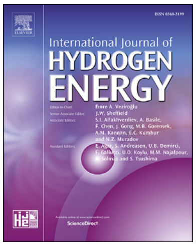
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 42 (2017) 18034–18044

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



Analysis of a new drying chamber for heat pump mint leaves dryer

Mustafa Aktaş [a,*], *Ataollah Khanlari* [b], *Burak Aktekeli* [c], *Ali Amini* [d]

[a] *Energy Systems Engineering, Technology Faculty, Gazi University, 06500 Ankara, Turkey*
[b] *Gazi University, Natural and Applied Science Institute, 06500 Ankara, Turkey*
[c] *Worker Health and Safety, Osmaneli Vocational School, Bilecik Şeyh Edebali University, Osmaneli, 11500 Bilecik, Turkey*
[d] *Atatürk University, Natural and Applied Science Institute, 25240 Erzurum, Turkey*

ARTICLE INFO

Article history:
Received 14 November 2016
Received in revised form
28 February 2017
Accepted 1 March 2017
Available online 11 April 2017

Keywords:
Drying
Mint leaves
Heat recovery
Cylindrical drying chamber

ABSTRACT

Drying is an energy intensive and time consuming process, so reducing amount of demanded energy and drying time are important issues for drying technology. The main aim of this paper is to analyze the drying characteristics of mint leaves in a new cylindrical form of drying chamber at low drying air temperature and by emphasizing on energy analysis. The dryer consists of air source heat pump system, air to air heat recovery unit and proportional temperature controller. Experiments were performed at 2, 2.5 and 3 m/s air velocities and at 35 °C cabin inlet air temperature. Mint leaves were dried from 9 g water/g dry matter to 0.1 g water/g dry matter. Designed drying chamber, with three stainless steel cylinders in circular nested form, has a positive effect for drying technology. This system has some advantages such as: drying of product by accessing a uniform air flow and preventing spread of light weight samples like mint leaves over drying system. Calculations based on experimental data show that in the best case, by consuming 3.164 kWh energy in a heat pump with 3.94 coefficients of performance, 4.56 kWh energy had been gained by heat recovery unit. Average 48% of energy was saved by means of heat recovery unit. Effective moisture diffusivity values varied from 3.50E−11 to 5.88E−11 for mint leaves.

Introduction

Drying of agricultural products provide effective and practical preservation method in order to reduce the losses after harvest. This process extends the shelf life of products and reduces the transportation costs. However, drying is energy intensive and time consuming process. So, reducing demanded energy and drying time by developing efficient systems is important [1,2]. This paper will examine the drying process of mint as one of the important products of agriculturing. Mint leaves are refreshing, antiseptic, anti-asthmatic, and anti-spasmodic and also mint leaves can be used as a medicinal and aromatic plant [3,4].

Academic studies on agricultural products drying follow two main streams. As the topic of this paper related to mint leaves, the literature review has been done with special focus on this product.

---

* *Corresponding author.*

E-mail addresses: mustafaaktas@gazi.edu.tr (M. Aktaş), ata_khanlari@yahoo.com (A. Khanlari), burak.aktekeli@bilecik.edu.tr (B. Aktekeli), ali82amini@gmail.com (A. Amini).

http://dx.doi.org/10.1016/j.ijhydene.2017.03.007

The first stream of academic studies on drying technology includes a quantitative description of drying processes by mathematical models. Estimating some important parameters like moisture content, drying time, consumed energy and the temperature distribution in drying chamber and inside product provide useful information for the practical and economic design of devices. Some models like exponential model, Page's semi-empirical model and Lewis model are available for describing the heat and mass transfer phenomena during the drying process. According to drying chamber design and drying product, these models have been hired by researchers to inspect the mechanism of drying.

Saleh and Badran have used the exponential model for describing Jews mallow and mint leaves drying in a domestic solar dryer. As the temperature profile uniformity is required for this model, they provided a simple and accurate design tool. Moisture content reduction of the tested products achieved to recommended level (6% wb) in 12 h. Comparing the experimental curves with the predicted ones showed the reliability of the exponential model. A reasonable agreement was found for the different tests which carried out for the entire drying period [5].

Doymaz studied thin-layer drying behavior of mint leaves for a temperature range between 35 and 60 °C. Four thin-layer drying models available in the literature were fitted to the experimental data. Among all the drying models, the logarithmic model was found to satisfactorily describe the kinetics of air-drying of mint leaves [4]. Biçer and Kavak Akpinar investigated the drying behavior of pumpkin experimentally in a cyclone type dryer. Drying air velocities were 1 and 1.5 m/s and air inlet temperatures were 60, 70 and 80 °C in that study. They also presented a mathematical model using non-linear regression analysis by using the curves of drying rate-moisture content obtained from the experimental data [6].

Özbek and Dadali investigated the effect of the microwave drying technique on moisture content, moisture ratio, drying rate, drying time and effective moisture diffusivity of mint leaves. To determine the kinetic parameters, the drying data were fitted to various models. The ratios of the differences between the initial and final moisture contents and equilibrium moisture content were calculated versus drying time. Among of the proposed models, the semi-empirical belongs to Midilli et al. gave a better fit for all drying conditions [7]. Determination of parameters that are used in the mathematical form of drying models, is not easy because of non-linearity. It needs a hard task from both an experimental and numerical point of view. So, there should be an optimization method for experimental efforts required to identify unknown parameters with minimal confidence intervals. Goujot et al. presented an optimized approach and implementation of the experimental estimation of 5 unknowns (related to heat and mass transfer) coefficients with a minimal number of experiments in the field of rice drying. They implemented this method in Matlab software as a Toolbox [8].

Kadam et al. studied the drying kinetics of mint leaves using a laboratory model tunnel dryer. The drying air temperature selected as 45, 50, 55, 60 and 65 °C. They found that effective moisture diffusivity increased with increase in drying air temperature. Also, drying air temperatures had no significant effect on the color of dried mint leaves [9].

The second stream of academic studies on drying technology includes using different drying systems. Using different units for heating, dehumidifying, air circulating and so on compose a combination that is described as the drying system. Diversity of drying systems like heat pump drying, infrared drying, microwave drying, convective drying and combinations of them have been proposed by researchers.

