CHAPTER 5

EXPERIMENTATION ON SOLAR-INFRARED ASSISTED HEAT PUMP DRYER

This chapter contains the details about the design, fabrication, and experimental performance analysis of the solar-infrared assisted heat pump dryer for the drying of the banana chips in a closed system model. A study on solar-infrared assisted heat pump dryers is carried out because it utilizes the renewable source of energy with an infrared heater to get a faster drying rate as compared to the simple HPD system. An evacuated tube-type solar water heater is used as the solar energy source for the heat pump dryer. In this, the air before entering the drying chamber is heated by hot water coming from a solar water heater. The basic heat pump cycle is used in this system as discussed in Chapter 3. A rectangular convective drying chamber with several trays of the improved design was used in the system. The analysis of solar-infrared assisted HPD was done for both open and closed cycle modes. The coefficient of performance (COP), moisture content, SMER, specific energy consumption, energy efficiency, energy utilization, irreversibility, and second law efficiency were compared for simple HPD, infrared-assisted HPD, solar-assisted HPD, and solar-infrared-assisted HPD.

5.1. Experimental setup and procedure

In this study, the design and development of a batch-type convective compact indirect expansion solar-infrared-assisted heat pump dryer (SIAHPD) were done, and the experiment was performed for the drying of food chips in a closed air cycle mode. Fig. 5.1 represents the schematic diagram of the SIAHPD. The SIAHPD system mainly comprises several subsystems such as a solar heater system, refrigeration cycle (heat pump system), infrared heater system, drying medium cycle (air cycle), and dryer system. The heat pump system consists of a semi-hermetic R134a compressor, wavy fin condenser, evaporator, and capillary tube expansion device. Four thermocouples (PT100) were used to indicate the refrigerant temperature at the evaporator inlet, compressor inlet, compressor outlet, and condenser outlet. The pressure gauges were used in the heat pump cycle to measure the condenser saturation pressure and the evaporator saturation pressure. Energy meters, as shown in Fig. 5.2, were used to measure the electric energy consumption of the fan, water pump, and compressor. Coriolis mass flowmeter was installed in the experimental setup at the outlet of the compressor to measure the refrigerant mass flow rate in the HP cycle. The HP system was designed so that the refrigerant inlet to the compressor would be in the superheated state and it would be in a sub-cooled state at the condenser outlet. The details of the specification of the different components of the heat pump system and the drying cabin are provided in Table 3.1.

