J. Agr. Sci. Tech. (2017) Vol. 19: 835-845

Experimental Investigation on Dill Drying in a Solar-Assisted Heat Pump Dryer

H. Jafarian[1], R. Tabatabaekoloor[1*], and S. R. Moosavi Seyedi[1]

ABSTRACT

In this study, a solar dryer assisted with heat pump was developed and thin layer drying of dill was carried out at air temperatures of 40, 50, and 60ºC and air velocities of 0.5, 1 and 1.5 ms^{-1}. Also, the drying rates, Specific Moisture Extraction Rate (SMER), and energy consumption were evaluated. Dill samples were dried from initial moisture content of 90% to the final moisture content of 10% in 195-275 minutes without assisted heat pump, and with assisted heat pump in 80-140 minutes. By using heat pump, the drying rate increased with increase in temperature at a given air velocity, thus, reducing the drying time. Increase in the air velocity at a given temperature improved the drying rate. By increasing the air velocity from 0.5 to 1.5 m s^{-1}, drying time decreased up to 42%. The specific moisture extraction rate values were found to vary between 0.078 and 0.18 Kg Kw^{-1} h^{-1}. The minimum value of energy consumption was 3312 kJ at air temperature of 60ºC and air velocity of 1.5 m s^{-1}. Also, the total energy consumption of dryer with heat pump was reduced by 19%, which reflects the higher energy efficiency.

Keywords: Drying rate, Energy efficiency, Solar drying.

INTRODUCTION

Dill (*Anethum graveolens L.*) is an annual, self-seeding plant that both its leaves and seeds are used as a seasoning (Ling, 2002). Its green leaves are wispy and fernlike and have a soft, sweet taste and widely used in Iran due to having many medicinal properties. It is also used as vegetables (Setayesh-Mehr and Ganjali, 2013).

Drying is a common method for preserving food and many products such as vegetables. The main advantage of drying is reducing food moisture content to increase their storage life time. Removing excess moisture in food reduces the storage and transport cost in addition to preventing food chemical waste (Ekechukwa and Norton (1999). Drying process consumes 7% to 15% of the total energy consumption in industry sector. On the other hand, magnificent amount of energy is wasted in this process (Chua *et al.,* 2000).

From the energy conservation point of view, the solar dryers can be proved to be a very useful device for vegetables drying. They can be used for the entire drying process or for supplementing artificial drying systems, thus reducing the total amount of fuel energy required (VijayaVenkataRaman *et al.,* 2012). One of the latest technologies for drying is using dehumidified system with a closed cycle. In these types of dryers, heat pump is being used to remove moisture from the exhaust air of dryer and to recover the latent and sensible energy. The main advantage of heat pump dryers over the other type of dryers is their ability to recover energy from the exhaust air of dryers. A lot of studies have been done on drying different materials with heat pumps (Fatouh *et al.,* 2006). Strommen *et al.* (2002) reported that heat pump dryers

[1] Department of Biosystems Engineering, Sari Agricultural and Natural Resources University, Sari, Islamic Republic of Iran.
[*] Corresponding author; email: r.tabatabaei@sanru.ac.ir

consume 60 to 80% less energy than conventional dryers at the same temperature, which makes use of heat pump dryers more reasonable. In comparison with other type of dryers, heat pump dryers have several advantages including higher energy efficiency, higher quality products, and the ability to perform independently of outdoor air condition. In addition, these systems require less energy and since they don't emit any harmful gas and smoke to atmosphere they are environmentally friendly (Krokida *et al.*, 2000). Using heat pump reduced 40% of the cost for drying banana (Prasertsan and SaenSaby, 1998).