Vyankatrao has compared drying process of three different leafy vegetables using traditional methods. These products include coriander, curry and mint leaves. He inspected effective drying method for retention of nutrients. Sun drying, red light drying and shade drying were his methods. First method includes the keeping of vegetables in a wooden tray and setting aside in sunlight. Red light drying treatment includes red colored glass that is set on vegetable tray and is kept in sunlight. Shade drying treatment includes vegetables that are arranged on wooden racks and keeping in the room. In case study of mint leaves, drying time was 5 days for red light drying, 6 and 8 days for sun drying and shade drying, respectively. Beta carotene content is 6.4 mg/100 g for fresh mint leaves which reduced to 3.94 mg/100 g in red light drying, 2.55 mg/100 g in sun drying and 4.18 mg/100 g in shade drying [10]. In another study, Wongsim et al. have designed a thermos-electric (TE) heat-pump drying system for drying kind of herb leaves named laurel clock vine. Their proposed device can be a convenient replacement for traditional heat-pump dryers that use chlorofluorocarbon (CFC) and hydro fluorocarbon (HFC) refrigerants in the cycle. Therefore, the harmful effect of this kind of emissions in earth temperature rising can be diminished. In this design, TE modules are used with its own rectangular fins as heat sink that are warming up the blowing air. Calculated coefficient of performance (COP) for the entire TE heat-pump drying system were 1.28 and 0.81 at air temperatures of 50 °C and 40 °C, respectively [11].

Kavak Akpinar investigated drying characteristics of mint leaves in the solar dryer with forced convection and under the sun with natural convection. Also, energy-exergy analysis of the solar drying process was performed [3].

Case studies show that, using microwave drying technique accelerates drying process effectively. Applying power density of 4, 5, 6, 7, 8, 9 and 10 W/g in Soysal's study shows that mint leaves are dried in 6–16 min. But this method leads to some decrease in brightness and greenness value of leaf's color [12]. According to Kripanand et al. studies microwave drying method provides less drying time beside appreciable losses of volatile oil, chlorophyll and other components when compared to the fresh mint leaves [13].

If the product is heat-sensitive, hot air drying method cannot be a perfect choice because the color, structure, and vitamins can be impaired by increasing the temperature. Vacuum drying method can be a good choice for these situations. Alibaş dried Celeriac slices by using vacuum drying. Six different pressures and three different temperatures were used in the vacuum drying process. Vacuum drying at 0.1 kPa and 75 °C provided the optimal results with respect to drying period, color, and energy consumption [14].

Afes-Boukadoum investigated the energy and exergy analyses of the solar drying process of mint. They used an indirect type passive solar dryer. Energy analysis allowed to quantify the solar energy received by solar heater and available for drying. Exergy analysis allowed estimating the energy losses during the drying process [15].

This study presents mint leaves drying process by employing a heat pump combined with heat recovery unit. Drying chamber's geometry has been designed in a closed type cylindrical form to achieve a uniform distribution of air flow around dried product and to prevent spreading of light weight samples like mint leaves over drying system. The contribution of new geometry is effective in drying of light weight herbs. This type drying chamber traps mint leaves and make it possible to impose a variety of air velocities.

Material and methods

Experimental setup

The dryer consists of compressor, condenser, evaporator, expansion valve, fan, controller, sensors, load cell, drying cabinet, and heat recovery unit. Details of the drying system are shown in Fig. 1. The equipments used in the dryer and their technical characteristics are shown in Table 1. Drying chamber was equipped with a digital weighing device to observe dried products' mass during the mint leaves drying. Temperatures were measured with K type thermocouple. An electronic control board was used to control drying air properties. Drying chamber's inlet air temperature was controlled proportionally by adjusting heat pump unit to obtain uniform drying conditions.

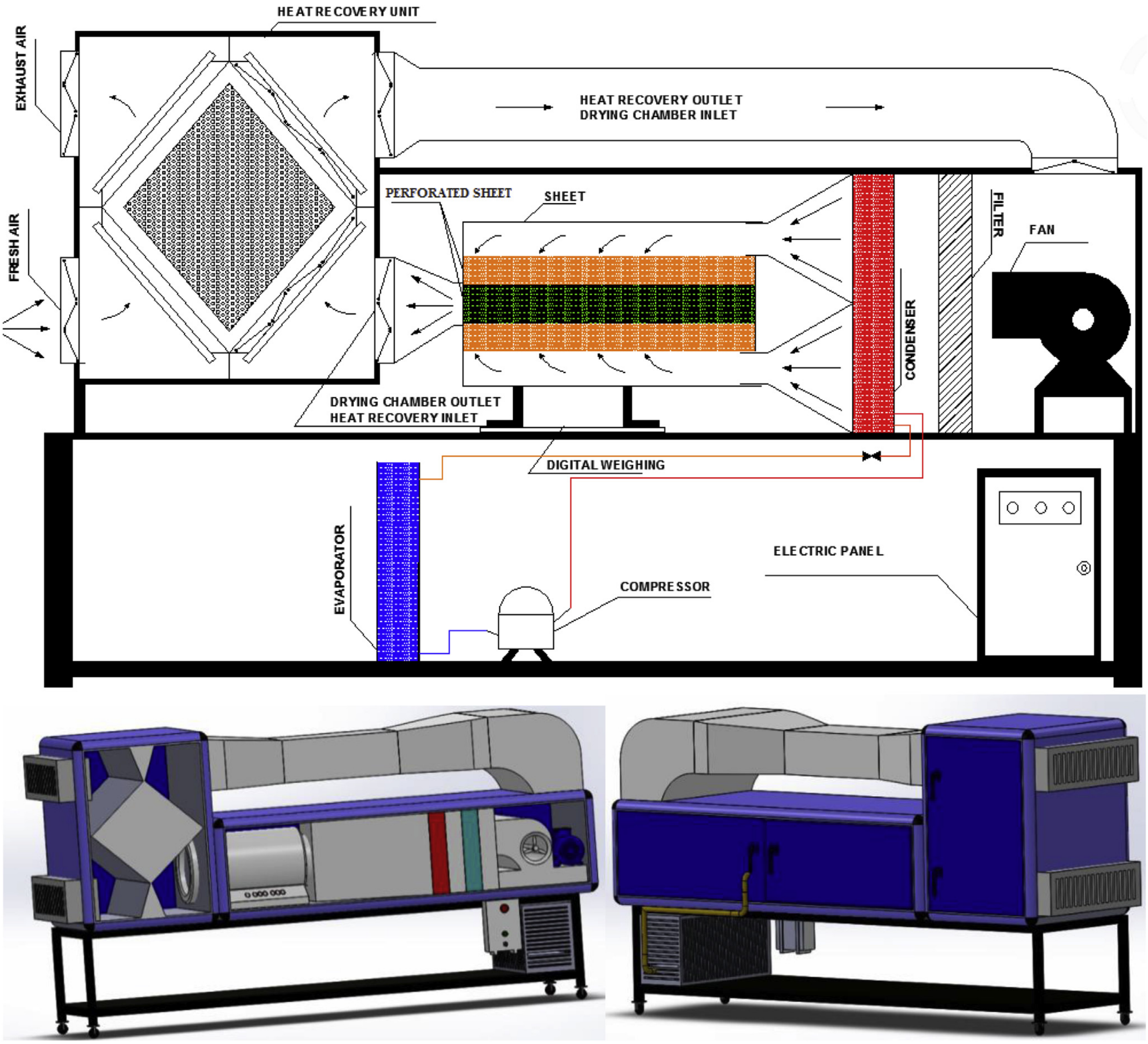


Fig. 1 – The drying system.

