CHAPTER 7

EXPERIMENTATION ON INTERMITTENT DRYING WITH SOLAR-ASSISTED HEAT PUMP DRYER

This chapter describes the design, development, thermal performance, and economic analysis of the intermittent drying of radish chips with a solar-assisted heat pump dryer. The application of renewable energy sources in the area of heat pump drying is very interesting due to the high drying rate with energy savings and very less environmental effect. In this direction, a solar-assisted heat pump dryer (SAHPD) utilizes renewable sources of energy (free of cost) (Khanlari et al., 2020). Hence it enhances the SMER with reduced energy requirement (electricity). On the other hand, the drying performance should be high at a higher drying temperature but the product temperature may be increased continuously by continuous drying and the drying material (both product surface and quality) can be deteriorated due to high temperature due to continuous heat input and hence the drying should be carried out at optimum temperature. To avoid the deterioration of the food products, intermittent drying may be applied because in intermittent, the energy supply is in different steps and the drying temperature may be maintained at an optimum level. Hence, people are taking great interest in the field of intermittent drying, especially heat-sensitive materials. It also increases the SMER and product quality. When the rate of diffusion from inside to the surface of the product is lower than that from the product surface to the dying air, the energy input to the system is stopped, and the moisture diffusion from the inside of the product to the surface is extracted naturally due to vapor pressure difference (this period is known as tempering period), which decreases the energy consumption (Herritsch et al., 2010).

Hence, SAHPD with intermittent drying may be an energy-efficient method. So in the present study, solar energy is utilized to increase the drying temperature using a solar water heater and air to a water heat exchanger with a heat pump system for intermittent drying. The main components of the drying system are the heat pump system, dryer system, and the evacuated tube type solar water heating system. In this study, the new generation future refrigerant R1234yf is used in the heat pump cycle and the COP of the overall system, energy efficiency, MER, specific SMER, exergy destruction, drying efficiency, payback period, and drying cost per unit material is investigated and compared for the different intermittent ratio for the drying of radish.

7.1. Material and methods

The present study focused on the design and fabrication of a convective solar-assisted-HP dryer for the intermittent drying of the food products using the solar water heater as a renewable source of energy and a future refrigerant R1234yf in the HP cycle, and the experiment was carried out for radish drying to analyze the system and dryer performance. Fig. 7.1 reveals the schematic diagram of the Solar assisted-HPD. The solar-assisted-HPD can be expressed by several sub-systems, evacuated tube solar water heater, hot water circulation system, heat pump (refrigerant) system, and drying system. The basic components of the heat pump system are a new future refrigerant (R1234yf), semi-hermetic compressor, wavy fin cross flows heat exchanger (condenser, evaporator), and expansion device (capillary tube), details are provided in Table 3.1. The fabricated experimental facility is shown in Fig. 7.2 with the HP drying and solar water heating system. To compute the refrigerant temperature in the HP cycle at the location of compressor input, compressor output, condenser output, and evaporator input, four resistant thermometers (PT100) are installed. The low temperature (evaporator) side pressure and the high temperature (condenser) side pressure is estimated by using the pressure gauges as shown in Fig. 7.2. Three energy meters are installed to measure the electric energy requirement by the compressor, pump, and fan.

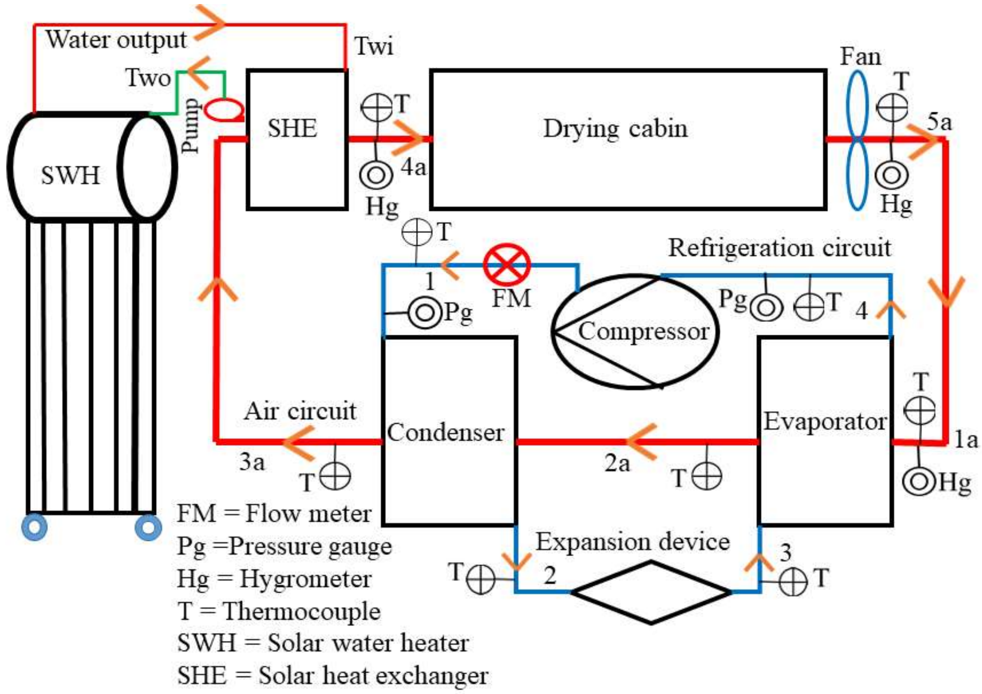

Fig. 7.1: Schematic of the presentation of the solar-assisted-HP dryer for intermittent drying

