

---

## CHAPTER 3

# EXPERIMENTATION ON SIMPLE HEAT PUMP DRYER

---

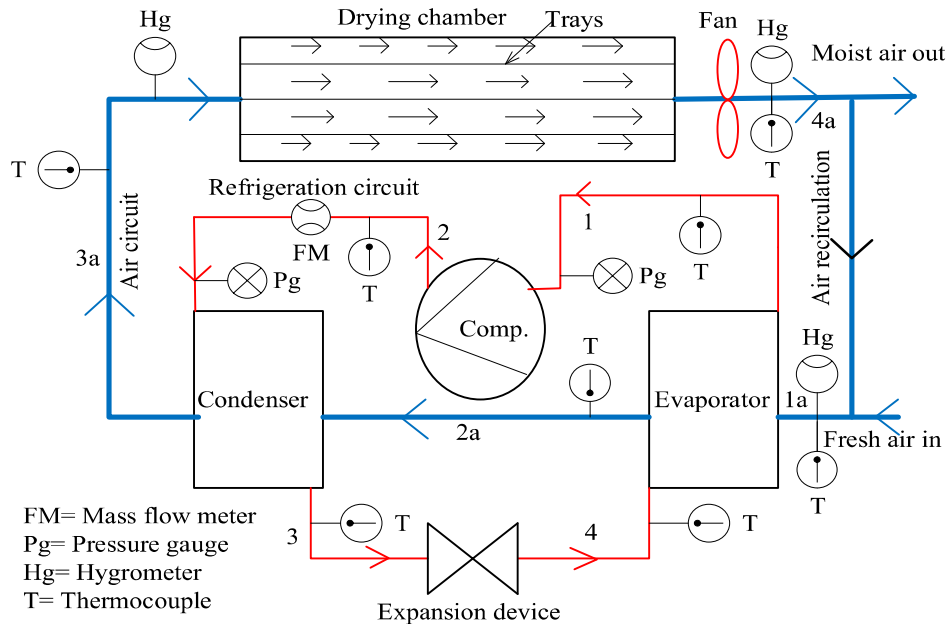
---

This chapter deals with the fabrication of the simple vapor compression heat pump dryer (HPD), instrument details, and experimental procedure. The experiment was performed to compare the open and closed systems for the drying of the banana and the potato chips. The closed and open system analyses are important to study due to the recovery of waste heat at the dryer outlet as compared to the open system. The experimental setup consists of the drying cabin, compressor, condenser, evaporator, fan, expansion device, and trays inside the cabin. The result obtained from the experiment for the drying of the banana and the potato chips in an open and closed system is also discussed in this chapter. The uncertainty of the experiment is given in this chapter for the different performance parameters.

### 3.1. Experimental setup and procedure

The design, development, and fabrication of a batch-type convective heat pump dryer are done, and the experiment was performed for the drying of the different agricultural products in an open and closed-loop system. Fig. 3.1 represents the schematic diagram of the open and closed-loop heat pump drying system. The location of the different components of the system and the measuring instruments are shown in Fig. 3.1. The system is designed in such a manner that it can be operated in two modes (open loop and closed loop) based on the recirculation of the dryer exhaust air through the drying system. For the open mode system, the exhaust air from the drying chamber outlet was directly allowed to go into the atmosphere. Whereas, for the closed mode system, the drying air is forced to recirculate in the system by opening the sliding door between the evaporator inlet and drying chamber outlet. The basic components of the

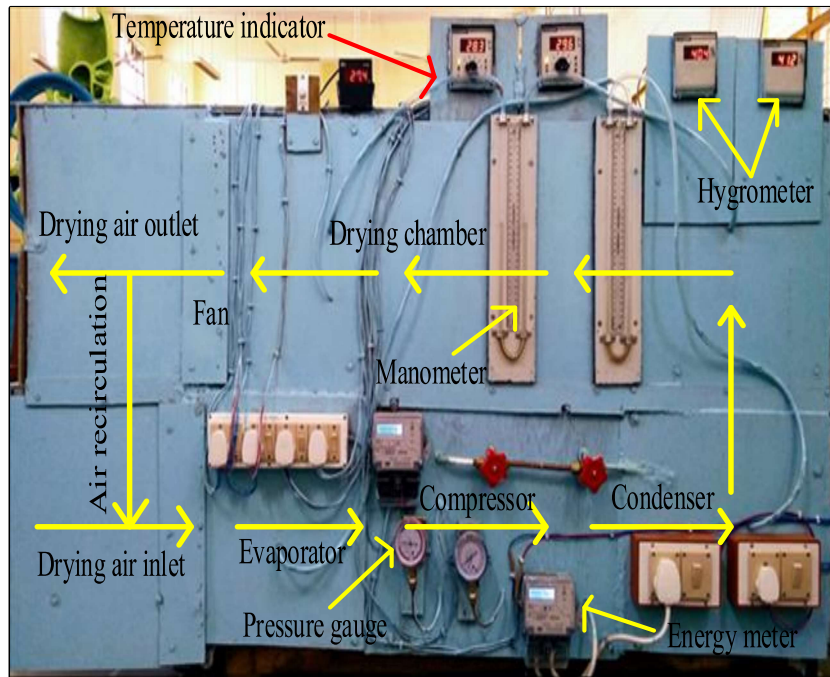
heat pump system are compressor, condenser, evaporator, and expansion device. The R134a refrigerant is used in the heat pump system for the cooling and heating in the evaporator and condenser respectively.



**Fig. 3.1:** Schematic diagram of the heat pump drying system

The evaporator, compressor, and condenser are fabricated in a line such that the evaporator (cooling and dehumidification) is located at the inlet of the drying system and the condenser is located just before the drying chamber inlet. The batch-type drying cabin consists of several trays inside it. The trays are made using aluminum strips, which have been designed to get uniform drying air-flow coverage by maintaining the optimum gap between the trays, and the stainless steel net to get the constant rate of moisture removal on both sides of the food chips by drying air. The gap between the two trays is 5cm and the area of each tray is  $0.18\text{m}^2$ . The drying cabin wall is made of plywood, and thermocol sheet is used as insulating material inside the wall to minimize the heat transfer from drying air to the surrounding. The drying air is circulated in the HPD system by using a fan (located at the drying cabin outlet). The fan is fabricated at the drying cabin outlet to get stable and uniform distribution of the air inside the cabin through the trays. The

developed experimental setup is shown in Fig. 3.2 and the detailed specifications of the different components are listed in Table 3.1 and the properties of measuring instruments are given in Table 3.2.