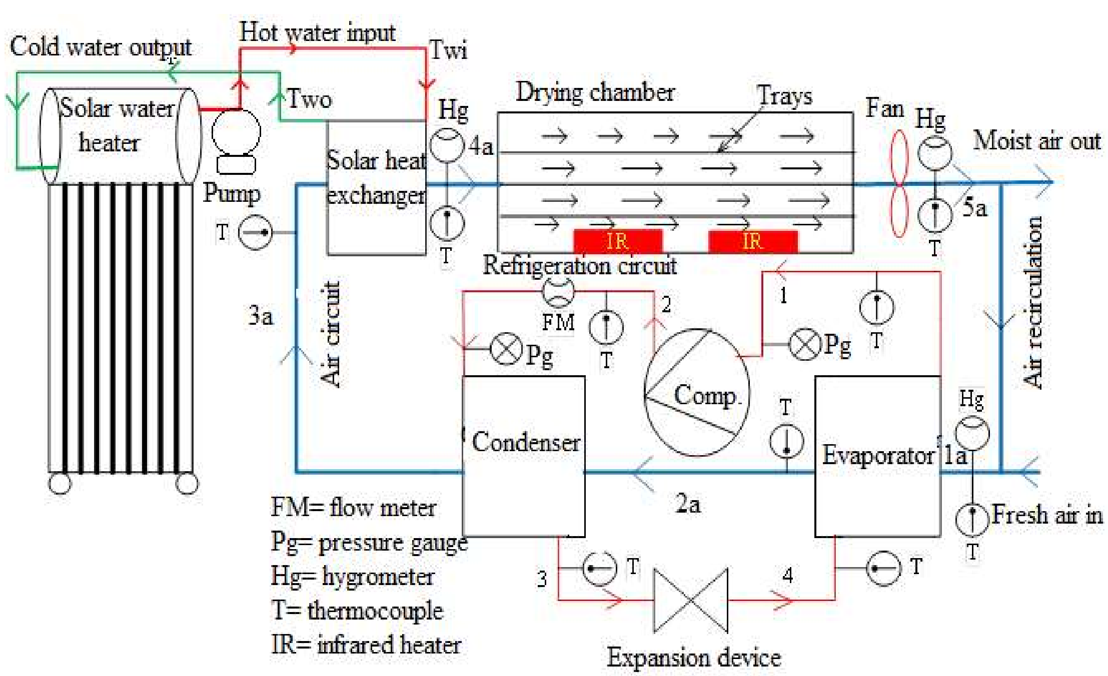

Fig. 5.1: Graphical representation of the heat pump drying system

Fig. 5.2: Photograph of the developed experimental setup of SIAHPD and drying chamber interior

The solar heating system consists of a solar water heater, water pump, and a wavy fin cross-flow heat exchanger. The solar water heater contains an insulated water tank with a capacity of 200 liters and 10 vacuum glass tubes of 54 mm diameter and transmittance of 82%. The total area of solar water heating tubes was $2m^2$. The water from the solar tank was circulated in the heat exchanger (Wavy fin, Cross-sectional dimension = 30.48 cm×33.02 cm, length of tube = 15.85m, diameter = 9.7mm) with the help of a water pump (rated power = 1/12hp, 220V, 50Hz, RPM = 6500). The solar heat exchanger was located just before the inlet of the drying chamber because the drying air coming from the condenser at a lower temperature is heated in the solar heat exchanger. The main advantage of using a solar water heater over the solar air heater or direct expansion solar heater is that in this, the air coming from the evaporator (dehumidified) was heated in a solar heat exchanger, which gives the more SMER rate as compared to the direct expansion solar heater or solar air heater, and it can store the hot water in the insulated water tank and can be used in the day time as well as night time also.

Two ceramic infrared heaters (rated power = 250W, dimension = 122mm×122mm, and rated voltage = 230V at 50Hz) were fitted at centers of two-half inside the drying cabin (Fig. 5.2) to remove the moisture from inside the product to the product surface and direct vaporization of moisture by infrared radiation. The infrared heater was connected with a load control unit (variac dimmer stat) to regulate the power input to the infrared radiation to get the optimum moisture extraction rate in the infrared radiation range of the 3-4 μm (wavelength) and maintain the material temperature below the 80°C. The infrared radiation source contains the maximum energy in the radiation bandwidth; that's why it was used with solar radiation and HPD to get faster moisture removal with maximum energy utilization. The main advantage of using the infrared radiation source heater is that it deeply penetrates the products and removes the moisture from the inside product at a faster rate (Aktas et al., 2017).

The solar-infrared-assisted heat pump drying system was operated for the drying of the banana chips in four different operational modes: simple-HPD, IAHPD, SAHPD, and SIAHPD. In the SAHPD, only solar energy was used to remove the moisture from the product by heating the drying air, but in the SIAHPD, the solar energy was used to heat the drying air and infrared radiation was used in the drying chamber to in-depth heat the product directly for higher moisture removal from the product. The fresh green color banana bought from the market was washed and sliced into 2 mm size chips. The initial and the final MC of the banana chips were obtained by using the oven method at 102±3°C. A sample of 4.5kg of banana chips was dried separately in the various drying modes. The banana chips were spread out on the tray in the drying chamber, and for the homogeneous drying, the banana chips were mixed from time to time. The velocity of the air and the temperature were adjusted to the desired values for the banana chips drying. After that, the HP system was switched on and waited until the steady-state condition was achieved to get the desired drying temperature. The air volume flow rate was kept the same for the drying of banana chips with different modes. Then the banana chips were weighted in digital balance and spread over the trays. Then, the trays were loaded inside the drying cabin and the fan was switched on to get the desired air mass flow rate, and infrared heater power was switched on to extract the moisture from the material by direct infrared radiation. The relative humidity and temperature at different positions were recorded periodically after every 15 minutes until the experiment ended. The weight loss from the drying material should be equal to the change in the humidity ratio of the drying air from dryer inlet to outlet and also equal to the moisture condensing in the evaporator. The energy meters were used to obtain the energy required for the pump, compressor, fan, and infrared heater. The average drying air temperature at the dryer inlet was between 62-67°C. Moisture reduction, MER, SMER, total energy input, COP, exergy loss, exergy efficiency, SEC, and drying efficiency were investigated.