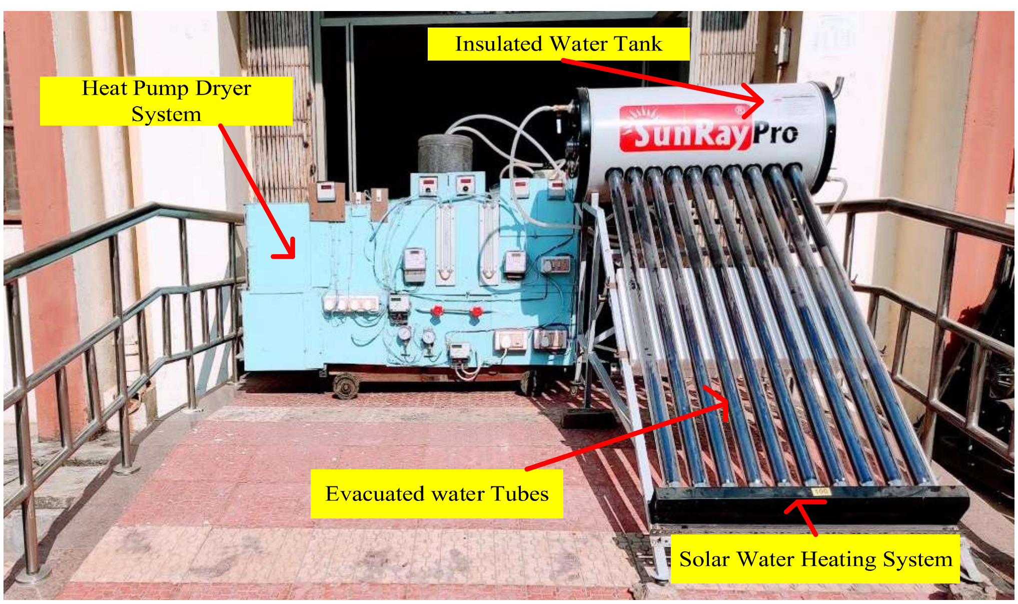

Fig. 7.2: Experimental facility of SAHPD for intermittent drying

The SWH system is the integration of the different sub-systems as evacuated tube type SWH, centrifugal pump, and heat exchange. Two resistant thermometers (Pt100) and a rotameter is installed to measure the hot water inlet and outlet temperature to the SWHE and to measure the flow rate of the water through the SWHE. The details and the specification of the solar water heating system are provided in the previous literature (details are provided in Chapter 5). The most advantage of the SWH system instead of the solar-air-heating system is that the SWH system can be used at night time also because, in this system, the heated water is stored in an insulated tank. In the SWH system, the dehumidified air coming out from the evaporator is heated in the SWHE after the condenser of the HP cycle, which enhances the SMER and energy efficiency as compared to the solar air heating system due to getting high drying air temperature. The convective drying cabin of the inside dimension of 0.35m × 0.4m × 0.7m and the drying chamber consisted of several trays inside it. The drying air flows in the HP drying system with help of a fan (220/230V, speed= 1350rpm, 50 Hz, power =70W, sweep = 300mm). The resistant thermometers and pressure transducer were used in the system to estimate the drop in pressure and temperature of the air in the drying cabin and the whole system.

The solar-assisted HP dryer system was designed and fabricated for the intermittent drying of the radish. The radishes were washed and sliced into 2 mm size. The moisture content (final and initial) of the radish chips was estimated by applying the oven method at 105°C. 4.5kg of radish chips was taken for the experiment in the solar assisted-HP dryer for different intermittency ratios. The radish chips on the trays loaded inside the drying cabin. Three hygrometers (at the inlet to the evaporator, drying cabin output, and input) and the resistant thermometers (Pt100) were used in the HP drying system to measure the evaporator inlet and outlet, condenser outlet, SWHE outlet, and drying cabin outlet temperature which was also used to optimize the drying air temperature by controlling the airflow rate through the system.

The intermittent drying experiment was carried out to evaluate the exergy, economic, and energy performance of the solar-assisted-HPD at different intermittency ratio for the radish chips. The solar water heating system was filled with water and kept in the sun until the temperature of water in the insulated tank reached the value (of 68-69°C). The fan and the pump connected to the SWH were switched on and the drying air velocity (1.0m/s) was fixed to the desired value. After that, the R1234yf HP system made switched on to reach the steady-state condition and required drying temperature at the drying cabin inlet. The airflow rate and the hot water recirculated through the system was kept the same for all intermittency ratio with solar assisted-HPD. Then the initial readings of the resistant thermometers, hygrometers, and the energy meters were recorded, and during the experiment (intermittent), the humidity at the evaporator inlet, drying cabin inlet and outlet, and drying air temperature at outlet and inlet to the SWHE, the evaporator, the condenser and drying cabin was recorded after every 10 minutes until the end experiment. The experiment was performed for the intermittency ratio of $\alpha = 1$, 0.2, 0.33, 0.5, and 0.66 with a solar-assisted-HP dryer, and the experiment was considered ended and the system is switched off when the drying cabin inlet and outlet humidity become same (no increase in humidity at dryer out). The decrease of MC from the product should be equal to the increase of drying air humidity in the drying cabin and also equal to the amount of moisture condensed over the evaporator for the closed system. The energy measuring device is connected to measure the energy required for the fan, pump, and compressor.

7.2. Data extraction

The intermittency ratio depends on the on/off mode of the drying process for which the system will remain in on condition for some time and in off condition for some other time. The intermittency ratio used in this study is based on/off period. Some people have used the intermittency ratio of the system as the ratio of on-time to the off time of the system and investigated the energy savings by this intermittency ratio (Chin and Law, 2010). Some people have used the intermittency as the ratio of on-time to the total time (on + off), and in this study, to get the advantages of intermittent drying, the intermittency ratio used is given by (Ong et al., 2012),

$$\alpha = \frac{t_{on}}{t_{on} + t_{off}} \Rightarrow \alpha = \frac{t_{on}}{t_d} \tag{7.1}$$

Where t_{on} is the period for which the drying system is on mode and t_{off} is the period for which the drying system is kept in off mode and off period is also known as the tempering period.