There are several investigations on modeling and simulating the drying process in heat pumps. One of these methods for increasing drying efficiency and reducing energy consumption in heat pump dryers is to use solar energy in closed cycle (Eltief *et al.*, 2007). In another investigation, performance and efficiency of heat pump dryer assisted with solar water heater have been investigated (Hawlader and Jahangeer, 2006). Optimization of heat pump dryers for drying fruits was investigated (Teeboonma *et al.*, 2003). Sevik *et al.* (2013) during drying mushroom with solar assisted heat pump found that the Specific Moisture Extraction Rate (SMER) varied between 0.26 and 0.92 kg kW^{-1} h^{-1}. Mortezapour *et al.* (2014) investigated drying kinetics and quality characteristics of saffron dried with heat pump assisted hybrid photovoltaic-thermal solar dryer. A mathematical model was developed to evaluate the performance of heat pump dryer for drying of aromatic plants (Hussain *et al.*, 2013). A comprehensive review of various designs, construction and operation of solar drying technologies was accomplished by Sharma *et al.* (2005).

In this study, the objective was to study a solar assisted heat pump system with flat plate collectors for dill (*Anethum graveolens L.*) drying experimentally in the drying system. The aims of this study were: (1) To develop a heat pump dryer which is assisted with solar collector for drying dill; (2) To investigate the effect of air temperature and air velocity on the drying rate, and (3) To evaluate the performance of the system by measuring the Specific Moisture Extraction Rate (SMER), energy consumption, and drying efficiency with and without heat pump.

MATERIALS AND METHODS

Experimental Setup and Process

The schematic and fabricated experimental set up is shown in Figure 1. It consists of a solar flat plate collector with 105×79 cm in cross section and 10 cm in height, a reciprocating compressor (1/4 HP) with Cop= 1.43, a fan and tube condenser (1/4 HP), a fan and tube evaporator (1/4 HP) and a stainless steel drying chamber with 50×40 cm in cross section and 40 cm in height. The solar collector was installed at angle of 36 degree due south which is the angle of latitude of the experimental site to absorb maximum solar radiation. The whole system was thermally insulated by glass wool with 40 mm thickness and thermal conductivity of 0.07 W mK^{-1} to minimize heat losses from absorber plate. The working fluid of heat pump was R-134 because it is environmentally friendly. All system components were connected together with 10 cm diameter air ducts and insulated with glass wool to minimize heat losses. The air flow was circulated through the cycle by DC fan supplied by 24V battery at three different speeds. A circular damper plate was used to change the air flow rate in exhaust duct of fan.

The moist and hot drying air from the drying chamber enters the evaporator of the heat pump system and then the air is cooled to dew point. The water vapor in the air condenses to liquid and dehydrated air enters the solar collector, and absorbs the heat without any increase in moisture content. Then, the heated air in collector is passed through the condenser and auxiliary heater and, finally, hot air with low humidity

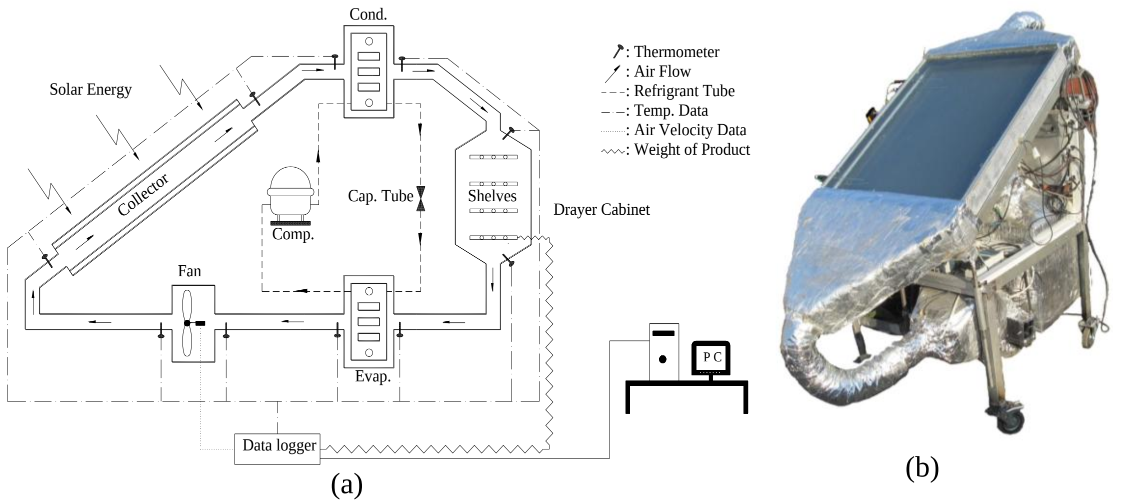

Figure 1. Schematic (a) and constructed (b) experimental set up of solar dryer with assisted heat pump.