Table 1 – Technical characteristics of equipment used in the dryer.

Equipment	Technical characteristics
Compressor	Inverter 0.736 kW, R-410A, 220–240 V
Evaporator	3.5 kW
Condenser	4.0 kW
Frequency inverter (used for fan)	AC variable speed drive, Power range 0,25 kW – 3 kW, 0,33 HP – 6 kW
Digital electric meter	Wide range measurement, 50 Hz, 220 V
Fan	1000 m^3/h, 0.37 kW, 3000d/d,
Thermocouple	K type
Digital weighting	Output (mV/V) 2.0, 5–12 V, 5 kg capacity –40~+80 °C, 5–12 (DC)

Detailed views of the drying chamber are shown in Fig. 2. The main contribution of this design can be explained by taking a look at drying chamber geometry. It has been designed in a way to satisfy two main goals: first, by a circumfluent air flow it desires to get a homogenous dried product and by a closed environment it prevents the escape of drying product which expose to the air flow, especially in the case of light weight vegetables. As it is seen in the design of the drying system; three stainless steel cylinders were used in circular nested form. Innermost and middle layer cylinders were made of stainless steel sheet perforated by 0.8 cm edge length squares. The outermost layer cylinder was made from flat stainless steel. Air flows from the interface of outer and middle cylinder, travel toward centric one by passing through nested interfaces radially. In this way, air can flow all over the surfaces of the product. After passing concentric cylinders, air flow comes to a heat recovery unit. It has been mounted just to output section of the drying chamber to reutilize the drying air heat energy. The system has been designed to work with 100% fresh air enhanced by air to air heat recovery unit. More homogeneous blowing of drying air above the dried product and more penetration of air has been considered in drying unit design. Using heat recovery unit in device will operate the system more efficiently by providing heat energy gained from wasted air.

Experimental procedure

Dry weight of mint leaves was determined by drying the samples in a drying oven at 105 ± 1 °C at atmospheric pressure. At the end of two consecutive measurements, samples were considered totally dry on condition that the weight change is below 1% [16].

To carry out an experiment, 200 g of mint leaves were used for drying. The experiments were conducted at 35 °C set temperatures and 2, 2.5 and 3 m/s air velocities. As the drying air temperature reached a set value, inverter decreased the compressor load.

It is worth to say that higher set temperatures have been tested by researchers. Ertekin and Heybeli have used 60 °C and 70 °C set temperatures in their infrared dryer for mint drying. According to their report, drying time was decreased effectively, but yellowness of the dried mint leaves was significantly increased when compared with fresh samples [17].

Drying at proper temperatures retains the natural enzymes and also prevents enzymatic deterioration during storage. So, set temperature close to natural outdoor condition was selected. According to calculations, when the sample weight reaches to 22 g, the drying process was stopped.

Calculations

The following stages were used to analyze the energy and mass transfer of the drying process.

For analyzing the flow regime Reynolds number is calculated by Eq. (1).

$$Re = \frac{uD_h}{\upsilon} \tag{1}$$

u is the mean velocity of air inside the cylinder that was 3, 2.5 and 2 (m/s) in this study. Anemometer device has been used in velocity measurement by adjusting its position in the cylinder entrance side.

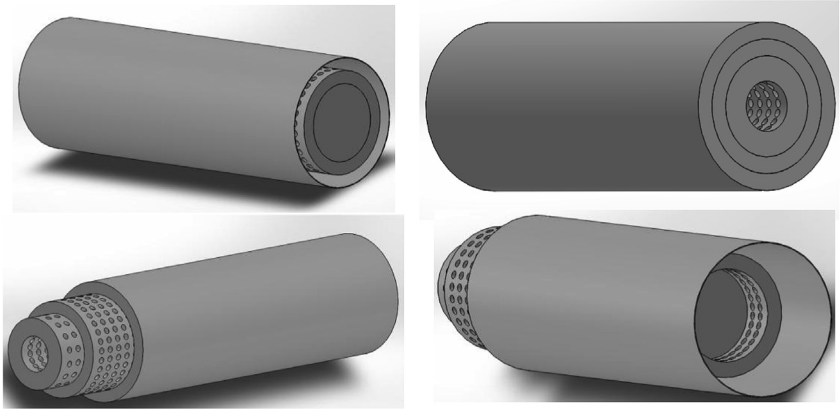


Fig. 2 – Detailed views of the drying chamber.

By substituting D_h and u values in Eq. (1), it is shown that external laminar flow prevails in this case. Eq. (2) is used for calculating Nusselt number in laminar flow.

$$Nu = 0.453Re^{0.5}Pr^{1/3} \tag{2}$$

According to the definition of Nusselt number, convection heat transfer coefficient of mint leaves in contact with air flow can be calculated by Eq. (3).

$$h = \frac{Nu\,k}{D_h} \tag{3}$$

By making an analogy between heat transfer and mass transfer, Sherwood number is extracted from the Nusselt number in the same way that is described in Eq. (4).

$$Sh = \frac{h_m D_h}{D} \tag{4}$$

Mass transfer coefficient can be calculated by considering Sherwood number and diffusion coefficient as known parameters in Eq. (4).