**Fig. 3.2:** Photograph of the developed experimental setup

**Table: 3.1. Specification of the different components of the HPD system**

Component	Specification
Compressor	Rated power requirement = 505 W, swept volume = 15.33 cm <sup>3</sup> , rated voltage = 230 Volts, 50Hz refrigerant used = R134a
Condenser	Wavy fin and tube 4-row cross flow heat exchanger type, length of tube = 31.7 m, dimension = 30.48 cm × 33.02 cm, diameter of tube (inside) = 9.7mm
Evaporator	Wavy fin and tube 4-row cross flow heat exchanger type, length of tube = 23.6 m, dimension = 30.48 cm × 33.02 cm, diameter of tube (inside) = 9.7mm
Capillary tube	Inside tube diameter = 1.27 mm, total length of tube = 60 cm

Fan	Rated power =70 W, speed = 1350 rpm, total sweep = 300 mm
Drying chamber	Convective batch type, length of drying chamber = 0.7m, width = 0.35m, height = 0.4m, no of trays inside chamber = 8, gap between trays = 2.5 cm, capacity of drying chamber = 5 kg

**Table: 3.2. Technical specification and uncertainty of measuring instrument**

Instrument	Specification	Accuracy
Resistant thermometer (PT100)	Range -50 to 250°C,	$\pm 0.5^\circ\text{C}$
Vane type anemometer	Velocity 0-20 m/s	$\pm 2\%$
Hygrometer	0-100% relative humidity	$\pm 2.5\%$
Energy meter	Supply 220V, 50 Hz	$\pm 1\%$
Coriolis mass flow meter	Range: 0–0.5 kg/s, maximum pressure = 25 bar, maximum temperature = 200°C	$\pm 0.5\%$
U-Tube manometer	Manometric fluid = water	$\pm 1\text{mm}$
Digital weighing machine	Measuring capacity of 10 kg	$\pm 2\%$
Pressure gauge	Measuring pressure of 30 bar	$\pm 3\%$

The pressure gauges (accuracy =  $\pm 3\%$ ) and thermocouples (accuracy =  $\pm 0.5^\circ\text{C}$ ) are installed at different locations to measure the condenser and evaporator pressures, and refrigerant temperatures in the heat pump system at the compressor inlet, outlet, condenser outlet, and the evaporator inlet. Hygrometers are installed to measure the relative humidity of air at locations of the evaporator inlet, drying chamber inlet, and drying chamber outlet. The U-tube manometers are used to calculate the total pressure

drop inside the drying chamber and the whole system. Energy meters are used to obtain the electrical energy consumption of the compressor and fan. The fan speed or air mass flow rate was controlled by an electric regulator, and the flow velocity of the drying air in the system is measured by using the vane type anemometer (accuracy  $\pm$  of 2%). Velocity has been measured at different positions of a cross-section and then taken as the average. Weighing balance is used to measure the weight of the drying material before and after the experiment. The mass flow rate of refrigerant has been measured by Coriolis mass flowmeter installed at the compressor outlet.

The HPD system has been operated for the drying of the banana and potato chips in the laboratory. Both the fresh pilled potato and banana bought from the retailer were washed with clean water and sliced into 2mm size chips. 0.5kg of material was used per tray for the drying. The initial and final moisture contents of the products were determined by the oven method (Zambrano et al., 2019). The microwave oven was used to determine the initial moisture content and the sample was put inside the oven for 15-20min. A sample of 4kg of banana and potato chips (separately) was dried using the open system and closed system heat pump drying. The banana and potato chips were spread out on the tray in the drying chamber, and for the homogeneous drying, the banana and potato chips were mixed from time to time. The temperature inlet to the drying chamber depends on the amount of heat transfer in the condenser from the refrigerant to the air, the velocity of the circulating air and the permitted drying temperature of the products. Air recirculation ratio and drying temperature have been controlled by adjusting vanes and fan speed controller.

The experiment was performed to estimate the performance of the system and drying kinetics of the banana and potato chips in HPD. The drying air velocity and the temperature were adjusted to the required values. After that, the HPD system was started

to get the desired drying temperature. The mass flow rate of air (0.073kg/s) was kept constant for the drying of banana and potato in open and closed systems. Then the banana and potato chips are weighted in digital balance and spread over the trays and loaded inside the HPD drying chamber, and the fan was switched on to get the desired air mass flow rate (0.073kg/s). Then the initial readings of the energy meter were noted, and during the experiment, the temperature and the relative humidity of drying air at the inlet to the evaporator, the inlet to the dryer, and the outlet to the dryer were recorded periodically after every 10 minutes until the experiment ended. The weight loss from the drying material should be equal to the change in the humidity of the drying air from dryer inlet to outlet. Three replicates were performed for each experiment.

### 3.2. Data analysis

The performance of the HPD system depends on the different parameters such as the inlet condition of the air to the evaporator, air recirculation ratio, and air velocity flowing through the system. The heat delivered by the refrigerant to the drying air in the condenser is given by,

$$Q_{cond} = \dot{m}_a c_{pam} (T_{3a} - T_{2a}) \quad (3.1)$$

Where  $\dot{m}_a$  ( $= A_{fr} \rho_a V_a$ ) is the mass flow rate of air and  $c_{pam}$  is the isobaric specific heat of humid air it is given as,  $c_{pam} = c_{pa} + \omega_a c_{pv}$

The coefficient of the performance (COP) of the heat pump is defined as the ratio of the heat delivered in the condenser to the energy input to the compressor and is given by,

$$COP_{hp} = \frac{Q_{cond}}{W_{comp}} \quad (3.2)$$

Similarly, COP for the whole system has been calculated by,

$$COP_{ws} = \frac{Q_{cond}}{W_{comp} + W_{fan}} \quad (3.3)$$

The heat delivered rate in the condenser by refrigerants is also given by the following,

$$Q_{cond} = \dot{m}_r (h_2 - h_3) \quad (3.4)$$

Volumetric heating capacity is an important parameter of the heat pump (represents the rate of heat delivered per unit refrigerant volume flow rate in the compressor), which is given by,

$$\text{Volumetric heating capacity} = (h_2 - h_3) \rho_1 \quad (3.5)$$

The moisture removed from the product ( $m_w$ ) at any time is the difference between the initial weight to the weight of the product at any time and is also equal to the moisture carried out by the drying air from the drying chamber. It is given by,

$$m_w = (m_{pi} - m_{pt}) = \dot{m}_a (\omega_{4a} - \omega_{3a}) t_d \quad (3.6)$$

The energy efficiency (the ratio of the energy used for removal of moisture from the product to the total energy required), which indicates how efficiently the energy consumed in the system removes the moisture from the product, is given by (Vieira et al., 2007),

$$\eta_{en} = \frac{h_{fg} m_w}{t_d (W_{comp} + W_{fan})} \quad (3.7)$$

The SMER is defined as the amount of moisture removal per unit of energy consumed and is given as,

$$\text{SMER} = \frac{m_w}{t_d (W_{comp} + W_{fan})} \quad (3.8)$$

Percentage of water loss from the product is calculated by the following,

$$\text{Water loss} = \frac{m_{pi} - m_{pt}}{m_{pi}} \quad (3.9)$$

The MER is defined as the moisture removed from the drying product per unit time and is given as,

$$\text{MER} = \frac{m_w}{t_d} \quad (3.10)$$

Specific energy consumption (SEC) of the HPD system is the amount of energy required to evaporate the unit mass of the moisture from the product and is given by,

$$\text{SEC} = \frac{t_d (W_{comp} + W_{fan})}{m_w} \quad (3.11)$$

The moisture content of the product on a dry basis and the moisture ratio (MR) can be given using the following,

$$(M_t)_{db} = \frac{m_{pt} - m_d}{m_d} \quad (3.12)$$

$$\text{MR} = \frac{(M_t - M_{eq})}{(M_0 - M_{eq})} \quad (3.13)$$

As the equilibrium moisture content is very small as compared to moisture content at any time and initial moisture content, the moisture ratio has been simplified as,

$$\text{MR} = \frac{M_t}{M_0} \quad (3.14)$$

The drying rate of the product during the drying has been calculated by,

$$\text{DR} = \frac{M_{t+dt} - M_t}{dt} \quad (3.15)$$

The effective diffusivity coefficient of the sliced potato and banana chips during drying was estimated by using the simplified mathematical Fick's second model. According to Fick's second law, the drying behavior of sliced potato chips can be described by (Aktas et al., 2017),