passes through the product. Then, the air reenters the evaporator and the cycle is repeated. In order to reach the desired temperature, two auxiliary heaters were installed just before drying chamber to increase the air temperature. The drying air temperature and relative humidity were measured by 16 temperature-humidity sensors in different locations of the apparatus. All data were collected and recorded at one-minute intervals. Four temperature sensors (TM947SD, Lutron, Taiwan) were located inside the solar collector; two sensors were located on the surface of absorber plate, while the two others were behind the cover glass. Six temperature sensors were located inside the air duct at different points such as before and after solar air collector, before and after drying chamber and condenser (SMT160, TIKA Eng. Co., Iran with accuracy ±0.7). Two relative humidity sensors (TM1240, TIKA Eng. Co., Iran with accuracy ±0.4) were used to measure drying air relative humidity in chambers outlet and air solar collectors' inlet. In order to measure the electrical power consumed by the compressor and auxiliary electrical heater, a watt meter (TM1510, TIKA Eng. Co., Iran with accuracy of 0.5%) was used. The mass losses were periodically measured with two load cell (L6DC3, Zemic Europe). The incident solar radiation was periodically measured by a solar meter (TES1333R, TES Company, Taiwan) beside the solar air collector. Anemometer (Am-4206, Lutron, Taiwan) was used to monitor the air velocity that passes through the tray in the drying cabinet. The Human-Machine Interface (HMI) was used to connect all these sensors together. In addition, controlling the temperature and relative humidity was possible through this software by activating heater and fresh air valve. The fresh air valve with 14.5 cm diameter is located between solar collector and condenser and it is deployed to let the ambient fresh air enter the dryers duct and mix with the drying air.

Test Procedure

The fresh dill was taken from a local market (Sari, North of Iran) and cleaned before use. The initial and final moisture content of dill was determined in a drying oven at 105ºC for 24 hours. The drying air temperatures were 40, 50, and 60ºC and the air velocities were 0.5, 1, and 1.5 m s^{-1}. Experimental tests were performed with and without heat pump. In each test, 200 g of dill were placed inside the drying chamber. The

[DOR: 20.1001.1.16807073.2017.19.4.16.7]

initial moisture content of the drying dill was about %90. Each experiment was ended when the weight of the stigmas decreased to final moisture content of about 10% (22.2 g). The experiments were carried out between 10 am to 3 pm on sunny days during November-December, 2014. The effect of different air mass flow rates and air temperatures with and without heat pump were investigated on drying rate. Also, the effect of heat pump unit was studied on the thermal efficiency of dryer. The hourly variation in solar radiation intensity and outdoor temperature at test location is shown in Figure 2. The average ambient temperature was 19.9ºC and average solar radiation was 764.8 W m^{-2} and maximum temperature was obtained at 11.30 am.

Efficiency Calculation

The performance of drying method is determined in terms of efficiency of the dryer which is defined as the ratio of heat utilized in evaporating the moisture from product during drying method to that of total incident solar radiation on the collector during drying. Instantaneous thermal efficiency of the solar collector (%) was calculated by the following relationship (Ramani *et al.*, 2010).

$$\eta_{collector} = \frac{Q}{A \times I_t} \quad (1)$$

Where, A is the surface area of solar collector (m^2); I_t is the solar radiation intensity (W m^{-2}), and Q is the heat delivered in the solar collector (W). The value of Q was estimated using the experimental values of the following equation (Pal *et al.*, 2008).

$$Q = C_P M_a \Delta T \quad (2)$$

Where, C_p is the specific heat capacity of dry air (kJ kg^{-1} $^{\circ}C^{-1}$); ΔT is the temperature difference between inlet and outlet of the solar collector (ºC), and M_a is the mass flow rate of dry air (kg s^{-1}).