Sherwood number is calculated by correlation expressed in Eq. (5) that is extracted by analogy with Nusselt number in Eq. (2).

$$Sh = 0.453Re^{0.5}Sc^{(1/3)} \tag{5}$$

Eq. (6) is used to calculate the Schmidt number that is defined as the ratio of momentum diffusivity and mass diffusivity [18]:

$$Sc = \frac{\upsilon}{D} \tag{6}$$

Moisture content

The moisture content of the sample can be calculated with the following equation [19]:

$$MC_{db} = \frac{M_i - M_d}{M_d} \tag{7}$$

Moisture ratio

Moisture ratio (MR) during drying experiments was calculated using the following equation:

$$MR = \frac{M - M_e}{M_o - M_e} \tag{8}$$

where M is the moisture content, M_e is the equilibrium moisture content, and M_o is the initial moisture content. However, due to the high moisture content of fresh product, Eq. (8) can be written as follows [20]:

$$MR = \frac{M}{M_o} \tag{9}$$

Drying rate

Drying rate (DR) of the products over drying experiments can be estimated by means of the following equations:

$$DR = \frac{MC_{t+dt} - MC_t}{dt} \tag{10}$$

Determination of effective moisture diffusivity

The effective moisture diffusivity coefficient of mint leaves during drying can be estimated mathematically by Fick's second model. According to this law, drying behavior can be described as follows:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n-1)^2}exp\left(-\frac{(2n-1)^2\pi^2 D_{eff}t}{4Ls^2}\right) \tag{11}$$

For long drying periods the above equation can be simplified as Eq. (12) [19]:

$$MR = \frac{8}{\pi^2}exp\left(-\frac{\pi^2 D_{eff}t}{4Ls^2}\right) \tag{12}$$

Heat pump dryer performance

The coefficient of performance of the heat pump (COP_{hp}) and the whole system (COP_{ws}) during the drying process can be represented as [21]:

$$COP_{hp} = \frac{\dot{Q}_{Cd}}{\dot{w}_C} \tag{13}$$

$$COP_{ws} = \frac{\dot{Q}_{Cd}}{\dot{w}_F + \dot{w}_C} \tag{14}$$

Recovered energy

The energy that recovered by the heat recovery unit can be calculated as:

$$Q_{recover} = \dot{m}_{air}C_{p,air}(T_o - T_{ex})\,t \tag{15}$$

If the air temperature was completely cooled to chamber inlet temperature, the maximum air heat recovery could be obtained. But in reality, the exhaust air temperature is always above the ambient temperature.

$$Q_{recover-max} = \dot{m}_{air}C_{p,air}(T_o - T_a)\,t \tag{16}$$

The specific heat capacity of the inlet air can be expressed by a polynomial function of temperature that has been shown in Eq. (17) [22]:

$$\begin{aligned} C_{p,air} = {} & 1009.26 - 0.0040403 \times T + 0.00061759 \times T^2 \\ & - 0.0000004097T^3 \end{aligned} \tag{17}$$

Experimental uncertainty

Uncertainty analysis provides a technical contribution to evaluate the experimental results. Total uncertainty values are calculated using the following equation [23].

$$W_R = \left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{1/2} \tag{18}$$

Results

According to dry basis, an initial moisture content amount of mint sample was 9 g water/g dry matter, amount of final moisture of dry matter was obtained 0.1 g water/g dry matter. Variation in moisture content as a function of drying time is shown in Fig. 3. It contains two different description of moisture content according to dry and wet basis.

Fig. 4 shows the variation of moisture ratio versus drying time. As it can be seen experiment 1 (35 °C–3 m/s) has the lowest drying time.

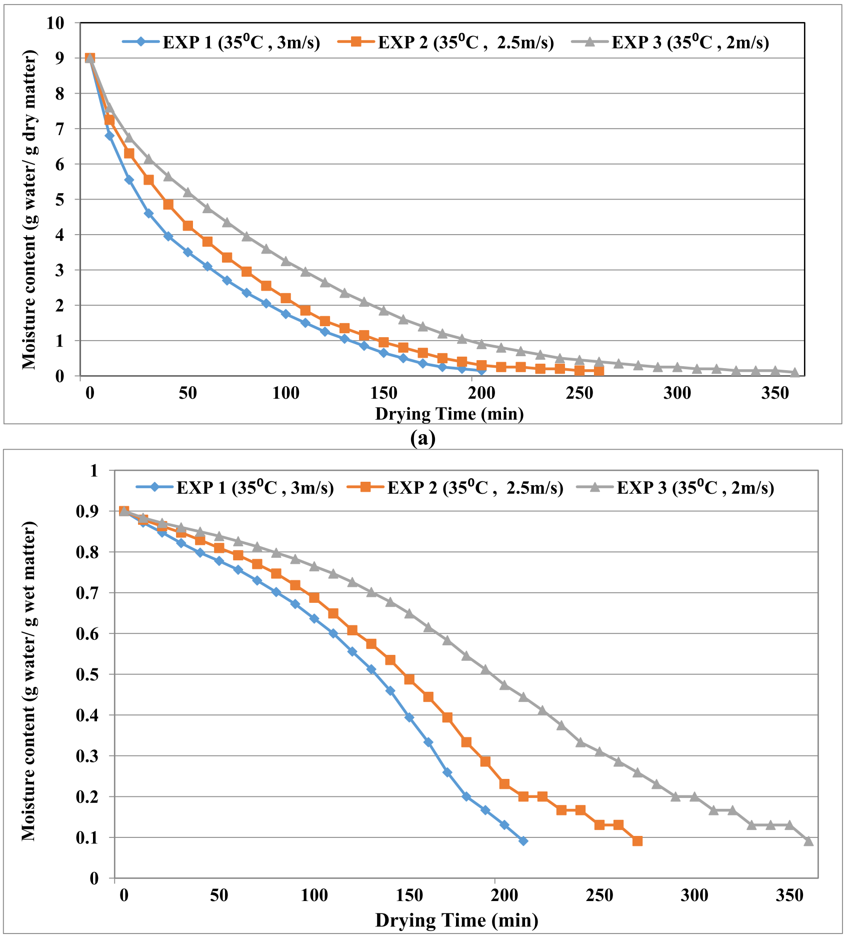
Variation in drying rate, according to drying time for different conditions was shown in Fig. 5. The air flow velocity variation had a strong role in conveying evaporated water from product surface and reducing drying time.

Fig. 6 shows energy consumption of drying system via time. The results show that experiment 1 with maximum air flow velocity has more energy consumption along drying time than the other two cases. The reason is that fan work continuously and need more energy when flow rate is high. This fact should make misunderstanding when it is compared with total energy consumption that has been noted in Table 2. By comparing the total energy consumption for three different cases, it can be concluded that there is no significant difference between mentioned values. The only parameter in this comparison is drying time that will take more value for experiment 3 with minimum air flow velocity.

The inverter decreased the compressor load to obtain set a temperature of drying air. So, drying air temperature fluctuations did not occur. Also, the total energy consumption was reduced using this control technique.