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)} \exp\left(-\frac{(2n-1)^2 \pi^2 D_{eff} t_d}{4L^2}\right) \quad (3.16)$$

Where  $D_{eff}$  is the effective diffusivity coefficient,  $L$  is the half-thickness of the potato and banana slice (m), and  $n$  is the positive integer. For long drying periods, the above Eq. can be simplified as (Aktas et al., 2017),

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t_d}{4L^2}\right) \quad (3.17)$$

$$\ln(MR) = -\left(\frac{\pi^2 D_{eff}}{4L^2}\right) t_d + \ln\left(\frac{8}{\pi^2}\right) \quad (3.18)$$

The effective diffusivity ( $D_{eff}$ ) of material is obtained by plotting from the experimental  $MR$  data in terms of  $\ln MR$  with time (s) followed by the estimation of slope

(Slope =  $\frac{\pi^2 D_{eff}}{4L^2}$ ) using Eq. (3.18) (Ekka et al., 2020),

The convective mass transfer coefficient has been calculated by (Cengel and Ghajar, 2011),

$$h_m = \frac{B_i D_{eff}}{L} \quad (3.19)$$

Where, the Biot number can be calculated by (Dincer and Hussain, 2002),

$$B_i = 24.85 \left(\frac{V_a}{k_c L}\right)^{-0.375} \quad (3.20)$$

Where,  $k_c$  is the drying constant of the product that can be calculated by the following relation (Aboltins, 2013),

$$k_c = -DR / (M_t - M_{eq}) \quad (3.21)$$

Exergies of refrigerant and humid air at any state have been calculated by, respectively,

$$E_x = \dot{m}_r \{(h - h_o) - T_o(s - s_o)\} \quad (3.22)$$

$$E_{xa} = \dot{m}_a c_{pam} \left[ (T_a - T_o) - T_o \ln \left( \frac{T_a}{T_o} \right) \right] \quad (3.23)$$

Hence, the exergy loss and exergy efficiency of compressor, condenser, expansion device, evaporator and dryer are given by, respectively (Ganjehsarabi et al., 2014),

$$Ex_{\text{dest,comp}} = W_{\text{comp}} + Ex_1 - Ex_2, \quad \eta_{\text{ex,comp}} = \frac{Ex_2 - Ex_1}{W_{\text{in}}} \quad (3.24)$$

$$Ex_{\text{dest,cond}} = Ex_2 - Ex_3 + Ex_{2a} - Ex_{3a}, \quad \eta_{\text{ex,cond}} = \frac{Ex_{3a} - Ex_{2a}}{Ex_2 - Ex_3} \quad (3.25)$$

$$Ex_{\text{dest,exp}} = Ex_3 - Ex_4, \quad \eta_{\text{ex,exp}} = \frac{Ex_4}{Ex_3} \quad (3.26)$$

$$Ex_{\text{dest,evap}} = Ex_4 - Ex_1 + Ex_{1a} - Ex_{2a}, \quad \eta_{\text{ex,evap}} = \frac{Ex_{2a} - Ex_{1a}}{Ex_4 - Ex_1} \quad (3.27)$$

$$Ex_{\text{dest,dryer}} = Ex_{3a} - Ex_{4a} + W_{\text{fan}}, \quad \eta_{\text{ex,dryer}} = \frac{Ex_{3a} - Ex_{4a}}{W_{\text{fan}}} \quad (3.28)$$

### 3.2.1. Experimental uncertainty

To support the experimental results, the uncertainty analysis has been carried out by using the method explained (Holman, 2001). Let the predicted parameter, R is a given function of the independently measured variables  $y_1, y_2, y_3, \dots, y_n$ . Thus,

$$R = R \left( y_1^{u_1}, y_2^{u_2}, y_3^{u_3}, \dots, y_n^{u_n} \right) \quad (3.29)$$

Let  $U_R$  be the uncertainty in the result and  $u_1, u_2, u_3, \dots, u_n$  be the uncertainties in the independent variables then the uncertainty in the result having variation is given by the following

$$U_R = \left[ \left( \frac{\partial R}{\partial y_1} u_1 \right)^2 + \left( \frac{\partial R}{\partial y_2} u_2 \right)^2 + \dots + \left( \frac{\partial R}{\partial y_n} u_n \right)^2 \right]^{1/2} \quad (3.30)$$

The technical specifications of the measuring instruments and the uncertainties are provided in Table 3.2. Based on the measured parameters by various instruments, the

total experimental absolute uncertainties found for estimated values of Drying efficiency (DE), energy efficiency ( $\eta_{en}$ ), total exergy destruction, moisture extraction rate (MER), total energy consumption, volumetric heating capacity,  $(COP)_h$  and SMER are  $\pm 9.47\%$ ,  $\pm 13.43\%$ ,  $\pm 1.81\%$ ,  $\pm 2.236\%$ ,  $\pm 1.49\%$ ,  $\pm 3.96\%$ ,  $\pm 4.12\%$ , and  $\pm 3.88\%$  respectively.

### 3.3. Results and discussion

Banana and potato chips have been dried in the HPD with and without recirculation of the drying air, and the performance of the HPD system has been investigated. The air velocity was fixed at about 0.6m/s for the open as well as the closed system for drying both banana and potato chips. For the open system, the drying air temperature for banana and potato chips was between 39.5°C to 43.8°C and 38.3°C to 42°C, respectively for the closed system drying of the banana and potato, the drying temperature was between 47.6°C to 51.8°C and 46°C to 53.7°C, respectively. The drying process has been carried out until the difference between the humidity at the drying chamber inlet and outlet becomes negligible, so the final MC of the product reaches to the desired value (11.6%). The experimental results obtained for the HPD system are listed in Table 3.3.