5.2. Data analysis

The performance parameters of the solar-infrared-assisted heat pump drying system have been evaluated based on various measured parameters such as temperature, pressure, the flow rate of air as well as refrigerant, power input, etc.

Energy efficiency is the ratio of the energy utilized to remove the water from the drying product to the total energy consumed in the system as given by (Aktas et al., 2017),

$$\eta_{en} = \frac{h_{fg} m_w}{\mathrm{t}_d (W_{comp} + W_{fan} + W_{IR} + W_{pump})} \tag{5.1}$$

SMER is the ratio of the total amount of moisture removed from the material to the energy required in the whole drying process and is given as (Sevik et al.,2019),

$$\mathrm{SMER} = \frac{m_w}{\mathrm{t}_d (W_{comp} + W_{fan} + W_{IR} + W_{pump})} \tag{5.2}$$

SEC of the heat pump drying system is given by the ratio of the amount of energy required to remove the unit mass of the moisture from the product and is given by (Sevik et al., 2019),

$$\mathrm{SEC} = \frac{\mathrm{t}_d (W_{comp} + W_{fan} + W_{IR} + W_{pump})}{\mathrm{m}_w} \tag{5.3}$$

The exergy destruction (or irreversibility) can be estimated by applying the general exergy balance equation as discussed in Chapter 3.

The exergy destruction and the efficiency of the solar water heat exchanger is calculated by,

$$Ex_{\mathrm{dest,SHE}} = \dot{m}_{hw}\left(e_{xw,in} - e_{xw,out}\right) + \dot{m}_a\left(e_{x3a} - e_{x4a}\right) + W_{pump} \tag{5.4}$$

$$\eta_{\mathrm{ex,SHE}} = \frac{\dot{m}_a\left(e_{x3a} - e_{x4a}\right)}{\dot{m}_{hw}\left(e_{xw,in} - e_{xw,out}\right) + W_{pump}} \tag{5.5}$$

The exergy destruction in the drying chamber is mainly due to the heat and the mass exchange between the product and air, and is estimated by the following (Atalay, 2019),

$$Ex_{\mathrm{dest},dryer} = \dot{m}_a\left(e_{x4a} - e_{x5a}\right) + W_{fan} \tag{5.6}$$

$$\eta_{\mathrm{ex},dryer} = \frac{\dot{m}_a\left(e_{x4a} - e_{x5a}\right)}{W_{fan}} \tag{5.7}$$

The exergy efficiency of the drying chamber for the infrared-assisted drying system can be estimated by (Atalay, 2019),

$$\eta_{\mathrm{ex},dryer} = \frac{\dot{m}_a\left(e_{x4a} - e_{x5a}\right)}{W_{fan} + \dot{E}_{abs}} \tag{5.8}$$

Based on the above definition, the absorbed exergy by the material can be given as the product of the energy absorbed by an energy quality factor which is given (Aghbashlo, 2016),

$$\dot{E}_{abs} = \beta \times \dot{Q}_{abs} \tag{5.9}$$

According to the various similar type of studies for obtaining the value of energy absorbed by the material, the quality factor is the ratio of the total exergy to the total energy value. This quality factor is a correlation to estimate the most feasible results. The quality factor is given as follows (Aghbashlo, 2016),

$$\beta = 1 + \frac{1}{3}\left(\frac{T_o}{T_{IR}}\right)^4 (\varepsilon_{IR})^{-1} - \frac{4}{3}(\varepsilon_{IR})^{-0.25}\left(\frac{T_o}{T_{IR}}\right) \tag{5.10}$$

Where T_{IR} is the infrared heater surface temperature,

The absorbed energy by the drying material can be obtained by applying the energy balance between the product and the infrared radiation because some part of infrared radiation is absorbed and the remaining radiations are transmitted, reflected by the surrounding, or emitted by the product. The absorbed energy is given as (Aghbashlo, 2016),

$$\dot{Q}_{abs} = IR_{radation} - IR_{reflected} - IR_{transmitted} - IR_{emitted} \tag{5.11}$$