Fig. 7 shows the efficiency of heat recovery unit in this study. It has been described by dividing the recovered heat value to the maximum value in the ideal case. The ideal case for heat recovery unit could be obtained when air temperature of exhaust air was cooled down to ambient temperature by passing from the heat exchanger. However, in real operation, the exhaust air temperature is usually above the ambient temperature. Related curves in Fig. 7 shows that heat recovery efficiency is so similar in three cases. However, according to theoretical analysis, it was expected that the case study with 2 m/s air flow should have maximum efficiency, because there is more time to heat transfer comparing with the other cases. The solution for understanding this confliction can be proposed by focusing on heat recovery unit flow operation range. Flow rates of 1000, 800 and 600 m^3/h used in these case studies are not in the range that heat recovery unit works efficiently. So, Fig. 7 has not been able to show efficiency differences in an obvious way.

Heat delivery in the condenser as a function of drying time was shown in Fig. 8. As it can be seen in Fig. 8, delivered heat in the condenser at EXP 1–3.0 m/s exhibited fluctuations



(a)

(b)

Fig. 3 – Variation of moisture content as a function of drying time a) Dry basis b) Wet basis.

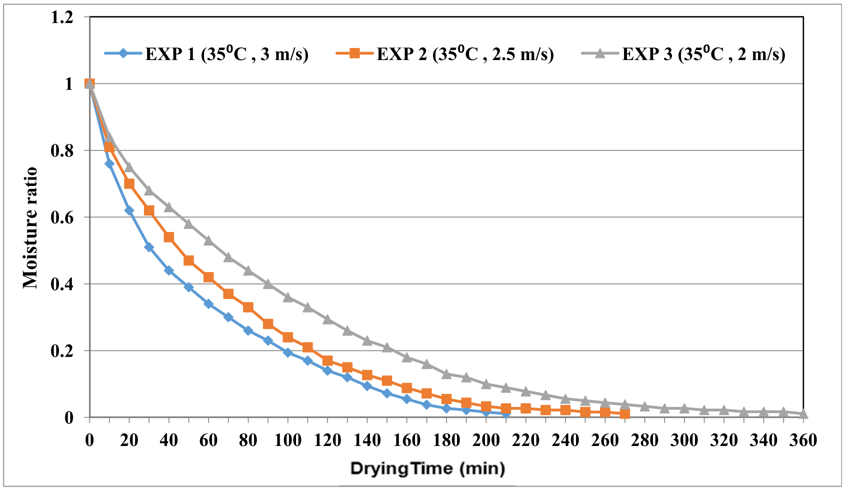


Fig. 4 – Variation of moisture ratio as a function of drying time.

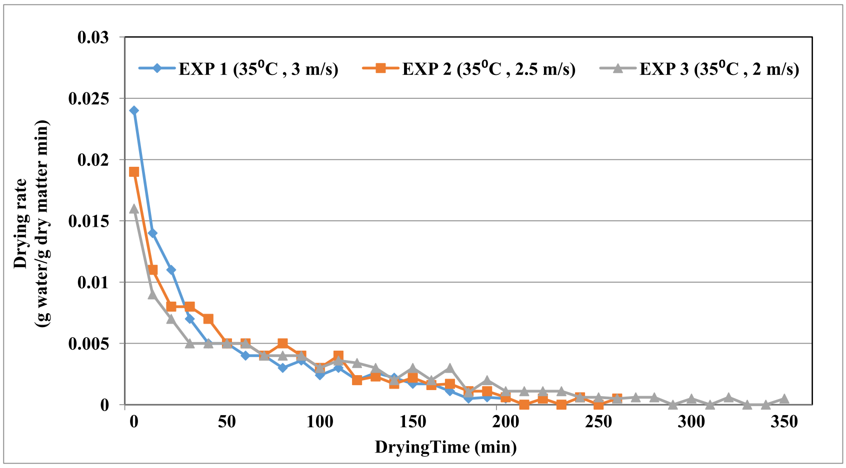


Fig. 5 – Variation in the drying rate as a function of drying time.

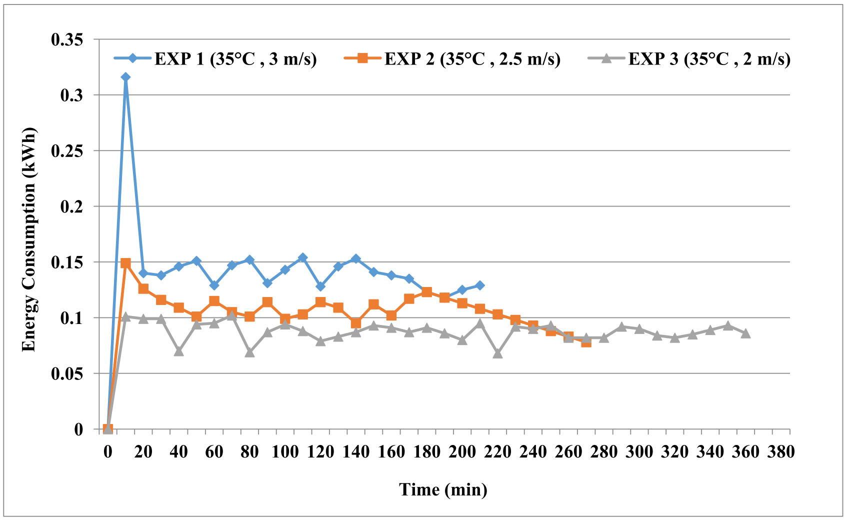


Fig. 6 – Energy consumption as a function of drying time.

Table 2 – Experimental results.

	Experiment 1	Experiment 2	Experiment 3
Drying time (hour)	3.5	4.5	6
Total energy consumption (kWh)	3.21	2.969	3.164
COP$_{ws}$	2.62	2.64	2.60
COP$_{hp}$	4.06	4.188	3.94
Drying air average temperature (°C)	35 °C	35 °C	35 °C
Drying air velocity (m/s)	3	2.5	2
Flow rate (m^3/h)	1000	800	600
Energy recovered from heat recovery unit (kWh)	3.95	4.28	4.56
Effective moisture diffusivity coefficient (D_{eff}), (m^2/s)	5.88E−11	4.79E−11	3.50E−11
Nusselt Number	74	67.5	60.4
Sherwood Number	5.58E+03	5.45E+03	5.42E+03

because of high air velocity. It means that heating up a high rate of air flow need more energy delivery of condenser that should be occurred frequently. Every peak value in this figure is indicating the start of the condenser working in the drying process. The variations of the heat delivered in the condenser in EXP 2–3 are more uniform than EXP 1.