So, a higher intermittency ratio means a higher active drying period. If the intermittency ratio increases then the energy efficiency will decrease, but the drying time will also decrease and needed a shorter drying time (Zhu et al., 2016). But the energy efficiency will increase as the intermittency ratio will decrease due to an increase in the tempering (off time) period which needed a longer drying time. For intermittent drying of food chips, a solar assisted-HP dryer consists of a drying medium cycle (air cycle), a refrigerant circuit, an SWH, and a solar water heat exchanger cycle. In the HP drying system, the airflow rate, the air temperature, and the air humidity are the most common parameters to figure out the performance and economic analysis of solar assisted-HP dryer for intermittent drying. By applying the energy-exergy analysis to the solar assisted-HP dryer intermittent drying system for radish chips were accomplished to find out the total energy transfer in the condenser, evaporator, and SWHE, energy efficiency, and the behavior of drying air temperature and the total cost of the drying per kg of material.

The heat exchange rate between the refrigerant and drying air in the HP condenser is given by,

$$Q_{cond} = \dot{m}_{air} c_{pam} (T_{3a} - T_{2a}) = \dot{m}_r (h_2 - h_3) \tag{7.2}$$

Where $\dot{m}_{air}$ is the mass flow rate and c_{pam} is the isobaric specific heat of moist air.

The heat gained by drying air from SWH through the SWHE is estimated by,

$$Q_{SWHE} = \dot{m}_{air} c_{pam} (T_{4a} - T_{3a}) = \dot{m}_{hw} c_{pw} (T_{wi} - T_{wo}) \tag{7.3}$$

Where $\dot{m}_w$ is the mass flow rate and c_{pw} is the isobaric specific heat of the water.

The heat pump cycle coefficient of performance (COP) is calculated by,

$$\text{COP} = \frac{Q_{cond}}{W_{comp.}} = \frac{h_2 - h_3}{h_2 - h_1} \tag{7.4}$$

The overall heating COP (OHCOP) is used to evaluate the combined performance of heat pump + solar heating systems, and it is estimated as the ratio of the amount of heat recovered in the HP condenser and SWHE to the total fan, compressor and pump energy input. The OHCOP is given as follows,

$$\text{OHCOP} = \frac{Q_{cond} + Q_{SWHE}}{W_{comp.} + W_{fan} + W_{pump}} \tag{7.5}$$

The moisture extracted from the product is calculated by,

$$m_w = (m_{pi} - m_{pt}) = \dot{m}_{air} (\omega_{5a} - \omega_{4a}) t_{on} \tag{7.6}$$

Where t_d is the on-period drying time step in an hour (10 min is taken for calculation) and m_w is moisture removed from the product during the time step.

The total moisture removal rate from the drying material is given as follows,

$$\text{MER} = \frac{m_w}{t_{on}} \tag{7.7}$$

Total moisture extracted from the product per unit energy input to the whole drying system is called specific moisture extraction rate (SMER) and is given as,

$$\text{SMER} = \frac{m_w}{\text{t}_{on}(W_{comp.} + W_{fan} + W_{pump})} \tag{7.8}$$

The energy efficiency of the drying system is an important parameter that indicates how efficiently the energy is consumed to remove the moisture from the product. Energy efficiency is the ratio of the energy utilized for the removal of moisture from the drying product to the total energy consumed in the system. The energy efficiency of the solar-assisted-HP dryer system is given by

$$\eta_{en} = \frac{h_{fg} m_w}{\text{t}_{on}(W_{comp.} + W_{fan} + W_{pump})} \tag{7.9}$$

Where h_{fg} is the water latent heat of vaporization.

The economic analysis of intermittent drying with a solar-assisted HP dryer depends on the initial cost and operating cost of the drying system. The capital cost of the drying system includes the costs of heat exchangers (condenser, SWHE, evaporator), compressor, capillary tube, fan, refrigerant, SWH, pump, duct, base structure, system fabrication, and labor. The thermal performance and the economic parameters are calculated by using the Eq. as discussed in previous Chapters 3 and 5.

7.3. Results and discussion

The chips (radish) were dried in the SAHPD for different intermittency ratio with a closed-loop system, and the economic, energetic, and exergetic performance of the drying system was investigated for different intermittency ratio of α=0.66, α=0.33, α=0.2 and compared with the continuous (α=1) drying. The experimental results observed for intermittent drying of radish with the SAHPD system are presented in Table 7.1. From the experimental result, it can be observed that the energy required for the system increases with the value of the intermittency ratio because as the intermittency ratio the on-time period of the system increases, and the energy requirement is higher for the continuous drying and lower for the intermittency ratio of α=0.2 respectively. The energy input is highest for continuous drying due to the continuous supply of energy for the drying system. But in intermittent drying, the energy is supplied for the on period and then stopped for the tempering period (in the tempering period, the moisture from inside material to the surface is extracted due to the vapor pressure difference) which increases the energy efficiency and decreases the energy requirement. The total energy consumption for the continuous, α=0.66, α=0.33, and α=0.2 are 3.035kWh, 2.288kWh, 2.018kWh, and 1.89kWh respectively.