The energy absorbed by drying material is a portion of energy that is directly exposed to the infrared heater. The radiation network method was used to estimate the actual amount of absorbed energy by the product (Aghbashlo, 2016). In the radiation network method, the drying chamber is considered as a three-surface closed volume with surfaces as a drying chamber wall, infrared heater, and drying product. By balancing the heat flow between the three surfaces, the absorbed energy can be written as (Aghbashlo, 2016),

$$\dot{Q}_{abs} = \frac{\sigma\left(T_{IR}^4 - T_M^4\right)}{\frac{1-\varepsilon_{IR}}{A_{IR}\varepsilon_{IR}} + \frac{1}{1/\left(1/A_{IR}F_{IR-M}\right) + 1/\left(1/A_{IR}F_{IR-DC}\right) + 1/\left(1/A_M F_{M-DC}\right)} + \frac{1-\varepsilon_M}{A_M\varepsilon_M}} \tag{5.12}$$

For the design and development of SIAHPD, with thermal analysis, the economic analysis must be considered. Economic analysis of SIAHPD depends on initial capital investment cost and running cost. The capital cost of SIAHPD includes the cost of compressor, heat exchangers (condenser, evaporator, and solar water heat exchanger), refrigerant, expansion device, fan, water heating system (evacuated tube type), water pump, air duct, basic structure, system installation cost, and labor cost. The total running cost of the dried product can be given by the following (Yahya et al., 2018),

$$C_{RU} = C_{RM} + C_P + C_L + C_m \tag{5.13}$$

Where, C_{RM}, C_p, C_L, and C_m are raw material cost, energy consumption cost, labor cost, and maintenance cost. Where maintenance cost (C_m) is considered as 2 % of the total capital cost (Yahya et al., 2018),

Hence, the total cost of the drying is given as,

$$C_{Total} = C_{IC} + C_{RU} \tag{5.14}$$

The total profit (C_F) by using a simple HP dryer or a Hybrid-source HP drying system for intermittent drying of banana chips is the difference between the total sale cost of the dried product and the total cost of the solar-assisted-HP dryer system and is given as the following,

$$C_F = C_{Total,\mathrm{sale}} - C_{RU} \tag{5.15}$$

The payback period (P_P) of the solar-assisted-HP dryer for intermittent drying is given as (Yahya et al., 2018),

$$P_P = C_{IC} / C_F \tag{5.16}$$

5.3 Results and discussion

The banana chips (agricultural product) were dried in the solar-infrared assisted HPD with recirculation of the drying air and the performances were estimated for HPD, SAHPD, IAHPD, and SIAHPD modes. For solar-assisted modes, performance is dependent on solar radiation and ambient condition at the location of the experiment.

The hourly solar radiation intensity first increases with becomes highest and then decreases. The average solar intensity is 539.77W/m^2. Hence, to get similar ambient conditions and solar radiation, all the experiments were conducted at similar times on different days. In the literature, people have done the experiment for the air velocity range of 0.5-2.5m/s [Aktas et al.,2017, Sevik et al.,2019] and hence the same velocity range has been considered and 1m/s has been taken as design velocity of drying air. However, due to the limitations of the fan speed installed in the experimental setup and other unaccounted resistances, the actual air velocity was measured as 0.8 m/s. The drying air velocity was 0. 8m/s for all types of drying experiments. Fig. 5.3 shows the photographs of the banana chips before drying and after drying in the solar-infrared-assisted heat pump dryer in the closed-loop system. The desirable product color has been observed.