**Table: 3.3. Performance comparison of experimental results**

Performance parameter	Closed system		Open system	
	Banana	Potato	Banana	Potato
Average drying temperature (°C)	50.5	50.4	41.4	40.8
Drying time (min)	220	320	300	370
Initial- final moisture content (% w.b.)	84-11.6	83.5-11.5	84-11.6	83.5-11.5
Total energy consumption (kWh)	2.41	3.51	3.3	3.564

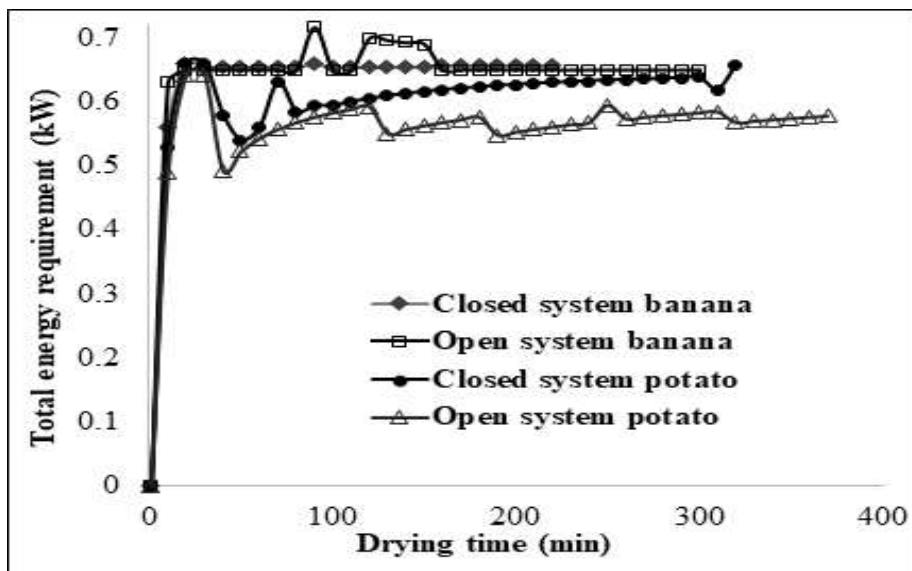
Volumetric heating capacity (MJ/m <sup>3</sup> )	12.1	10.03	12.05	9.7
Average COP <sub>hp</sub>	3.09	2.85	3.89	3.93
Average COP <sub>ws</sub>	2.82	2.58	3.55	3.63
Average MER (kg/h)	0.8127	0.6745	0.62	0.6
Average SMER (kg/kWh)	1.248	1.0498	0.924	0.981
Average SEC (kWh/kg)	0.80128	0.95256	1.0822	1.01936
Average drying efficiency (%)	55.9	58.09	45.8	52.01
Average diffusivity (m <sup>2</sup> /s)	2.37E <sup>-10</sup>	1.31E <sup>-10</sup>	1.02E <sup>-10</sup>	0.92E <sup>-10</sup>
Average mass transfer coefficient (m/s)	9.89E <sup>-7</sup>	7.78E <sup>-7</sup>	2.15E <sup>-7</sup>	2.23E <sup>-8</sup>

It can be observed that the closed system drying is best in terms of energy consumption, MER, SMER, and drying efficiency because specific energy consumption is the lowest in this system. However, the COP was good in the open system HPD drying for banana and potato chips as compared to the closed system because in the open system the values of humidity and temperature at the inlet to the evaporator are low (the COP of the heat pump increases with decrease in temperature and humidity at evaporator inlet). Average COP values of heat pump for an open and closed system for banana and potato chips are 3.89, 3.93, and 3.09 and 2.85 respectively, and the values of COP for heat pump obtained in the present study are in the acceptable range given in the literature from 2.8 to 3.7 (Aktas et al., 2015). The volumetric heating capacity indicates the heating capacity for a given compressor size and the average values for banana and potato chips in open and closed systems are 12.05, 12.1 and 9.7, 10.03MJ/m<sup>3</sup>, respectively. From the experimental results, it can be estimated that the drying time is low and the moisture

extraction rate was maximum for the closed system drying for banana and potato chips as compared to the open system. Total drying times for banana and potato chips in open and closed system drying are 300, 370, and 220, 310 minutes respectively. The moisture removed from the products mainly depends on the moisture diffusivity, and it increases with an increase in the drying air temperature and air velocity. Hence, the drying air inlet temperature and velocity are having a meaningful effect on the product moisture diffusivity as well as the mass transfer coefficient. The moisture from the interior of the product is forced to diffuse to the surface of the product and carried away by the drying air. The moisture diffusivity of banana and potato chips was estimated for open and closed mode drying using Eq. (3.18). The moisture diffusivity was calculated by plotting a graph between  $\ln(MR)$  versus time. The average value of the moisture diffusivity of banana and potato chips varies from  $1.02E^{-10}$  to  $2.37E^{-10} m^2/s$  and  $0.92E^{-10}$  to  $1.31E^{-10} m^2/s$  for open and closed system drying. The average value of the mass transfer coefficient of potato and banana chips varies from  $2.23E^{-8}$  to  $2.15E^{-7} m/s$  and  $7.78E^{-7}$  to  $9.89 E^{-7} m/s$  for open and closed system drying, and these values are close to the experimental result of mass transfer coefficient ( $2.064E^{-7} m/s$ ) obtained in convective drying of the banana chips by Silva et al. (2012). The mass transfer coefficient and moisture diffusivity are quite higher for the closed system due to higher drying temperature as compared to an open system. Total energy consumption is lower for the closed system as compared to the open system due to the utilization of the energy of exhaust air from the drying chamber (leading to lower drying time and hence lower energy consumption). Exhaust energy is directly wasted in the atmosphere in an open system. The average drying efficiency is better for the closed system due to the getting of higher drying temperature for the same mass flow rate of inlet air. The average values of the specific energy consumption for banana and potato chips in open and closed system drying are 1.0822, 0.80128, and

1.01936, 0.95256kWh/kg respectively and the SEC is nearly 25.96% more in an open system as compared to the closed system for banana chips.

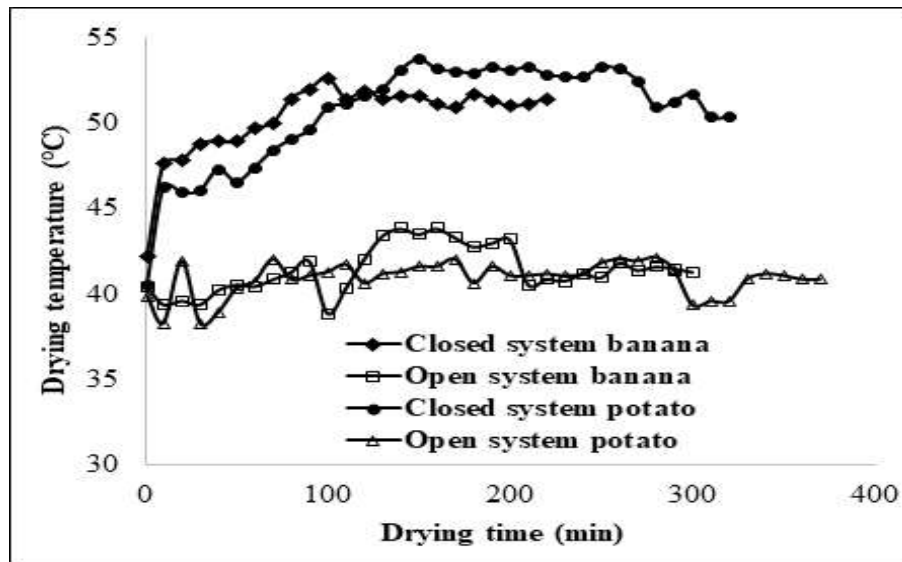
The total energy consumption in the HPD system mainly depends on the energy consumed by the compressor and the fan. The total energy consumption is lowest for the closed system as compared to the open HPD drying due to higher air temperature and less drying time at the same mass flow rate of the air. The energy consumption for banana and potato chips in the open and closed systems were 3.3, 2.41, and 3.564, 3.51kWh, respectively as shown in Fig. 3.3.