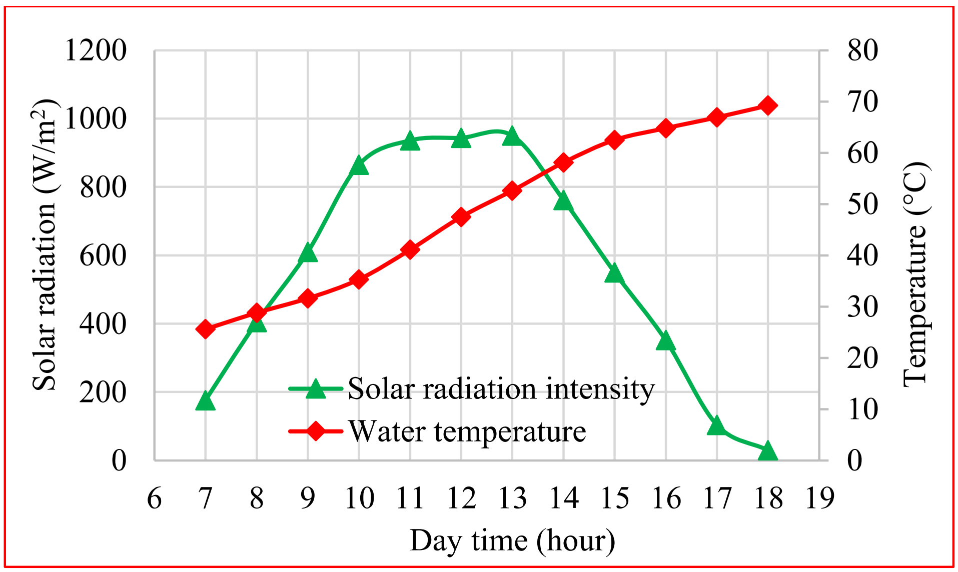

Fig. 7.3: Solar radiation and water temperature variation with day hour

For the solar-assisted HP dryer, the solar radiation intensity coming solar water heater, the atmospheric temperature, and humidity are important parameters at a specific location for the intermittent drying. In this intermittent drying with SAHPD, the solar radiation was utilized to heat the water in the SWHS and finally, this hot water heats the drying air coming out from the HP condenser. The hourly radiation data for March and the water temperature inside the insulated tank are shown in Fig. 7.3. The sun radiation (intensity) increases with day hours reaching the maximum value and then starts to decrease. The temperature of water in the insulated tank increases with the day hour as the water is heated with solar radiation continuously. The average solar intensity and the maximum water temperature were 604.91W/m^2 and 68.7°C respectively.

The thermal performance of the intermittent drying with a solar-assisted HP dryer depends on the intermittency ratio, air temperature and humidity, air velocity, and diffusivity of the drying product. The drying of the radish was carried out to get the final MC of 11.9% from the initial value of 92.4% (wet basis) for the different intermittency ratio (α= 1, α= 0.66, α= 0.33, α= 0.2). From the experimental result, it can be observed that the total drying time is lower for the continuous drying and higher for the intermittency ratio of 0.2, but the actual drying time (on period) is lower for the intermittency ratio of 0.2 and higher for the continuous drying. The total drying time for the intermittency ratio of α= 1, α= 0.66, α= 0.33 and α= 0.2 are 220min, 230min, 390min and 480minutes respectively. But the actual drying time for which the system is in on condition for intermittency ratio of α= 1, α= 0.66, α= 0.33, and α= 0.2 are 220min, 170min, 150min, and 120minutes respectively. The average drying temperature for the intermittent drying with the SAHPD system is 52.32°C. The experimental results obtained from the intermittent drying of radish chips with SAHPD for different intermittency ratio is provided in Table 7.1.

Table: 7.1. Performance comparison of experimental results for intermittent drying

Performance parameter	Intermittency ratio (α)			
	Continuous (α=1)	α=0.66	α=0.33	α=0.2
Average drying temperature (°C)	52.1	52.3	52.3	52.6
Total drying time (min)	220	230	390	480

Total actual drying time (min)	220	170	150	120
Total energy consumption (kWh)	3.035	2.288	2.018	1.89
Avg. COP_{hp}	4.7	4.62	4.48	4.32
Avg. OHCOP	5.82	5.75	5.61	5.53
Avg. SMER (kg/kWh)	1.334	1.77	2.007	2.143
Avg. MER (kg/h)	1.1045	1.43	1.736	2.025
Avg. energy efficiency (%)	31.43	38.3	43.15	49.16
Avg. drying efficiency (%)	26.93	35.63	39.62	44.25