Fig. 5.3: Photograph of the banana chips before drying (a) and after drying (b)

The experimental results of different modes are listed in Table 5.1. The energy requirement is highest for the infrared-assisted heat pump system drying due to the highest consumption of energy by the infrared heater (two heaters each of 250W). The energy consumption is lowest for the SAHPD due to the very low power consumption by the water pump (50W) and getting higher drying air temperature, which also decreases the drying time and finally energy consumption for the compressor, fan, and pump. In SIAHPD, a higher rate of drying was obtained because of the dual effect of increasing moisture removal potential of dying air due to temperature increase by solar heating and direct moisture removal by infrared radiation. However, the SMER is less than that of SAHPD due to extra energy consumption by the infrared heaters. The average drying air temperature is between 47-51°C for the simple HPD and IAHPD, and it is between 62-67°C for the SAHPD and SIAHPD. The optimum drying temperature for the banana chips to get the best color and quality of the dried product is in the range of 60-70°C (Liete et al., 2005). It implies that the solar-assisted dying modes yield the best color and quality product.

Table 5.1: Comparison of various parameters

Performance parameter	Types of the drying system			
	HPD	IAHPD	SAHPD	SIAHPD
Moisture content (% w.b), initial-final	83.8-11.5	83.8-11.5	83.8-11.5	83.8-11.5
Total drying time (min)	345	255	225	180
Average drying temperature (°C)	50.25	50.54	65.1	65.7
Total energy consumption (kWh)	2.75	2.98	2.024	2.52
Average MER (kg/h)	0.4747	0.7068	0.8224	1.1618
Average SMER (kg/kWh)	0.975	0.968	1.45	1.351
Average SEC (kWh/kg)	1.0256	1.033	0.6896	0.7402
Average Drying efficiency (%)	31.38	40.39	50.49	61.92
Energy efficiency (%)	54.1	39.44	58.5	47.73

The drying temperature is lowest for the simple-HPD and IAHPD systems for banana chips drying due to using the only heat pump system for air heating before the entrance of the drying cabinet. The dryer inlet temperature depends on the condenser saturation temperature and the amount of heat delivered by the refrigerant to the air in the condenser and the heat given by the water to the air in the solar heat exchanger. The performance of the drying system depends on the drying air temperature, humidity, air mass flow rate, and the effective diffusivity of the material. The drying process is carried out until the difference between the humidity at the drying chamber outlet and inlet has become negligible. From the result, it can be concluded that the time for drying chips is lowest for the solar-infrared-assisted HPD and highest for the simple HPD. The drying time depends on the mass transfer coefficient, diffusivity, drying air humidity, velocity, and temperature. So the drying time was lowest for the SIAHPD due to the effect of the high-temperature drying and the direct effect of the infrared radiation on the moisture removal from the product. Total drying time for banana chips in a closed system drying with simple HPD, IAHPD, SAHPD, and SIAHPD are 345, 255, 225, and 180min, respectively.

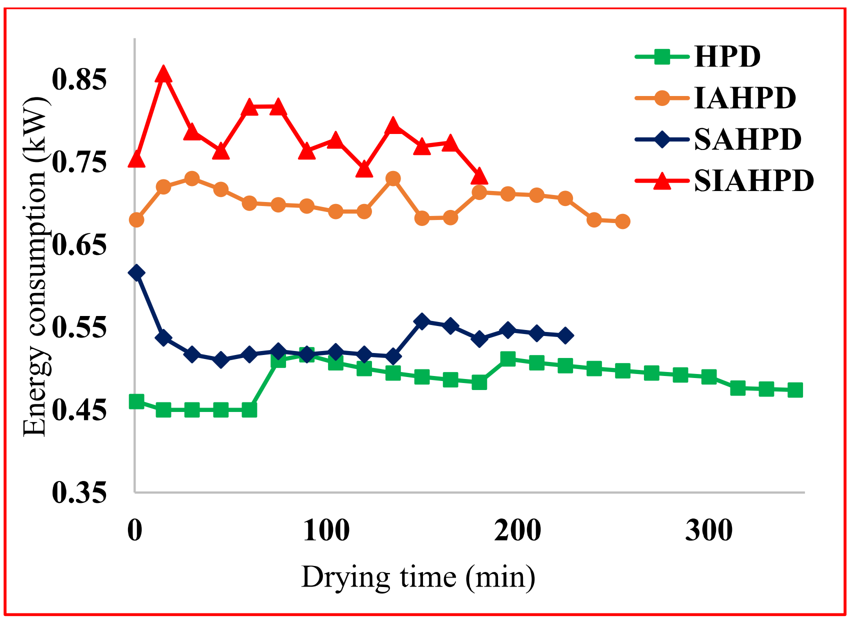

Fig. 5.4: Variation in energy requirement with drying time

Fig. 5.4 shows the energy required for the drying system due to the compressor, fan, infrared heater, and pump for all types of the drying system. As discussed earlier, due to free thermal energy received from the collector for the solar-assisted systems and extra energy consumed by infrared heaters for the infrared-assisted systems, the energy consumptions are much higher for the infrared-assisted drying system. The average energy consumption for the drying of banana chips in simple-HPD, IAHPD, SAHPD, and SIAHPD are found to be 2.75kW, 2.98kW, 2.024kW, and 2.52kW respectively.