The total solar energy can be estimated based on fan and compressor electrical energy using Equation (3) (Duffie and Beckman, 2013).

$$E_{el} = P_{fan} \times t + P_{comp} \times t + P_{auxiliary\ heater} \times t \quad (3)$$

In which, E_{el} is electrical energy (kJ); P_{fan} is the power of blower fan (kW); P_{comp} is the power of compressor (kW); $P_{auxiliary\ heater}$ is the power of auxiliary heater (kW), and t is the time in second. The total energy (E_t) is sum of electrical energy (E_{el}) and solar energy (E_s).

$$E_t = E_{el} + E_s \quad (4)$$

Where,

$$E_s = \int_0^t Q \times \Delta T \quad (5)$$

In which, E_s is the solar energy (J); Q is the heat delivered in the solar collector (W), and ΔT is time (s). The solar energy factor (S_f) represents value of total energy consumption supplied by solar energy (Biondi *et al.*, 1988).

$$S_f = E_s / E_t \quad (6)$$

The drying efficiency can be obtained by the following formula:

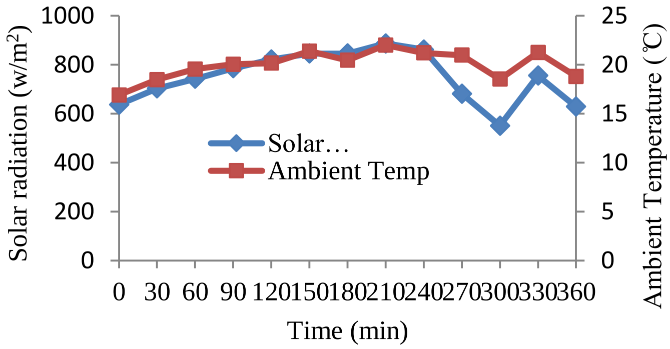

Figure 2. Variation in solar radiation intensity and ambient temperature during the experiment.

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$$\eta_{\text{dryer}} = \frac{Q_{\text{drying}}}{E_t} \quad (7)$$

The required energy for drying can be defined as:

$$Q_{\text{drying}} = M_{\text{wd}} h_{fg} \quad (8)$$

Where, Q_{drying} is energy required for drying (kJ); h_{fg} is the latent heat of vaporization of air (kJ kg^{-1}), and M_{wd} is the mass of moisture removed during drying (kg). $M_{\text{wd}} = 0.1778$ and $Q_{\text{drying}} = 0.1778 \times 2257.03 = 401.3$ kJ.

The Specific Moisture Extraction Rate (SMER) is usually used to analyze dryers' performance in terms of energy consumption. The SMER shows the ratio between the amount of evaporated water and the total energy supply. A high SMER would indicate an efficient drying process with low energy losses.

. The higher value of *SMER* reflects higher energy efficiency. The *SMER* value of heat pump dryers can be characterized by a variety of criteria such as air temperature, air humidity, evaporating and condensing temperature and overall efficiency of heat pump.

RESULTS AND DISCUSSION

Performance Evaluation

The thermal efficiency of flat plate collector for different treatments is given in Figure 3. The thermal efficiency of solar dryer with heat pump was higher than that observed for without heat pump. When the heat pump and the solar collector worked together, the system resulted in an increase in the thermal efficiency. The air inlet temperature is an operational parameter which strongly influences the performance of collector. Increasing the inlet air temperature decreases the temperature difference between the inlet and outlet air. Therefore, thermal efficiency of solar collector decreases. It is seen from Figure 3 that the thermal efficiency of collector decreased as the temperature of inlet air to drying chamber increased. Also, the thermal efficiency was increased by increasing the air flow rate. The maximum value of the collector efficiency was obtained at 40ºC and 1.5 m s^{-1} with heat pump. There are two reasons for this. First, due to the higher amount of air flow rate, more energy is absorbed by absorber plate through forced convection. Second, by increasing the mass flow rate, heat loss is decreased from collector due to absorber plate temperatures drop. As the air is further cooled in the collector, the collector thermal loss decreases and absorption ability in absorber plate is increased. Similar results were observed by Duffie and Beckman (2013), Zomorodian *et al.* (2007), and Mortezapour *et al.* (2012).