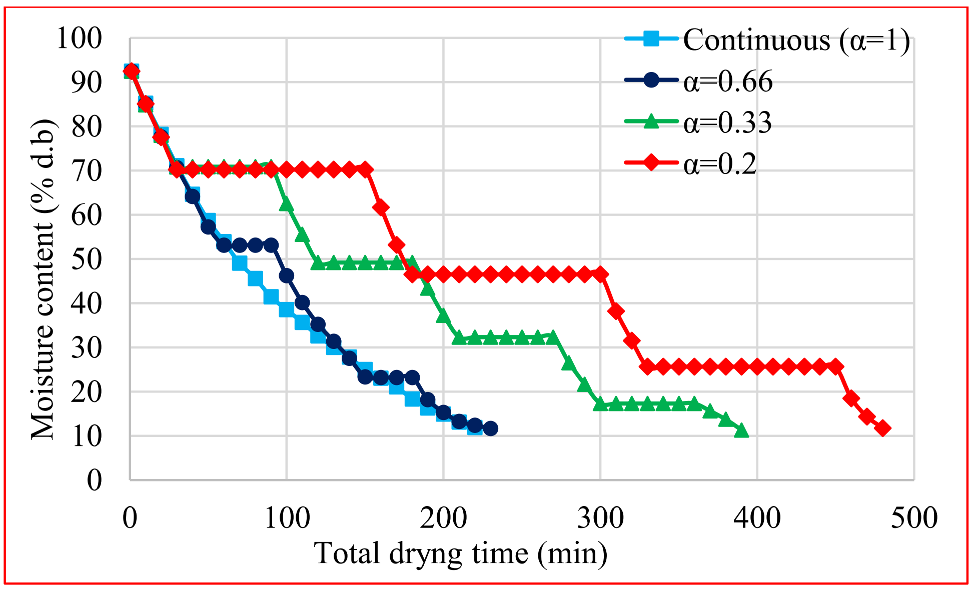

Fig. 7.4: Moisture content variation of product with total drying time

The velocity of air (1.0m/s) and water flow rate of 1.5LPM for all experiments were kept constant with the SAHPD system. Fig. 7.4 depicts the variation of the MC of the material for the different intermittency ratio with the total drying time. The MC decreases at a faster rate for the intermittency ratio of 0.2 in the active drying time because of the higher tempering (off time) period which causes the natural extraction of moisture from the inner product to the surface due to vapor pressure difference and increases the moisture extraction rate as compare to the continuous drying.

The COP of the HP system was a little bit higher for the higher value of the intermittency ratio (α=1) due to the lower values of temperature and humidity input to the evaporator (the value of COP of HP decreases with an increase in evaporator inlet air temperature and humidity) as compared to the higher intermittency ratio. The COP of the SAHPD system for intermittency ratio of α= 1, α= 0.66, α= 0.33 and α= 0.2 are 4.7, 4.62, 4.48 and 4.32 respectively. The OHCOP is the function of heat exchange in the condenser, SWHE, and the energy input to the compressor, pump, and fan in the drying system. The OHCOP of the overall SAHPD system was a little bit higher for the higher value of the intermittency ratio. Fig. 7.5 shows OHCOP variation with total drying for the continuous and the intermittent drying and the for the tempering period, the values of OHCOP are zero as shown in the figure. The average values of OHCOP for the intermittency ratio of α= 1, α= 0.66, α= 0.33 and α= 0.2 are 5.82, 5.75, 5.61 and 5.53 respectively.

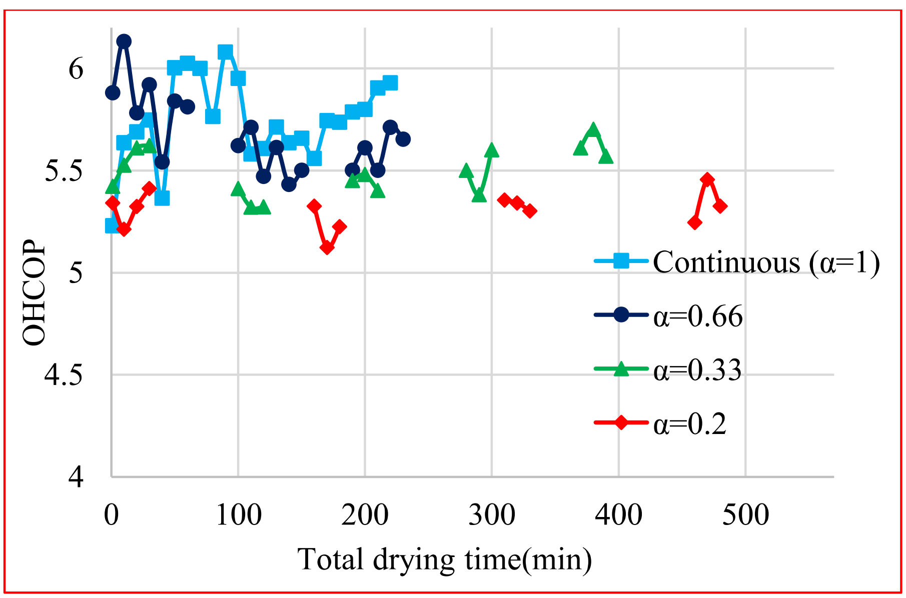

Fig. 7.5: OHCOP variation with total drying time

Fig. 7.6 represents the variation of the MER with the total drying time with a solar-assisted-HP dryer for different intermittency ratio. For the intermittent drying during one period, initially, the MER increases with time due to the higher MC of the product but after some time it decreases due to the decrease in the MC of the product, and for the intermittent drying it repeated the same trend for every cycle of drying again and again. The average MER is higher for the intermittency ratio of 0.2 (due to a higher tempering period in which, the moisture from the product is extracted to the surface due to the natural vapor pressure difference without any external means) and lower for the continuous drying (drying air extract the moisture first inside to the surface of the product and then carried out the moisture from the surface which decrease the rate of moisture extraction). The average values of MER with SAHPD drying for the intermittency ratio of continuous (α =1), α = 0.66, α = 0.33 and α = 0.2 are 1.1045kg/h, 1.43kg/h, 1.736kg/h and 2.025kg/h respectively.