The SEC is highest for the simple HPD system because of getting the low temperature for the same air mass flow rate and lower moisture removal rate and higher energy consumption. SEC is the lowest for the SAHPD drying system due to the high-temperature drying and lower energy consumption by the water pump and compressor. The average values of the SEC for banana chips in simple HPD, infrared-assisted HPD, SAHPD, and solar-infrared-assisted HPD systems are 1.0256, 1.033, 0.6896, and 0.7402kWh/kg, respectively and the SEC is nearly 55.22% more in simple HPD system as compared to the SAHPD drying system. And the specific energy consumption for SAHPD is almost in the range of a solar dryer integrated with a solar air heater (1.07 kWh/kg and 0.56 kWh/kg, respectively, Ekka et al., 2020).

In terms of COP, the simple heat pump drying for banana chips is best because in a simple HPD system the values of humidity and inlet temperature to the evaporator are low (the COP of the heat pump increases with a decrease in humidity and temperature at evaporator inlet). The COP is better for the simple HPD system for given environmental conditions as compared to the other drying systems, and the average values of COP for the simple HPD, IAHPD, SAHPD, and SIAHPD are 2.61, 2.303, 2.01, and 1.94, respectively (Ganjehsarabi et al., 2014). Fig. 5.5 shows the variation of the COP of the various drying system with drying time. The nature of the variation is fluctuating for the coefficient of the performance according to time. The COP of all types of systems 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 re-circulated to the evaporator, and the humidity and the temperature of dryer outlet air continuously changes with time, and thus the COP was also varying with time. The average COP is lowest for the SIAHPD system due to the high moisture content 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 energy consumed by the compressor and decreases the heating capacity of drying air in the condenser.

