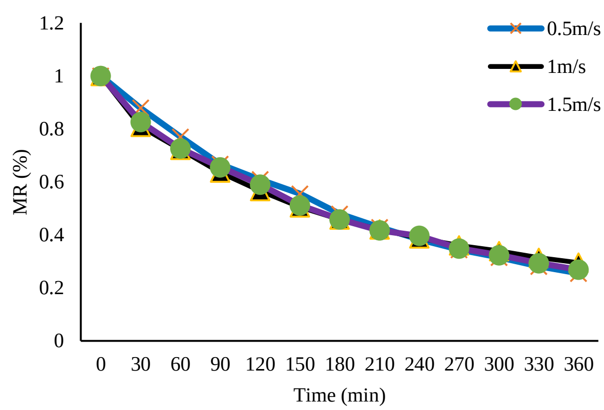

Fig 8. Moisture ratio variations of onion slices at different air velocity in a thickness 8 mm and without the heat exchanger

CONCLUSIONS

The results of this research show that decreasing the air velocity from 1.5 to 0.5 m/s increased the drying time from 1.05 to 1.25 times. In addition, the heat exchanger did not have a significant effect on the onion drying time and did not have a significant effect on raising the temperature of the dryer. It was found that the drying velocity is lower at the air velocity of 0.5 m/s compared to the air velocity of 1.5 m/s**.** Therefore, air velocity of 1.5 m/s is more suitable for drying than lower velocities.

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