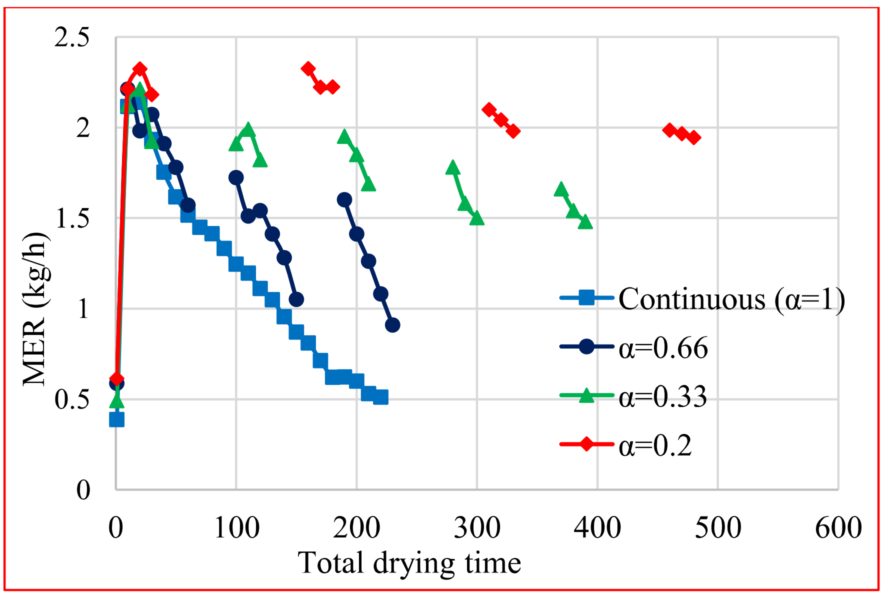

Fig. 7.6: MER variation with total drying time

Fig. 7.7 shows the SMER variation with the total drying time for the intermittent and continuous drying. For the continuous and the intermittent drying during on period, the SMER increases with time due to having a higher MC of product, but after some time it decreases due to the decrease in the MC of the product, and for the intermittent drying it is repeated the same trend for every cycle of drying. The average SMER is higher for the intermittency ratio of 0.2 and lower for the continuous drying. The average value of

SMER increases with the decrease in intermittency ratio because a lower intermittency ratio means a higher the tempering period and higher the moisture extraction from products with the same energy input. The average values of SMER with SAHPD drying for the intermittency ratio of continuous (α = 1), α = 0.66, α = 0.33 and α = 0.2 are 1.334kg/kWh, 1.77kg/kWh, 2.007kg/kWh and 2.143kg/kWh respectively.

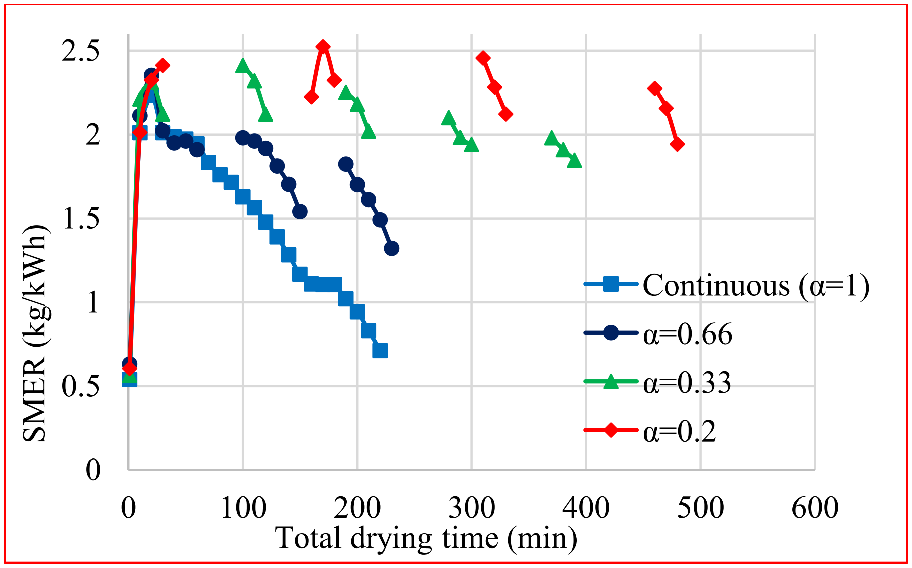

Fig. 7.7: SMER variation with total drying time

Drying efficiency tells the information about how efficiently the air extracts the moisture from material in the drying cabin. Fig. 7.8 represents the variation of the drying efficiency with the total drying time (on period + off period) with the SAHPD system for intermittent and continuous drying. For continuous drying, the drying efficiency decreases with time due to a decrease in the MC of the product and finally moisture extraction from the product because drying efficiency depends on the inlet and outlet temperature and the saturation temperature of the air in the drying cabin. For the intermittent drying, the drying efficiency is higher as compared to the continuous drying due to the higher moisture removal in the drying cabin (because of the tempering period), and the value of drying efficiency increases with a decrease in the intermittency ratio.

The average values of drying efficiency for the intermittency ratio of continuous (α=1), α = 0.66, α = 0.33 and α = 0.2 are 26.93 %, 35.63 %, 39.62 % and 44.25 % respectively.