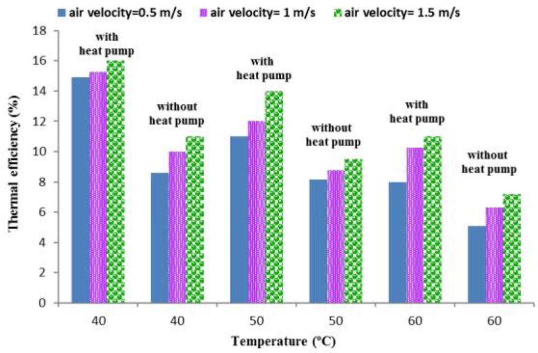

Figure 3. Effect of temperature on thermal efficiency at different air velocities with and without heat pump.

The effect of heat pump on relative humidity is shown in Figure 4. After putting the sample in the dryer, the relative humidity of circulating air rose abruptly. Then, the air valve operated and let the hot air to enter and mix with ambient air, which resulted in reducing relative humidity. By utilizing the heat pump, the relative humidity decreases with time, because partial vapor of circulated air is absorbed in evaporator. The evaporator in heat pump reduces the inlet air temperature to the solar collector and, consequently, inlet air is more cooled. Mortezapour *et al.* (2014) indicated that applying heat pump with the dryer reduced relative humidity of drying air and,

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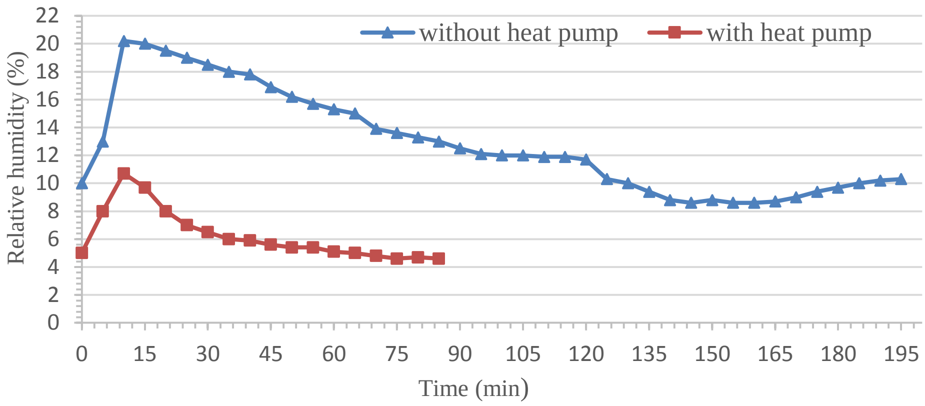

Figure 4. Variation in relative humidity of drying air during drying time.

consequently, shortened drying time by 40%. On the other hand, reduction in inlet air to collector resulted in lower differences between inlet air and ambient temperature with heat pump which led to increase collector efficiency (Duffie and Beckman, 2013). Aktas *et al.* (2009) reported that the heat pump affected the amount of moisture evaporated from the product.

The Specific Moisture Extraction Rate (SMER) at different temperatures and air velocities is shown in Figure 5. The specific moisture extraction rate values were found to vary between 0.078 and 0.18 kg Kw^{-1} h^{-1}. The higher value of *SMER* was obtained at air temperature of 60ºC and air velocity of 1.5 m s^{-1} with heat pump assisted system, which reflects the higher energy efficiency of this system. For justification of this result, as Figure 6 shows, the minimum energy consumption was achieved at this point. In general, energy consumption for solar drying of dill without using heat pump increases the energy consumption and, therefore, it reduces the *SMER*. Hussain *et al.* (2013) found the average *SMER* of 0.038 kg Kw^{-1} h^{-1} for aromatic plants. Sevik *et al.* (2013) reported that *SMER* values for mushroom drying with solar assisted heat pump system varied between 0.26 and 0.92 kg Kw^{-1} h^{-1}. Also, similar finding was reported by Perera *et al.* (1997).