**Fig. 3.3:** Variation in energy requirement with drying time

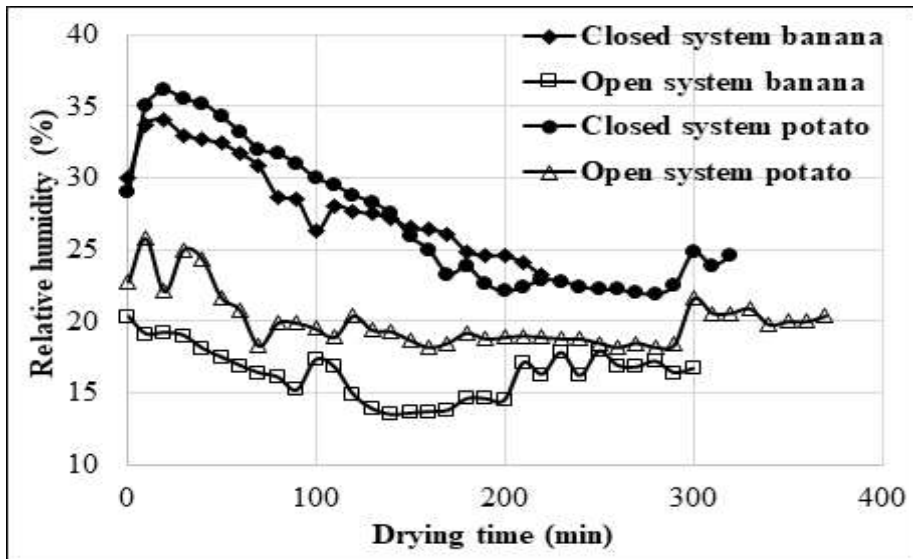
Fig. 3.4 shows the drying air temperature at the dryer inlet. The average dryer inlet temperature is higher for the closed system drying as compared to the open system due to the recirculation of the dryer exit air directly to the evaporator, which utilizes the exit energy of the drying air, and the drying temperature is minimum for the open system for both banana and potato chips drying. The dryer inlet temperature depends on the condenser saturation temperature and the amount of heat delivered by the refrigerant to the air and the mass flow rate of the drying air. The condenser outlet temperature is fluctuating due to the change in the humidity and the temperature of the air inlet to the

evaporator. The average drying temperature for the open system is 41°C and the same for the closed system is 50.4°C.

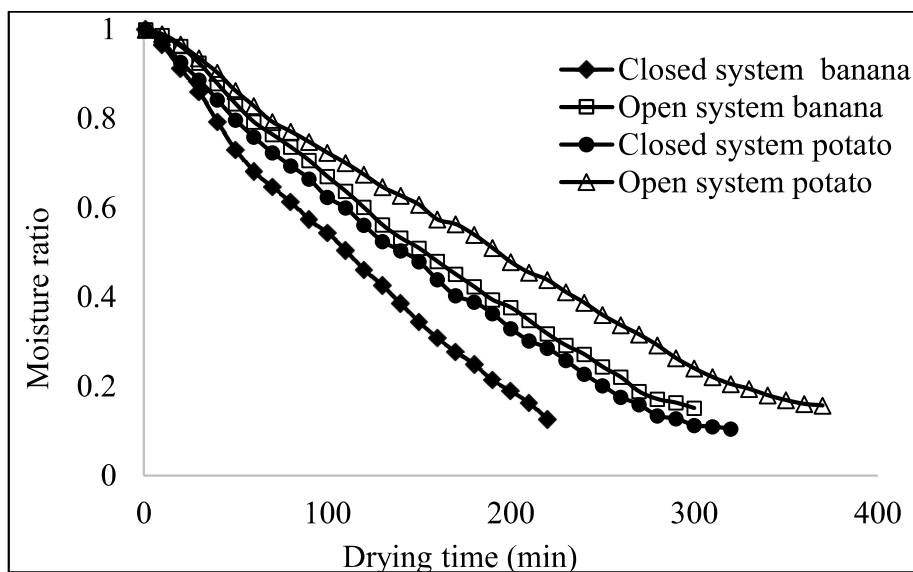


**Fig. 3.4:** Variation in drying temperature with drying time

Fig. 3.5 shows the variation of relative humidity at the dryer inlet with drying time. The relative humidity at the dryer inlet is higher for the closed system due to the recirculation of the air having higher moisture content. The moisture ratio is an important parameter in drying because it helps in the calculation of the moisture diffusivity and the mass transfer coefficient. It is defined as the ratio of the moisture content of the product at any time to the initial moisture content of the product, as shown in Fig. 3.6, the moisture ratio of the product decreases with the drying time due to the decrease in the moisture content of the product. The moisture ratio decreases at a faster rate for the closed system HPD due to the higher air temperature, which removes the moisture from the product at a greater rate. For the studied condition, initially, the moisture ratio decreases at a faster rate, but after some time as the moisture content decreases, it changes at a slower rate. The change in the moisture ratio is faster for the closed system banana chips drying because, for banana chips, the effective diffusivity was higher as compared to the potato chips.