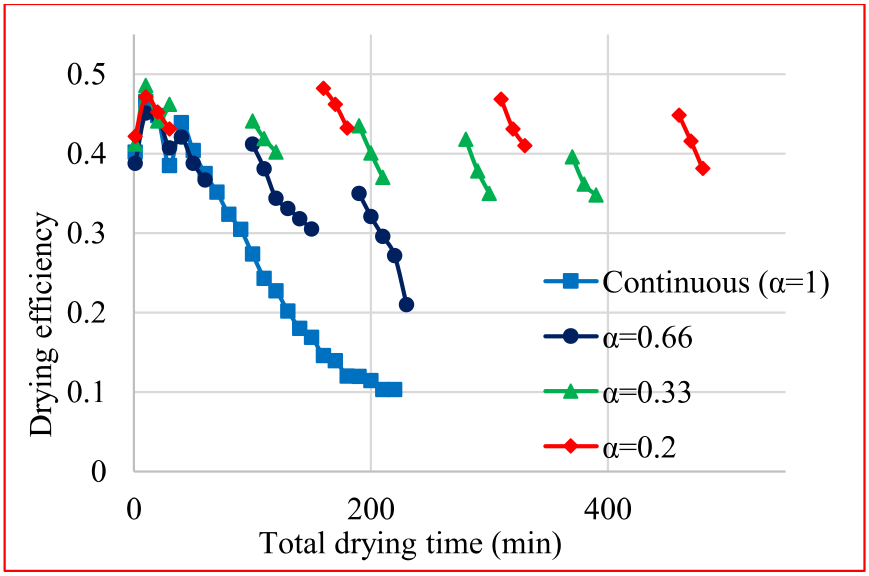

Fig. 7.8: Drying efficiency variation with total drying time

The energy efficiency of the solar-assisted HP dryer indicates the efficient utilization of the input energy for the evaporation of moisture from the product. Fig. 7.9 shows the energy efficiency variation of intermittent drying for radish with the SAHPD system with total drying time. The energy efficiency is highest for the lower value of the intermittency ratio, and lower for the higher value of the intermittency ratio (continuous). The value of the intermittency ratio increases with the increase in the tempering period (off time) which finally increases the average value of energy efficiency (due to the natural extraction of moisture from the inner surface of product to outer surface in tempering period without external energy input). The average energy efficiency value for the intermittency ratio of continuous (α =1), α = 0.66, α = 0.33 and α = 0.2 are 31.43%, 38.3%, 43.15% and 49.16% respectively.

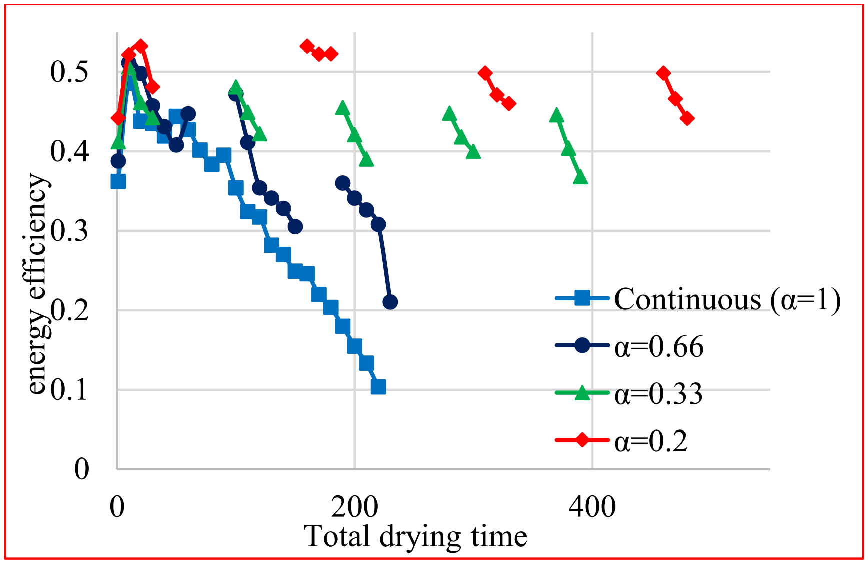

Fig. 7.9: Energy efficiency fluctuations with total drying time

Exergetic investigation is the most relevant methodology to evaluate the thermal performance and efficient energy utilized in any solar-assisted HP dryer. The exergy destruction and efficiency of components are provided in Table 7.2. The destruction of exergy was higher for the compressor and the solar water heat exchanger. The exergy destruction through the evaporator was due to the cooling and the condensation of air and moisture over the cold finned surface. The exergy destruction was lower for the expansion device for both continuous and intermittent drying due to the negligible heat exchange in the expansion device. The exergy destruction was a little bit higher for the lower value of intermittency ratio due to the high MC of air in the system. The total values of exergy destruction with SAHPD system for the intermittency ratio of continuous ($\alpha = 1$), $\alpha = 0.66$, $\alpha = 0.33$ and $\alpha = 0.2$ are 0.953, 0.972, 0.986 and 1.023kW respectively.

Table: 7.2. Component wise exergy destruction (kW) and efficiency for intermittent drying

Component	Intermittency ratio (α)							
	Continuous (α = 1)		A =0.66		A =0.33		A =0.2	
	$E_{x,dest}$	η_{ex}	$E_{x,dest}$	η_{ex}	$E_{x,dest}$	η_{ex}	$E_{x,dest}$	η_{ex}
Condenser	0.221	0.882	0.212	0.854	0.214	0.853	0.226	0.836
Compressor	0.248	0.683	0.255	0.672	0.262	0.668	0.278	0.654
Expansion device	0.106	0.851	0.108	0.826	0.109	0.819	0.112	0.792
Evaporator	0.143	0.582	0.151	0.576	0.157	0.568	0.167	0.552
Dryer cabin	0.0182	0.243	0.0181	0.233	0.0186	0.227	0.0195	0.221
Solar water heat exchanger (SWHE)	0.221	0.697	0.232	0.676	0.227	0.658	0.234	0.648

The economic investigation of the SAHPD for different intermittency ratio was considered for the total profit (annual) by selling the dried product, initial capital investment, total annual running cost, and payback period for continuous and intermittent drying. The annual maintenance, initial investment cost, effective running cost, total selling cost, net profit, the cost of the dryer, and the payback period are listed in Table 7.3. The annual (300 days) and daily running costs of the solar-assisted-HP dryer were calculated for the radish chips with the SAHPD system for different intermittency ratio (α = 1, α = 0.66, α = 0.33, and α = 0.2). The running cost for all intermittency ratio includes the energy requirement cost, product cost, and labor cost. The energy requirement cost is the most important cost among the running costs for the SAHPD system for intermittent drying. The payback period for different intermittency ratio is predicted based on the running cost (annual) and the annual selling cost of dried product. The total initial cost of the solar-assisted HP dryer system is calculated as $892.94. The annual (300 days) total running cost for the intermittency ratio of the continuous (α = 1), α = 0.66, α = 0.33 and α = 0.2 are calculated as $2333.86, $2243.86, $2210.86 and $2192.86 respectively. The annual (300 days) total selling cost of the dried product for all the intermittency ratio is $2754. The annual total profit gain for radish drying with the SAHPD system for the intermittency ratio of the continuous (α =1), α = 0.66, α = 0.33, and α = 0.2 are calculated as $420.14, $510.14, $543.14 and $561.14 respectively. The payback period of the solar-assisted-HP dryer for the intermittency ratio of the continuous (α=1), α= 0.66, α= 0.33, and α= 0.2 are estimated as 2.17 years, 1.75 years, 1.644 years, and 1.591 years respectively. The per kg drying cost of the radish chips with SAHPD is lower for the intermittency ratio of 0.2 and higher for the continuous drying and the value of per kg drying cost for the intermittency ratio of α =1, α = 0.66, α = 0.33, and α = 0.2 are calculated as 0.576$/kg, 0.554$/kg, 0.545$/kg, and 0.541$/kg respectively.