By increasing the drying temperature, more electrical energy is consumed by turning auxiliary heaters in order to supply the desired temperature for drying due to temperature differences with outdoor. On the other hand, reducing the drying time causes a decrease in fan and auxiliary heater electrical consumption time. Also, the maximum value of collector thermal efficiency was obtained at 40ºC and 1.5 m s^{-1} with heat pump and it increased by decreasing the drying air temperature (Figure 3). Mortezapour *et al.* (2014) showed that drying time decreased by 62%

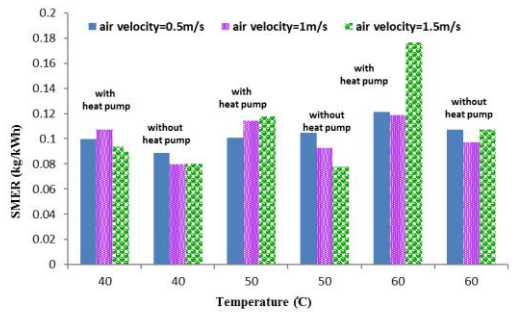

Figure 5. The *SMER* values in different treatments for drying dill.

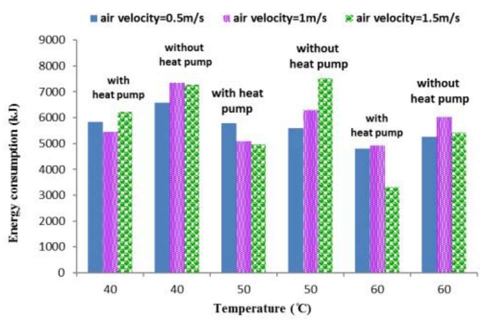

Figure 6. Energy consumption in different treatments of drying dill.

with increasing air temperature from 40 to 60ºC. Aktas *et al.* (2009) showed that in closed cycle dryers, increasing drying air temperature caused electrical energy reduction for drying bay leaves.

The dryer energy consumption is decreased by using heat pump (Figure 6). This is because of recovering energy and decreasing drying time. The energy consumption is increased without heat pump. By increasing the mass flow rate, the heat pump thermal performance coefficient and the *SMER* is increased. It should be noted that by increasing the air velocity, the drying air releases more moisture content to the drying chamber, resulting in less vaporization rate in the drying chamber. Therefore, the drying chamber outlet temperature increases and, because of decreasing collector outlet air temperature, more energy is consumed by the auxiliary heater. Mortezapour *et al.* (2012) found that energy consumption decreased by 33.3% with heat pump in comparison with drying without heat pump.

Effect of Temperature on Moisture Loss

Drying rate at different temperatures for the two systems (with and without heat pump) is given in Figure 7. The results indicated that the drying rate increased with increase in temperature at a given air velocity, thus, reducing the drying time. The drying rate with heat pump was significantly faster than that observed for without heat pump. At temperature of 60ºC, when we used heat pump, the final moisture content was achieved after 80 minutes , while at the same temperature and without the heat pump, it was achieved after 200 minutes. Also, at two other temperatures similar results were observed. It can be due to better thermal efficiency of the system when we use heat pump (Figure 3). Drying rate at air temperature of 40ºC had a slower trend than the other two temperatures and sample needed more time to reach the final moisture content. Therefore, significant reduction of drying time by using heat pump in solar