Fresh mint leaves were dried in dryer. Fig. 9 shows the pictures of fresh and dried mint leaves. By doing sensory analysis, it is figured out that dried mint leaves have not exposed to any color and taste change after drying process. Temperatures above 40 °C was caused mint leaves to be ruined, additionally they are starting to burst in this range of temperature. So, air flow above the mentioned temperature was avoided in experiments.

Table 2 shows some parameters that are important in drying process including: drying time, total energy consumption, coefficient of performance, drying air velocity, Nusselt number, Sherwood number, and energy recovered from heat recovery unit. Drying case with minimum air flow velocity includes higher drying time. This case includes minimum value of Nusselt and Sherwood number. It means that heat

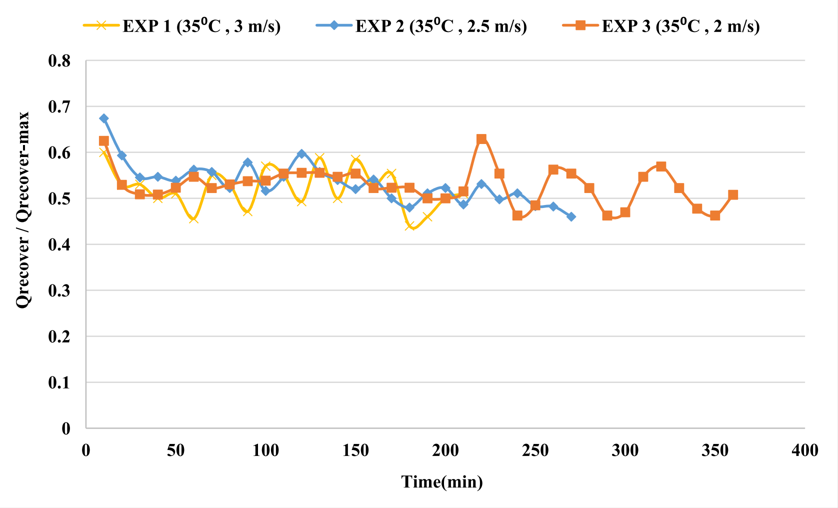


Fig. 7 – Heat recovery unit efficiency as a function of drying time.

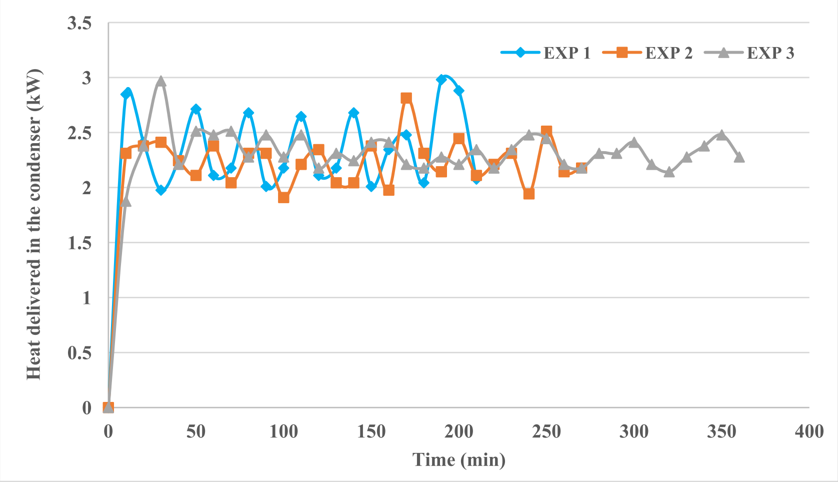


Fig. 8 – Heat delivered in the condenser as a function of drying time.

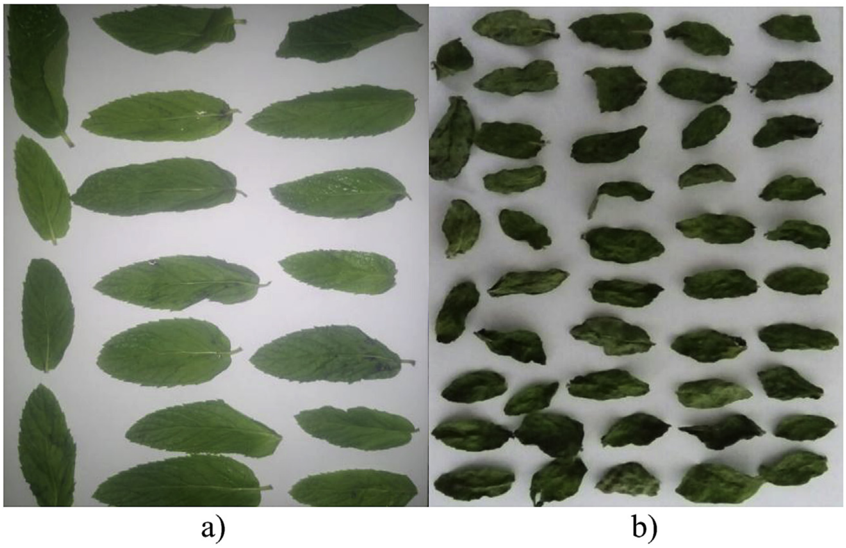


Fig. 9 – Mint leaves (a) before drying, (b) after drying.

transfer rate for Experiment 3 was lower in compare with other cases. Total energy consumption for three experiments have not been deviated from the average value of 3 kWh. It means that by neglecting heat losses and drying time, the energy needed for reducing the moisture content of a certain weight of material to the required moisture content is almost constant.

By comparing energy values in Table 2, it is revealed that recovered energy is more than consumed energy in all cases. It can be a little confusing at first look, so explaining one case study can be helpful in finding the role of heat recovery unit. In experiment 1, total consumed energy of compressor is 1.915 kWh. By considering coefficient of performance of heat pump (4.06), the total energy that have been released by the condenser is 7.77 kWh. On the other side, recovered energy by heat recovery unit is 3.95 kWh. It means that 51% of energy was saved by means of heat recovery unit. It can be concluded that in drying processes with long duration, heat recovery unit has more chance to recover more energy from wasted energy.

Effective moisture diffusivity coefficient values that were reported in Table 2, are comparable with the same parameter values that were reported by Kadem et al. as 1.23×10^{-10} – 2.65×10^{-10} m^2/s [9] and Kane et al. as 1.98×10^{-11} – 1.42×10^{-10} m^2/s [24]. According to their results, effective moisture diffusivity of mint leaves found to increase with the increase in drying air temperature. But in this study, as the set temperature is constant, variation in this parameter is affected by air flow rate. Increasing in drying air velocity in cylinder amplifies drying process. Therefore, effective moisture diffusivity is increased as the air flow rate is increased.