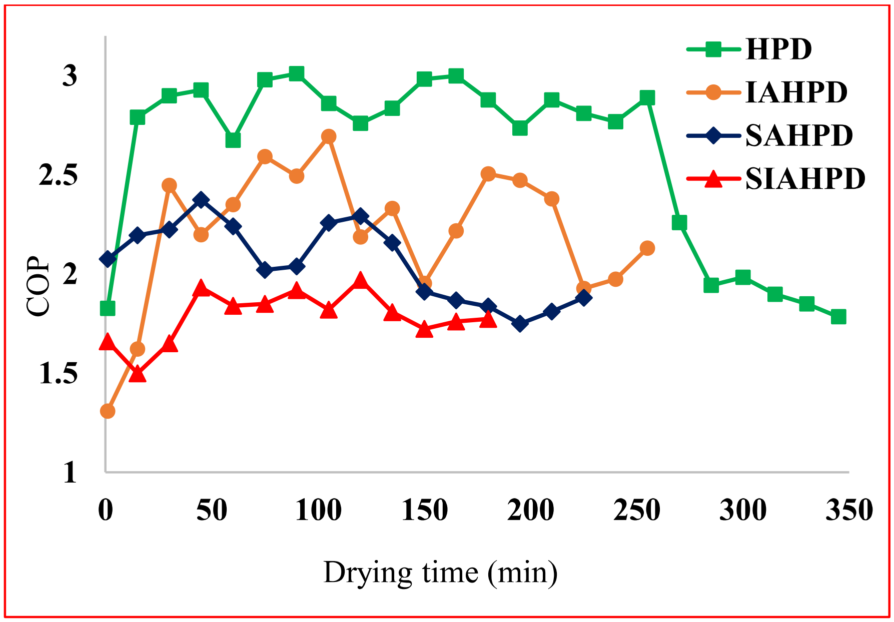

Fig. 5.5: Variation in COP with drying time

Fig. 5.6 represents the variation of the energy efficiency of the drying unit for the simple HPD, IAHPD, SAHPD, and SIAHPD systems according to drying time. The energy efficiency depends upon the vaporization of the moisture from the product and the energy consumption in the HPD system, and it is the ratio of the energy of the vaporization of water from material to the total energy input to the system. The energy efficiency first increases with time and reaches the peak value and then decreases after some time because starting the moisture removal from the product first increases its value with time but after some time moisture removal from the product decreases due to the loss in the moisture content of the material and hence decrease in moisture removal potential (difference in specific humidity of product surface and air). The energy efficiency is highest for the SAHPD drying due to the higher drying temperature and lowest energy consumption, and lowest for the IAHPD drying system due to the high energy consumption of the infrared heater (Aktas et al., 2017). The average value of the energy efficiency for the simple HPD, IAHPD, SAHPD, and SIAHPD system are 54.1 %, 39.44 % and 58.5%, 47.73%, respectively.