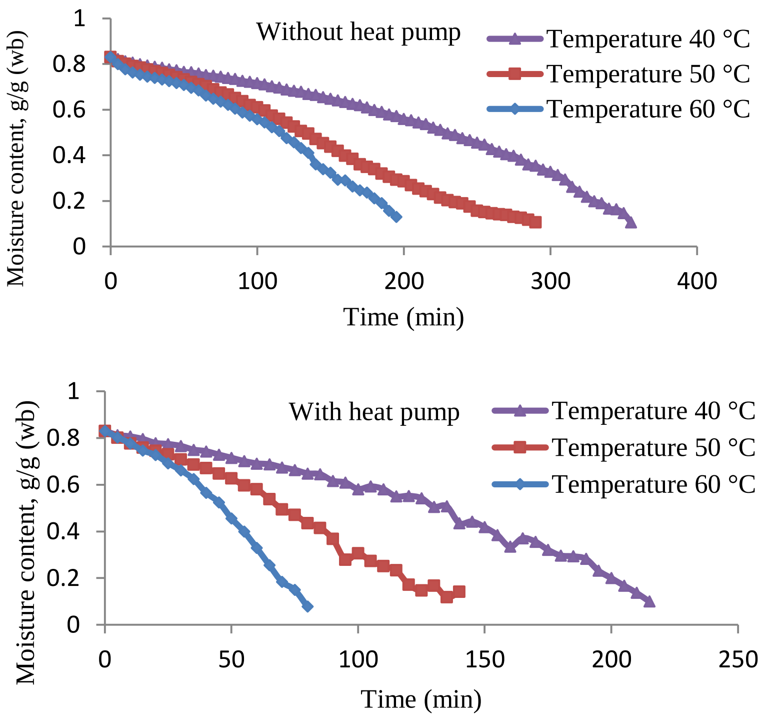

Figure 7. Effect of temperature on drying rate with and without heat pump at air velocity of 1.5 m s^{-1}.

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dryers and higher thermal efficiency is a key point that should be considered as an alternative for using solar drying systems. This is because higher partial vapor pressure difference between drying air and the product enhance the vaporization rate (Mortezapour *et al.*, 2014). Tulek (2011) showed that, during mushroom drying, increasing temperature from 50 to 70ºC increased the drying rate by 36%. Also, the results from this study are in agreement with researches by Sharma *et al.* (2005) and Silva *et al.* (2008).

Effect of Air Velocity on Moisture Loss

The effect of different air velocities on moisture loss for the two systems is shown in Figure 8. The results indicated that the drying rate significantly increased by using the heat pump thus reducing the drying time. By using heat pump at the air temperature of 60ºC, the drying time reduced about 49-58%. This result could be due to the higher thermal efficiency of the system equipped with heat pump. The moisture loss at air velocity of 1.5 m s^{-1} had significant difference with the other two velocities. The drying time decreased with increase in air velocity because of the increased moisture removal effect at the surface of the product. Also, it increased transfer heat from collector to drying air, which led to shorter drying time. Similar finding was reported by Sharma *et al.* (2005). As it is seen, by increasing the air velocities, drying time decreased more, especially at the end of the process. This is because of increasing heat and mass transfer coefficient in high mass flow rate, which enhanced the moisture content removal from the product (Fatouh *et al.*, 2006; Madhyanon and Soponronnarit, 2005). The result indicates that by increasing the air velocity from 0.5 to 1.5 m s^{-1}, drying time is decreased up to 42%. As it is clear from Figures 7 and 8, drying time decreased more when dryer worked with heat pump.