After the experiment, uncertainty analysis is performed to determine the error rates of the experimental data. The energy consumption of the dryer were measured by an electricity meter (220 V, 50 Hz, one-phase, LCD display, accuracy ±1% and uncertainty ±1.41%). This uncertainty value is in acceptable range.

Table 3 summarizes some studies related to heat pump application in various fields. Refrigerant, heat pump and whole system coefficient of performance of each study can be found in this list. Heat pump coefficient of performance of this study was obtained 4.06 that is among high values when it is compared to other similar studies. Also, 2.62 value in this study belongs to a coefficient of performance of the whole system that has not deviated from average values resulted in other researches.

Table 3 – Some studies related to heat pump application.

	Refrigerant	COP_{WS}	COP_{HP}
Zhang et al. [25]	R134a	–	3,36–5,94
Sivasakthivel et al. [26]	R22	3,1–2,8	3,5–3,3
Pitarch et al. [27]	R407C	2,8–3,9	–
	R410A	2,7–3,6	–
	R290	3,1–3,7	–
	R744	2,5–4,7	–
Qiu et al. [28]	–	2,23-4	–
Ceylan & Gürel [29]	–	5	–
Bellomarea & Minettob [30]	R441A	–	4
Aktaş et al. [31]	R134a	2,4–3,2	2,8–3,7
Chaiwongsa & Wongwises [32]	R134a	–	2,87–3,32
Şevik [33]	R134a	1,96–2,28	–
Esen & Inalli [34]	R22	2,69–3,45	–
Huang & Chyung [35]	R134a	–	5,3
Hossain et al. [36]	–	–	5,45
Fadhelet al. [37]	$CaCl_2$–NH_3	–	2-2,2
Fadhela et al. [38]	$CaO/Ca(OH)_2$	–	2.87
Oktay & Hepbaşlı [39]	R22	2.47–3.95	–
Huang et al. [40]	R134a	2.58–3.32	–
Guoyinget al. [41]	R22	3.9–4.32	–
This study	R-410A	2.62	4.06

Conclusions

This study presents mint leaves drying process by employing a heat pump combined with heat recovery unit. A generic geometric design for drying chamber was presented in this study. It has been designed in a cylindrical form to provide a uniform distribution of air flow around dried product. It was observed that air flow velocity variation between 2 and 3 m/s had not strong role on evaporation rate according to average mass transfer coefficient values.

As drying process is intensive energy consuming, so enhancing the efficiency of the system can be done by hiring different technologies. Using a heat recovery unit is one of effective methods that can rise up energy efficiency of drying system that is realized by gaining a part of the exhausted heat. The average percentage of recovered heat has been calculated as 48%. Consequently, heat recovery unit can be used efficiently in drying applications.

The highest recovered energy was obtained at 2 m/s air velocity and 35 °C set temperature, the reason is that air flow with minimum velocity has more time to get energy from exhausted air in inside heat recovery unit. Also, drying time for this case study was longer than others to facilitate more recovered heat.

This study has a contribution on drying chamber design. It uses three stainless steel cylinders with a circular nested form that has some advantages. First of all, drying product can access a uniform air flow that penetrates from external perforated sheet to central cylinder. So, homogeneous dried product is obtained. The second advantage of using such a closed type cylindrical drying chamber is that prevent spreading light weight samples like mint leaves over drying system. Monitoring drying parameters like MC, DR, MR and D_{eff} and system efficiency indicators like COP_{hp}, COP_{ws} values show that the new cylindrical drying chamber has comparable performance compared with other drying systems that were reported in the literature.

REFERENCES

[1] Shabbir I, Mirzaeian I. Feasibility analysis of different cogeneration systems for a paper mill to improve its energy efficiency. Int J Hydrogen Energy 2016;41(37):16535–48.

[2] Xiao-Wei L, Yuan Y, Huang X, Kai-Feng L. Visible-infrared optical properties measurement of the mesoporous TiO_2/carbon materials. Int J Hydrogen Energy 2016;41(35):15638–45.

[3] Kavak Akpinar E. Drying of mint leaves in a solar dryer and under open sun: modelling, performance analyses. Energy Convers Manag 2010;51:2407–18.

[4] Doymaz I. Thin-layer drying behavior of mint leaves. J Food Eng 2006;74:370–5.

[5] Saleh A, Badran I. Modeling and experimental studies on a domestic solar dryer. Renew Energy 2009;34:2239–45.

[6] Biçer Y, KavakAkpinar E. Investigation of drying behavior of pumpkin in a cyclone type dryer. Gazi Univ J Sci 2003;16:159–69.

[7] Özbek B, Dadali G. Thin-layer drying characteristics and modelling of mint leaves undergoing microwave treatment. J Food Eng 2007;83:541–9.

[8] Goujot D, Meyer X, Courtois F. Identification of a rice drying model with an improved sequential optimal design of experiments. J Process Control 2012;22:95–107.

[9] Kadam DM, Goyal RK, Singh KK, Gupta MK. Thin layer convective drying of mint leaves. J Med Plants Res 2011;5:164–70.

[10] Vyankatrao NP. Effect of drying methods on nutritional value of some vegetables. In: Proceeding of the national conference on conservation of natural resources & biodiversity for sustainable development; 2014. p. 72–9.

[11] Wongsim K, Jamradloedluk J, Lertsatitthanakorn C, Siriamornpun S, Rungsiyopas M, Soponronnarit S. Experimental performance of a thermoelectric heat-pump drying system for drying herbs. J Electron Mater 2015;44:2142–5.

[12] Soysal Y. Mathematical modeling and evaluation of microwave drying kinetics of mint (*Mentha spicata* L.). J Appl Sci 2005;5(7):1266–74.

[13] Kripanand SM, Guruguntla S, Korra S. Effect of various drying methods on quality and flavor characteristics of mint leaves (*Mentha spicata* L.). J Food Pharm.Sci 2015;3:38–45.

[14] Alibaş I. Determination of vacuum and air drying characteristics of celeriac slices. Gazi Univ J Polytech 2012;6(16):1–13.

[15] Afes-Boukadoum AB, Benzaoui A. Energy and exergy analysis of solar drying process of Mint. Energy Procedia 2011;6:583–91.

[16] AOAC. Official method of analysis, association of official analytical chemist. Arlington: Virginia: IAC; 1990.