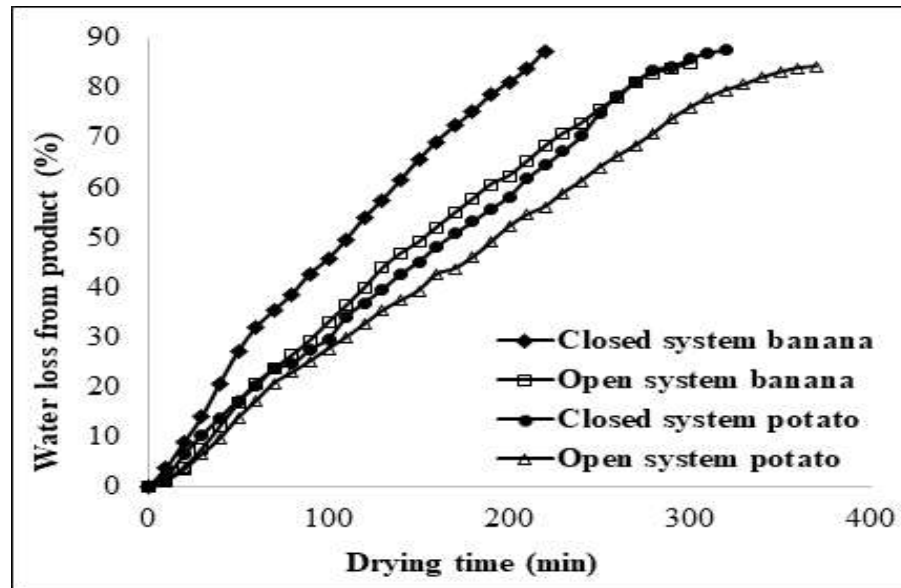


**Fig. 3.5:** Variation of relative humidity at dryer inlet with drying time

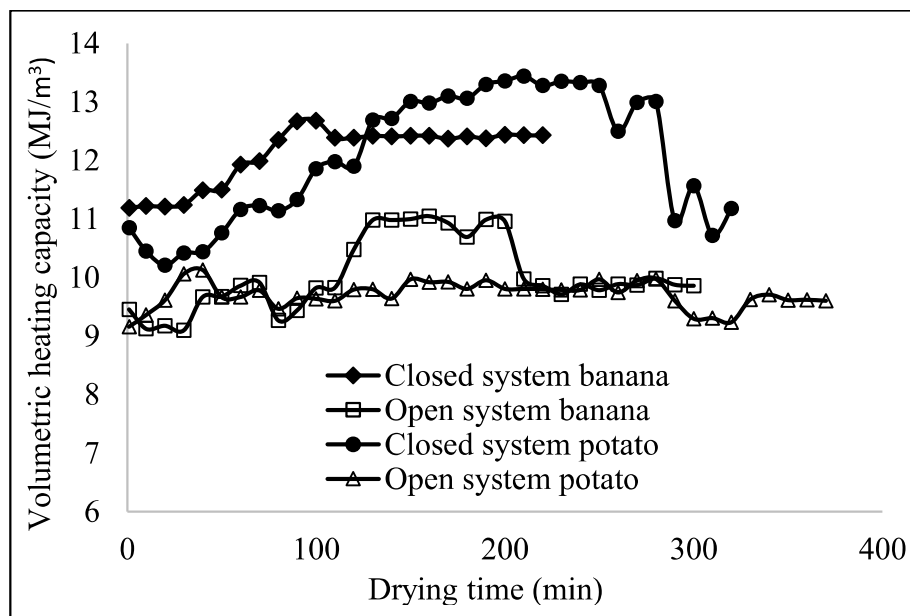


**Fig. 3.6:** Change in moisture ratio with drying time

Fig. 3.7 shows the variation in the percentage of water loss from the product with the drying time. As shown in the figure, the water loss increases with time because as time increases, the moisture from the product removes, and the weight of the product decreases. For studied design and operating conditions, water loss is maximum for the closed system drying of the banana chips due to the higher value of mass transfer coefficient and moisture diffusivity.



**Fig. 3.7:** Variation in water loss from the product with drying time

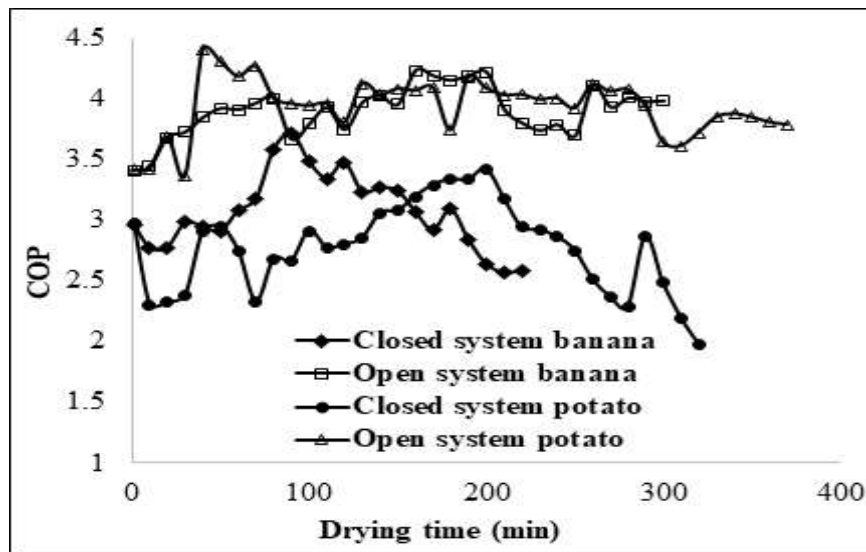


**Fig. 3.8:** Variation in volumetric heating capacity with time

Volumetric heating capacity in the HPD indicates the heat given by refrigerant in the condenser per unit volume of the refrigerant flow. Fig. 3.8 shows the variation of the volumetric heating capacity according to the drying time. The value of volumetric heating capacity is higher in the case of closed system drying for banana and potato chips as compared to the open system due to the higher saturation condenser pressure and lower

saturation evaporator pressure in a closed system. Higher condenser saturation pressure gives a higher density which leads to higher volumetric heating capacity.

Fig. 3.9 indicates the variation of the COP of the HPD system with drying time. The nature of the variation was fluctuating for the coefficient of the performance according to time. The COP of the open, as well as closed system drying, is fluctuating with time due to the change in the humidity and the temperature inlet to the evaporator. In a closed system, the dryer outlet air is directly recirculated to the evaporator, and the humidity and the temperature of the dryer outlet air continuously changes with time. Thus the COP is also varying with time. In the open system also, the humidity and temperature of the air inlet to the evaporator change, which causes the change in COP of the heat pump system.

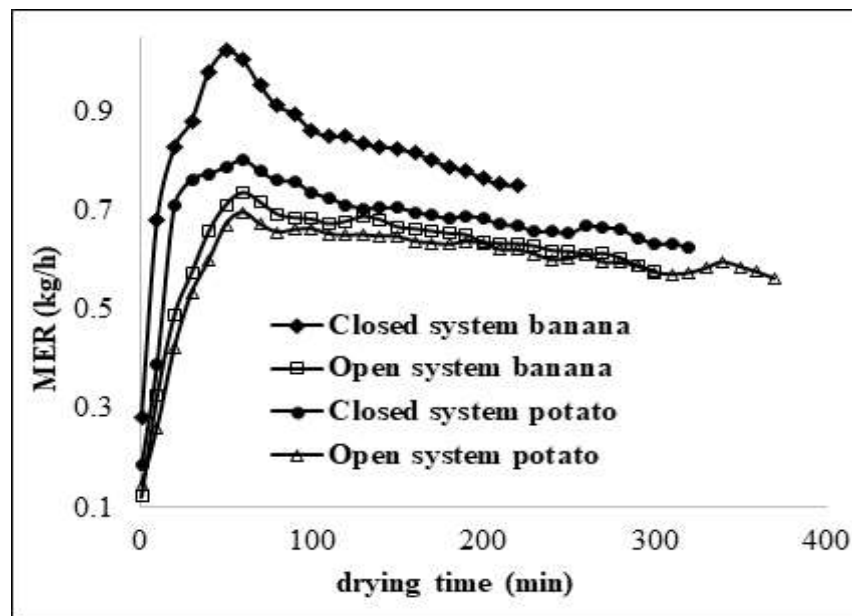


**Fig. 3.9:** Variation in COP with drying time

The average COP is lower for the closed system as compared to the open drying due to the high humidity ratio and temperature of the air at the evaporator inlet because the degree of superheat at the compressor inlet increases with humidity and temperature, which finally increases the condenser temperature and the energy input to the compressor. Thus the COP of the heat pump system decreases with an increase in the

moisture and temperature of the inlet air to the evaporator. So the COP is better in the case of open system drying for both banana and potato chips and lowest for the closed system drying for banana and potato.

The performance of the HPD depends on that how fast the drying air can carry out the moisture from the drying product, and it varies with the moisture content of the product, diffusivity, mass transfer coefficient, air temperature, and the air velocity. The moisture extraction rate of the HPD first increases with time to the maximum value, but after some time, it decreases because of the decrease in the moisture content of the material as shown in Fig. 3.10.