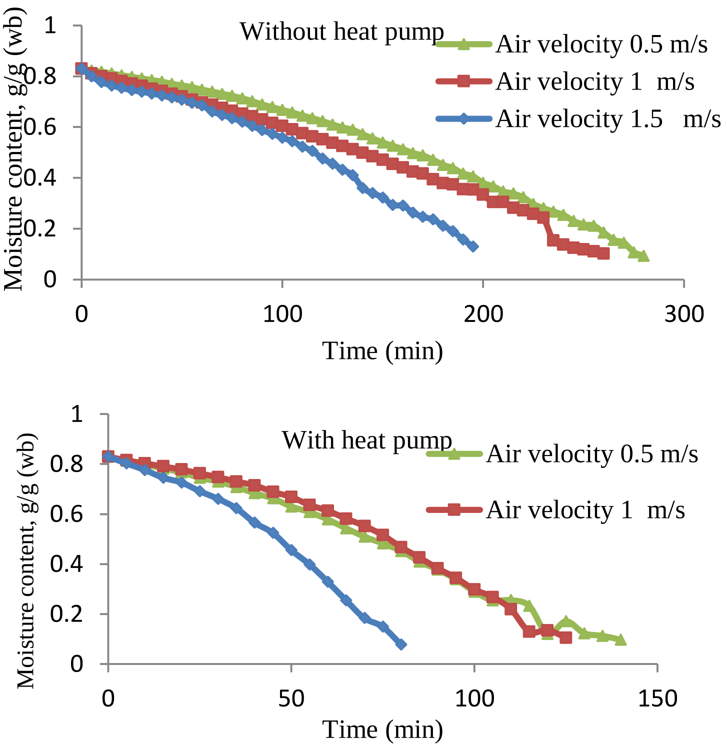

Figure 8. Effect of air velocity on drying rate with and without heat pump at *T*= 60ºC.

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The effect of air velocity on drying time is less important than the effect of air temperature on drying rate. This finding is in accordance to the results of a research on herbal leaves by Kaya and Aydin (2009).

CONCLUSSIONS

In this study, a solar dryer assisted with heat pump was developed for thin layer drying of dill. Experimental tests with and without heat pump were performed in order to study the performance of dryer by determining the drying rate, Specific Moisture Extraction Rate (SMER), and energy consumption. Also, the effects of air temperature and air velocity were investigated. Results indicated that the higher value of *SMER* was obtained about 0.18 kg by using heat pump at air temperature of 60ºC and air velocity of 1.5 m s^{-1}, which reflects the higher energy efficiency. The thermal efficiency of solar dryer with heat pump was higher than that observed for without heat pump. By using heat pump and increasing drying air temperature, total energy consumption decreased. The maximum value of collector thermal efficiency was obtained at 40ºC and 1.5 m s^{-1} with heat pump. Increasing the air velocity at a given temperature improves the drying rate and, as a result, the drying time is shortened.

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بررسی تجربی خشک کردن شوید در یک خشک کن خورشیدی مجهز به پمپ حرارتی

ح. جعفریان، ر. طباطبایی کلور، و س. ر. موسوی سیدی

چکیده

در این تحقیق یک خشک کن خورشیدی با پمپ حرارتی کمکی ساخته شد و رفتار خشک کردن لایه نازک گیاه شوید در حالت با و بدون استفاده از پمپ حرارتی در دمای 40، 50 و 60 درجه سانتیگراد و سرعت هوای 0/5، 1 و 1/5 متر بر ثانیه مورد بررسی قرار گرفت. همچنین، سرعت خشک کنی، سرعت استخراج رطوبت ویژه و مصرف انرژی ارزیابی شد. نمونه های شوید در حالت بدون استفاده از پمپ حرارتی در زمان 197 الی 275 دقیقه و در حالت با پمپ حرارتی از 80 الی 140 دقیقه خشک شدند و از رطوبت اولیه 90درصد به رطوبت نهایی 10 درصد کاهش یافتند. استفاده از پمپ حرارتی در یک سرعت هوای ثابت موجب افزایش دما و سرعت خشک کنی و در نتیجه کاهش زمان خشک کردن شد. افزایش سرعت هوای خشک کنی در یک دمای ثابت سرعت خشک کنی را بهبود بخشید و با افزایش سرعت از 0/5 به 1/5 متر بر ثانیه زمان خشک کردن حدود 42 درصد کاهش یافت. تغییرات سرعت استخراج رطوبت ویژه بین 0/078 و 0/18 کیلوگرم بر کیلو وات ساعت بود. کمترین مقدار مصرف انرژی 3312 کیلو ژول در دمای 60 درجه سانتیگراد و سرعت هوای 1/5 متر بر ثانیه بدست آمد. همچنین، مصرف کل انرژی خشک کن با پمپ حرارتی 19٪ کاهش یافت و این امر نشان دهنده بازده انرژی بالاتر است.

[DOR: 20.1001.1.16807073.2017.19.4.16.7]