[17] Ertekin C, Heybeli N. Thin-layer infrared drying of mint leaves. J Food Process Preserv 2013;38:1480–90.

[18] Çengel Y, Ghajar AJ. Heat and mass transfer fundamentals and applications. McGraw-Hill; 2011.

[19] Aktaş M, Ceylan I, Yilmaz S. Determination of drying characteristics of apples in a heat pump and solar dryer. Desalination 2009;239:266–75.

[20] Ghasemkhan H, Keyhani A, Aghbashlo M, Rafiee S, Mujumdar AS. Improving exergetic performance parameters of a rotating-tray air dryer via a simple heat exchanger. Appl Therm Eng 2016;94:13–23.

[21] Sevik S, Aktas M, Dogan H, Koçak S. Mushroom drying with solar assisted heat pump system. Energy Convers Manag 2013;72:171–8.

[22] Zare D, Minaei S, MohamadZadeh M, Khoshtaghaza MH. Computer simulation of rough rice drying in a batch dryer. Energy Convers Manag 2006;47:3241–54.

[23] Özdemir MB, Aktaş M, Şevik S, Khanlari A. Modeling of a convective-infrared kiwifruit drying process. Int J Hydrogen Energy 2017;42:18005–13.

[24] Kane CSE, Sid'Ahmed MAO, Kouhila M. Evaluation of drying parameters and sorption isotherms of mint leaves (*M. pulegium*). Rev des Energies Renouvelables 2009;12:449–70.

[25] Zhang S, Zhang L, Wei H, Jing J, Zhou X, Zhang X. Field testing and performance analyses of ground source heat pump. Energy Build 2016;133:615–27.

[26] Sivasakthivel T, Murugesan K, Kumar S, Hu P, Kobiga P. Experimental study of thermal performance of a ground source heat pump system installed in a Himalayan city of India for composite climatic conditions. Energy Build 2016;131:193–206.

[27] Pitarch M, Peris EN, Maciá JG, Corberán JM. Experimental study of a subcritical heat pump booster for sanitary hot water production using a subcooler in order to enhance the efficiency of the system with a natural refrigerant (R290). Int J Refrig 2016;73:226–34.

[28] Qiu Y, Li M, Hassanien HE, Wang Y, Luo X, Yu Q. Performance and operation mode analysis of a heat recovery and thermal storage solar-assisted heat pump drying system. Sol Energy 2016;137:225–35.

[29] Ceylan I, Gürel AE. Solar-assisted fluidized bed dryer integrated with a heat pump for mint leaves. Appl Therm Eng 2016;106:899–905.

[30] Bellomarea F, Minettob S. Experimental analysis of hydrocarbons as drop-in replacement in household heat pump tumble dryers. In: Energy Procedia 69th Conference of the Italian Thermal Engineering Association, 81; 2015. p. 1212–21.

[31] Aktaş M, Şevik S, Özdemir MB, Gönen E. Performance analysis and modeling of a closed-loop heat pump dryer for bay leaves using artificial neural network. Appl Therm Eng 2015;87:714–23.
[32] Chaiwongsa P, Wongwises S. Experimental study on R-134a refrigeration system using a two-phase ejector as an expansion device. Appl Therm Eng 2008;28:467–77.
[33] Şevik S. Experimental investigation of a new design solar-heat pump dryer under the different climatic conditions and drying behavior of selected products. Sol Energy 2014;105:190–205.
[34] Esen H, Inalli M. Modeling of a vertical ground coupled heat pump system by using artificial neural networks. Exp Syst Appl 2009;36:10229–38.
[35] Huang BJ, Chyung JP. Performance characteristics of integral type solar assisted heat pump. Sol Energy 2001;71. 403–314.
[36] Hossain MA, Gottschalk K, Hassan MS. Mathematical model for a heat pump dryer for aromatic plant. Procedia Eng 2013;56:510–20.
[37] Fadhel MI, Sopian K, Daud WRW. Performance analysis of solar-assisted chemical heat-pump dryer. Sol Energy 2010;84:1920–8.
[38] Fadhel MI, Saqaff A, Alkaff A, Teo WC, Sopianb K. Analysis of a solar assisted CaO/Ca(OH)$_2$ chemical heat pump drying system. Int J Smart Grid Clean Energy 2015;4:311–5.
[39] Oktay Z, Hepbaşlı A. Performance evaluation of a heat pump assisted mechanical opener dryer. Energy Convers Manag 2003;44:1193–207.
[40] Huang BJ, Lee JP, Chyng JP. Heat-pipe enhanced solar-assisted heat pump water heater. Sol Energy 2005;78:375–81.
[41] Guoying X, Xiaosong Z, Shiming DA. Simulation study on the operating performance of a solar-air source heat pump water heater. Appl Therm Eng 2006;26:1257–65.

Nomenclature

$C_{p,air}$: specific heat capacity of air, kJ/kgK
COP_{hp}: coefficient of performance of the heat pump
COP_{ws}: coefficient of performance of whole system
DR: drying rate, g water/g dry matter min
D: diffusion coefficient, m^2/s
D_{eff}: effective diffusivity coefficient, m^2/s
D_h: hydraulic diameter, m
h_m: mass transfer coefficient, m/s
k: thermal conductivity, W/mK
MC_{db}: moisture content, g water/g dry matter
M_i: initial wet weight, g
M_d: final dry weight, g
MC_t: moisture content at time “t”, g water/g dry matter
MC_{t+dt}: moisture content at time “t + dt”, g water/g dry matter
MR: moisture ratio
M: moisture content of the product at any level and at any time, g water/g dry matter
M_e: equilibrium moisture content, g water/g dry matter
M_o: initial moisture content, g water/g dry matter
$\dot{m}_{air}$: air flow rate, kg/s
Nu: Nusselt number
Pr: Prandtl number
$Q_{recover}$: heat gained by recovery unit, kJ
$Q_{recover-max}$: maximum heat gained by recovery unit, kJ
R: the function uncertainty
Re: Reynolds number
Sc: Schmidt number
Sh: Sherwood number
T: temperature, °C
T_a: inlet air temperature, °C
T_{ex}: exhaust air temperature, °C
T_o: drying chamber outlet temperature, °C
υ: kinematic viscosity, m^2/s
u: mean velocity of air, m/s
t: time, minute
$\dot{w}_C$: power input to compressor, kW
$\dot{w}_F$: power input to fan, kW
W_R: the total uncertainty, %
w_1, w_2, w_n: the uncertainties in the independent variables
x: independent variables