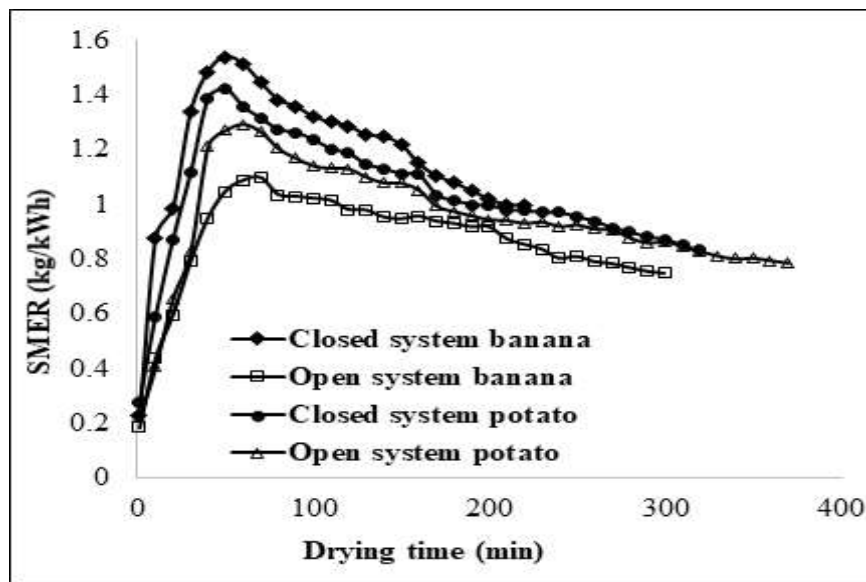


**Fig. 3.10:** Variation in moisture extraction rate with drying time

The MER is higher for the closed system heat pump drying of banana chips as compared to the other system drying in the present study because of higher drying temperature and the high value of effective diffusivity and hence higher moisture removal potential (in humid ambient conditions). However, the system can give the opposite performance behavior in dry conditions. The average value of MER for banana chips in an open and closed system is 0.62, 0.8127kg/h, and for potato chips drying are

0.6, 0.6745kg/h respectively. For an open system, the MER is lowest due to getting the lower drying temperature because of the loss of energy at the dryer outlet.

Fig. 3.11 indicates the change of the specific moisture extraction rate with the drying time for the banana and potato chips. The SMER is the total amount of moisture removed per unit of energy consumed. The SMER is also dependent on the total moisture content of the drying material, drying air velocity, and temperature. The SMER first increases with time due to the establishment of the heat and mass transfer between the drying product air, but after some time, it decreases due to the decrease in the moisture content of the material.

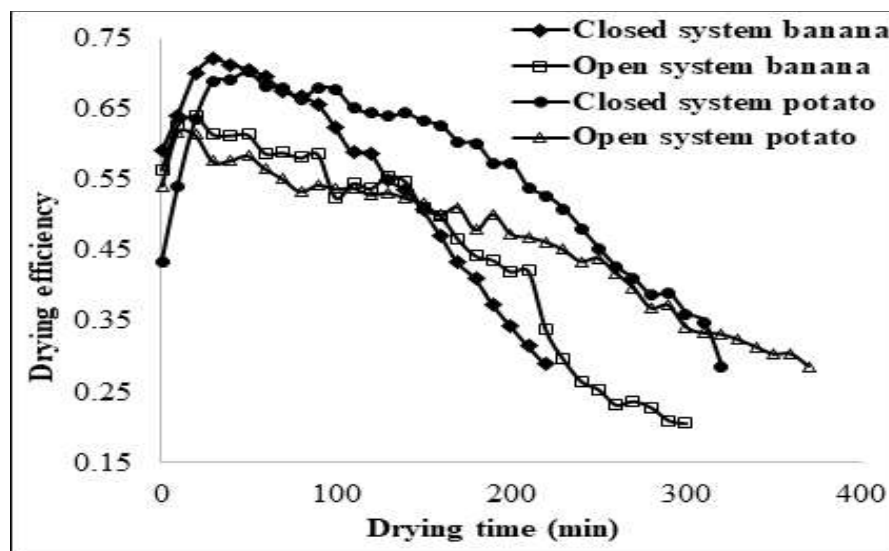


**Fig. 3.11:** Specific moisture extraction rate with drying time

The average SMER is higher for the closed system heat pump drying of the banana chips compare to the open system drying due to the high drying temperature and the higher value of the effective diffusivity with an average value of 1.248kg/kWh and the minimum is for the open system drying of banana chips with an average value of 0.924kg/kWh. The SMER is lowest in the case of an open system for the banana because of more power consumption as compared to the open system for potato. For the open system, the SMER is low due to the loss of energy at the outlet to the dryer, so the drying temperature is low

for the same mass flow rate of the air. The average values of SMER for potato chip drying in open and closed systems are 0.981 and 1.0498kg/kWh, respectively.

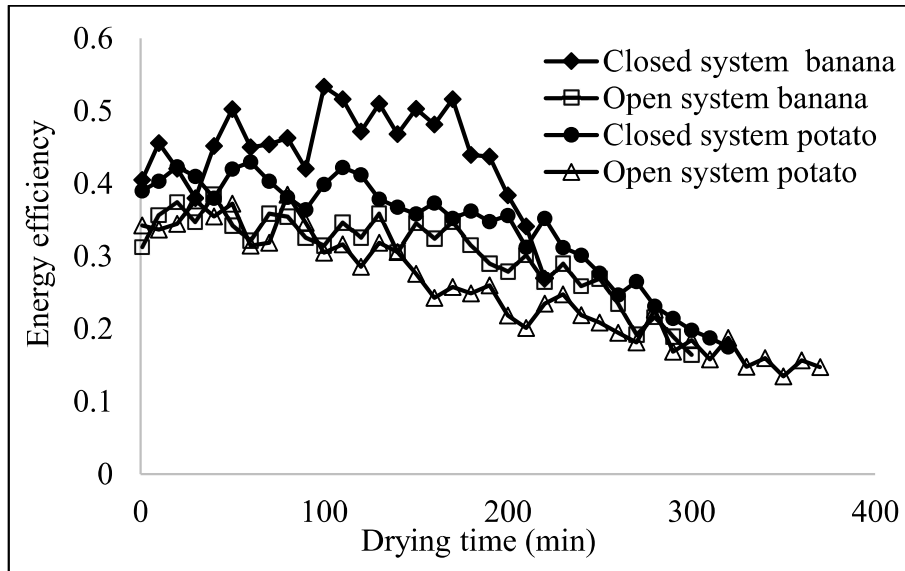
Drying efficiency gives the indication the how efficiently the drying air is removing the moisture from the product in the drying chamber without the loss of heat and bypassing through the drying chamber. The drying efficiency depends on the drying chamber inlet temperature and humidity, outlet temperature, and humidity, and the saturation temperature at a wet-bulb temperature in the drying chamber. Fig. 3.12 shows the variation in drying efficiency with time. The drying efficiency first increases with time due to the decreases in dryer outlet temperature, but after some time it starts to decrease due to the increases in the dryer outlet temperature. The drying efficiency is higher for the closed system drying as compared to the open system because of the higher drying temperature in the closed system. The drying efficiency decreases at a faster rate for the banana chips drying due to a higher heat transfer rate between product and air and a high value of effective diffusivity.