Table: 7.3. Economic analysis for intermittent solar-assisted-HP dryer

Parameter	Cost of the parameter ($) / intermittency ratio			
	Continuous (α =1)	α =0.66	α =0.33	α =0.2
Compressor	136.03	136.03	136.03	136.03
Condensers	89.75	89.75	89.75	89.75
Evaporator	72.92	72.92	72.92	72.92

Expansion device	3.51	3.51	3.51	3.51
Drying cabin	46.61	46.61	46.61	46.61
Refrigerant (R134a)	24.68	24.68	24.68	24.68
Fan	16.83	16.83	16.83	16.83
Water pump	25.24	25.24	25.24	25.24
Solar water heater	266.45	266.45	266.45	266.45
Solar heat exchanger	44.88	44.88	44.88	44.88
The fabrication cost of the system	166.04	166.04	166.04	166.04
The total initial investment in the system	892.94	892.94	892.94	892.94
Total energy consumption (kWh/day)	9.105	6.864	6.054	5.67
Cost of the raw product (radish, 13.5 kg/day)	2.45	2.45	2.45	2.45
Raw material cost (annual, 300 days)	735	735	735	735
Labour cost ($/day)	4.03	4.03	4.03	4.03
Labour cost (annual, 300 days)	1209	1209	1209	1209
Maintenance cost (2 % of initial cost), annual	17.86	17.86	17.86	17.86
Running cost of the system($/day)	1.24	0.94	0.83	0.77
Running cost of the system(annual, 300 days)	372	282	249	231
Total running cost of system (annual, 300 days)	2333.86	2243.86	2210.86	2192.86
Total selling cost of dried material ($/day)	9.18	9.18	9.18	9.18

Total selling cost of dried material ($/year)	2754	2754	2754	2754
Total profit ($/year)	420.14	510.14	543.14	561.14
Payback period (year)	2.125	1.75	1.644	1.591
Total drying cost per kg drying material ($/kg)	0.576	0.554	0.545	0.541

7.4. Highlights

The SAHPD system has been designed and fabricated in the laboratory and the thermal performance of the system was experimentally investigated for the different intermittency ratio (α =1, α = 0.66, α = 0.33, and α = 0.2). A comparative study of different operating modes of the system (with different intermittency ratio) has been carried out for drying radish at a constant flow rate of air (v = 1.0 m/s). Effects of total drying time (on period + off period) on energy, exergy, and economic parameters for intermittency ratio of α =1, α = 0.66, α = 0.33, and α = 0.2 have been investigated. The following conclusions can be made from the discussion section:

- The total drying time for the intermittency ratio of α=1, α=0.66, α=0.33, and α=0.2 is 220 min, 230 min, 390 min, and 480 minutes respectively. But the actual drying time for which the system was in on condition is 220min, 170min, 150min, and 120minutes respectively for the same intermittency ratio.
- The total energy consumption for the continuous, α =0.66, α=0.33, and α=0.2 are 3.035kWh, 2.288kWh, 2.018kWh, and 1.89kWh respectively.
- The COP of the SAHPD system for intermittency ratio of α =1, α = 0.66, α = 0.33, and α =0.2 are 4.7, 4.62, 4.48, and 4.32 respectively.

- The average value of OHCOP is higher for the intermittency ratio of 0.2 and the average values of OHCOP for the intermittency ratio of α =1, α =0.66, α =0.33, and α =0.2 are 5.82, 5.75, 5.61 and 5.53 respectively.
- The average values of MER with SAHPD drying for the intermittency ratio of continuous (α=1), α= 0.66, α= 0.33 and α= 0.2 are 1.1045kg/h, 1.43kg/h, 1.736kg/h and 2.025kg/h respectively.
- The SMER is higher for the intermittency ratio of 0.2 and lower for the continuous drying. The average values of SMER with SAHPD drying for the intermittency ratio of continuous (α =1), α = 0.66, α = 0.33 and α = 0.2 are 1.334kg/kWh, 1.77kg/kWh, 2.007kg/kWh and 2.143kg/kWh respectively.
- The total values of exergy destruction with SAHPD system for the intermittency ratio of continuous (α =1), α = 0.66, α = 0.33 and α = 0.2 are 0.953kW, 0.972kW, 0.986kW and 1.023kW respectively.
- The per kg drying cost of the radish chips with SAHPD is lower for the intermittency ratio of 0.2 and higher for the continuous drying and the value of per kg drying cost for the intermittency ratio of α=1, α = 0.66, α = 0.33, and α = 0.2 are calculated as 0.576$/kg, 0.554$/kg, 0.545$/kg, and 0.541$/kg respectively.
- The annual total profit gain for radish drying with the SAHPD system for the intermittency ratio of the continuous (α =1), α = 0.66, α = 0.33, and α= 0.2 are calculated as $420.14, $510.14, $543.14 and $561.14 respectively.
- The payback period of the solar-assisted-HP dryer for the intermittency ratio of the continuous (α =1), α = 0.66, α = 0.33, and α = 0.2 are estimated as 2.17 years, 1.75 years, 1.644 years, and 1.591 years respectively.