**Fig. 3.12:** Variation of drying efficiency with drying time

Energy efficiency gives information about the utilization of the total energy input in the moisture removal from the products. Fig. 3.13 shows the variation in the energy

efficiency of the drying system for the banana and potato chips in an open and closed system according to time. The energy efficiency of the system depends upon the vaporization of the moisture from the products and the energy input to the HPD system, and it is the ratio of the energy of the vaporization of moisture to the total energy input to the system.



**Fig. 3.13:** Variation in energy efficiency with drying time

The energy efficiency first increases with time and reaches the peak value and starts to decrease after some time because in starting, the moisture removal from the product initially increases, but after some time moisture removal from the product decreases because of the decrease in the moisture content of the material. The energy efficiency is maximum for the banana chips drying in a closed system and minimum for the banana chips drying in an open system. The energy efficiency is maximum for closed system drying because in a closed system the drying temperature is higher than in an open system which gives the more moisture removal rate from the product. The average values of the energy efficiency for the banana in closed and open system drying are 44.67% and 30.35%, respectively, and for potato chips in closed and open systems, the values are 33.9% and 25.5%, respectively. The obtained values of the energy efficiency for the open

and closed system drying of the banana and potato chips were compared with the literature and the values are in the acceptable range (Aktas et al., 2015).

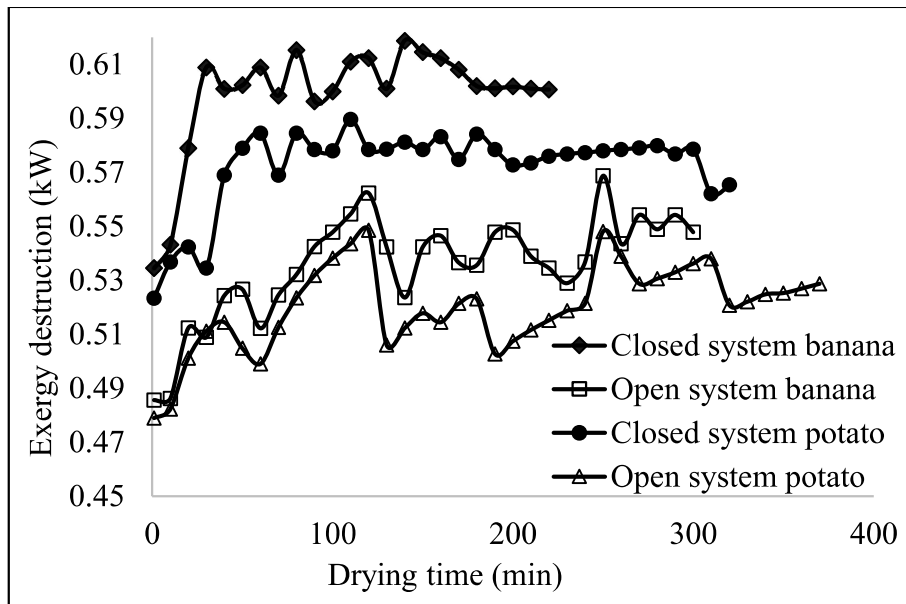
Table 3.4 shows the energetic performances of different components in the HPD. The exergy destruction is higher in the compressor due to the reciprocating part of the system, and due to the higher degree of superheat. In the evaporator, the exergy losses are higher due to the condensation of the water vapor. The maximum exergy loss takes place in the first stage of the drying, and after that, it decreases slowly. The total exergy losses in a closed system for banana and potato chips drying were 0.5918kW, 0.563kW and for an open system drying are 0.5371kW, 0.5189kW, respectively, and the values are compared with the previous work in the literature and for heat pump dryer are in the acceptable range (Aktas et al., 2015).

**Table: 3.4. Exergetic performances of components for banana and potato chips drying**

Component	Closed system				Open system			
	Banana chips		Potato chips		Banana chips		Potato chips	
	$E_{xdest}$	$\eta_{ex}$	$E_{xdest}$	$\eta_{ex}$	$E_{xdest}$	$\eta_{ex}$	$E_{xdest}$	$\eta_{ex}$
Compressor	0.233	0.699	0.238	0.661	0.1802	0.771	0.1674	0.761
Condenser	0.0993	0.82	0.0941	0.807	0.153	0.715	0.141	0.736
Capillary	0.0498	0.865	0.0456	0.857	0.0456	0.901	0.0377	0.906
Evaporator	0.1645	0.526	0.142	0.511	0.142	0.598	0.157	0.571
Dryer	0.0452	0.335	0.0433	0.306	0.0163	0.2601	0.0158	0.231

Fig. 3.14 shows the destruction of the total exergy in the HPD drying system with drying time. The exergy destruction is maximum for the closed system as compared to the open system drying because at higher temperature destruction is also higher (exergy

destruction in the condenser is very high due to higher temperature difference between refrigerant and air in the condenser, as discussed earlier). The exergy destruction is minimum in the open system drying due to the lower drying temperature and lower value of superheat.



**Fig. 3.14:** Variation in the total exergy destruction with drying time

### 3.4 Highlights

A comparative study of open and closed systems heat pump dryers has been carried out experimentally for the drying of the 2 mm thin banana and potato chips at a constant volume flow rate of the air. The drying kinetics of the banana and potato chips is also considered to study the effective moisture diffusivity and the mass transfer coefficient in the drying. The following important points are made for the studied case:

- Total energy consumption is lowest for the closed system heat pump drying of banana and potato chips. The total energy consumptions for banana chips in the open and closed systems were 3.3, and 2.41kWh, and for potato chips are 3.564, and 3.51kWh, respectively.

- COP<sub>hp</sub> of the open system is better. The average COP<sub>hp</sub> of open and closed systems for banana chips drying was 3.89, and 3.09, and for potato chips are 3.93, and 2.85, respectively.
- The energy efficiency is higher for the banana chips drying in a closed system and lower for the banana chips drying in an open system.
- The mass transfer coefficient and moisture diffusivity are better for the closed system. Average values of effective moisture diffusivity for banana chips vary between  $1.02E^{-10}$  to  $2.37E^{-10}$  m<sup>2</sup>/s and the mass transfer coefficient varies between  $7.78E^{-7}$  to  $9.89E^{-7}$  m/s.
- MER is highest for a closed system. The average values of moisture extraction rate for banana chips in the open and closed systems were 0.62, and 0.8127kg/h, and for potato chips in open and closed systems are 0.6 and 0.6745kg/h, respectively.
- SMER is better for the closed system. The average values of SMER for banana chips in open and closed systems are 0.924, 1.248kg/kWh, and for potato chips in open and closed systems were 0.981, 1.0498kg/kWh, respectively.
- Specific energy consumption is lowest for a closed system. SEC for banana chips in open and closed systems are 1.0822, 0.80128 kWh/kg, and for potato chips in open and closed systems are 1.01936, 0.95256 kWh/kg, respectively.
- Total exergy destruction is highest for the closed system and minimum for the open system heat pump drying for both banana and potato chips drying.
- Based on the performance parameters such as MER, SMER, and drying efficiency, the closed system drying is better than the open system drying in the given humid and hot atmosphere for the fruits and the vegetable drying.

*This page is intentionally left blank*