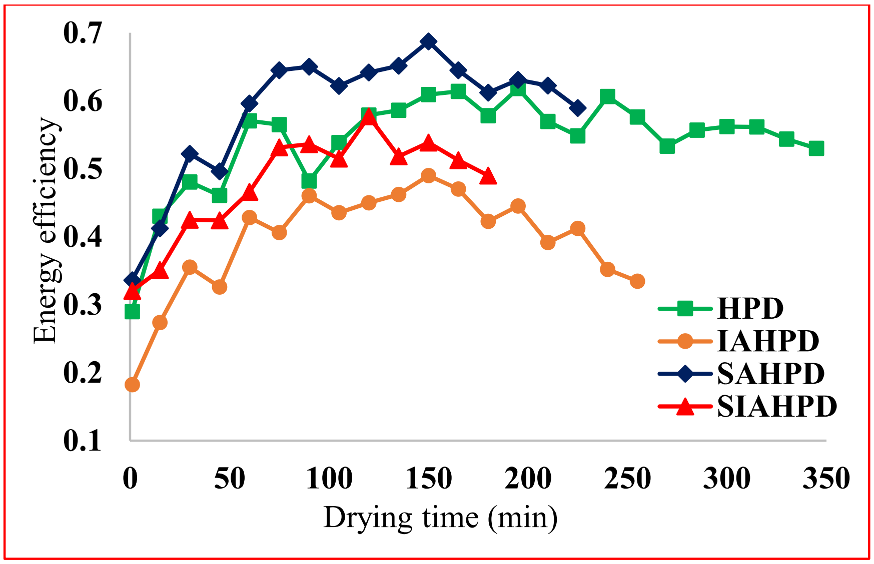

Fig. 5.6: Variation in energy efficiency with drying time

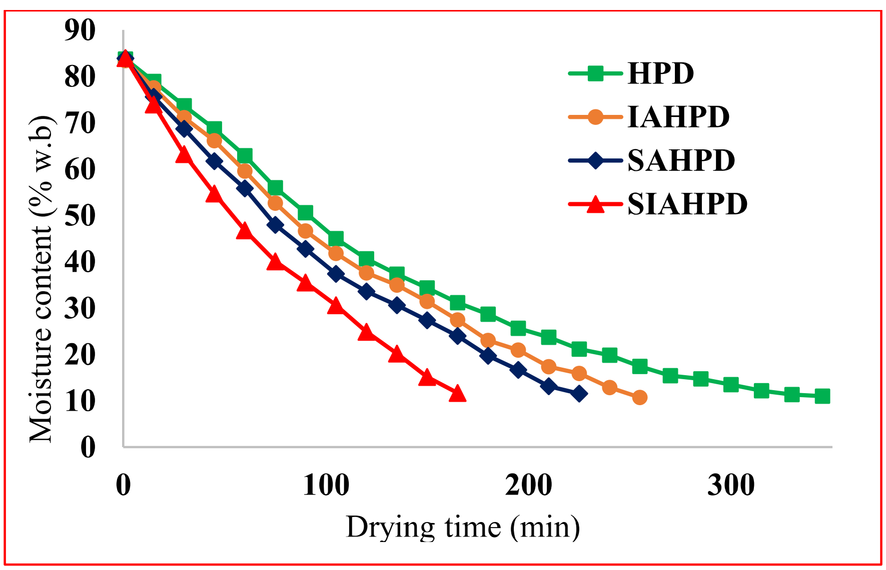

Fig. 5.7: Change in moisture content with drying time

As shown in Fig. 5.7, the moisture content decreases with the drying time because of the removal of the moisture from the material by drying air and the direct effect of infrared radiation. The MC decreases at a faster rate for the SIAHPD due to the higher drying temperature and direct effect of infrared radiation, which removes the moisture from the product at a higher rate. Initially, the MC decreases at a faster rate, but after some time, as the diffusion of moisture from the inside product to the outer side decreases, it decreases at a slower rate. The change in the MC is slowest for the simple HPD due to low drying temperature.

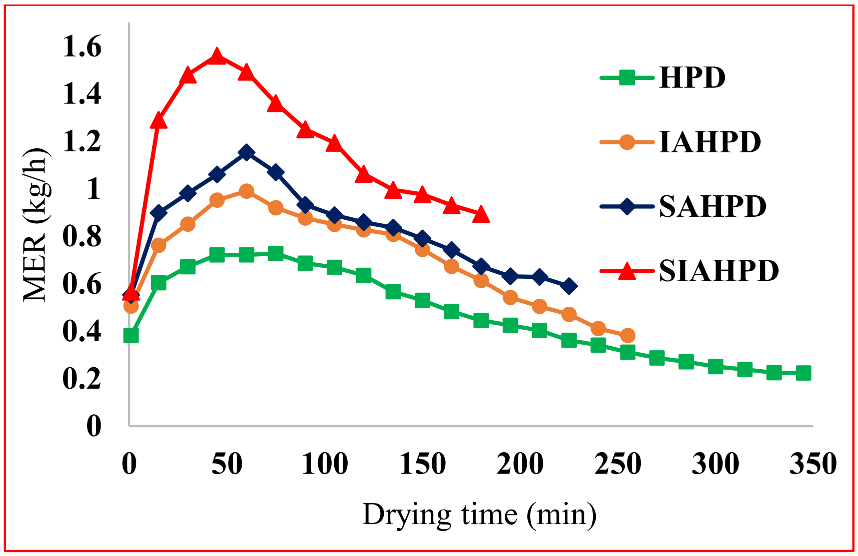

Fig. 5.8: Variation in moisture extraction rate with drying time

The performance of the HPD depends on product MC, diffusivity, mass transfer coefficient, drying air velocity, air temperature, and direct effect of infrared radiation. The MER first increases with time till the maximum value, but later some time, it starts to decrease due to the loss in material MC (decrease in drying air humidity potential) as shown in Fig. 5.8. The MER is highest for the SIAHPD because of the higher drying temperature and faster moisture removal from the product due to the direct effect of the infrared radiation on the product. The infrared radiation directly penetrated the product and removed the moisture from inside to the surface of the product, which is carried away by the high-temperature drying air. The MER rate is lowest for the simple HPD due to the low temperature. The average value of MER for banana chips drying in simple HPD, IAHPD, SAHPD, and SIAHPD are 0.4747, 0.7068, 0.8224, and 1.1618kg/h, respectively.

Fig. 5.9 shows the change of the SMER with the drying time for the four different types of drying. SMER depends on the MC of drying material, drying air velocity, and temperature. The SMER first increases with time because of the initiation of the mass and heat exchange between the drying air and product, but after some time, it started to decrease due to the loss in the MC from the material. The average SMER is highest for SAHPD due to the high drying temperature (high moisture removal potential) and lower value of the energy input as compared to the SIAHPD with a mean value of 1.45kg/kWh and the lowest is for IAHPD with a mean value of 0.968 kg/kWh, which was nearly similar to the simple HPD. The result of SMER for the simple HPD (0.975kg/kWh) is similar to the result given in the literature (Hadi et al., 2014). The MER is better for IAHPD, but the SMER is minimum because of more power consumption (due to the infrared heater) as compared to the simple HPD. For the SIAHPD system, the SMER is low due to the high-grade energy consumption by the infrared heater as compared to the SAHPD system.

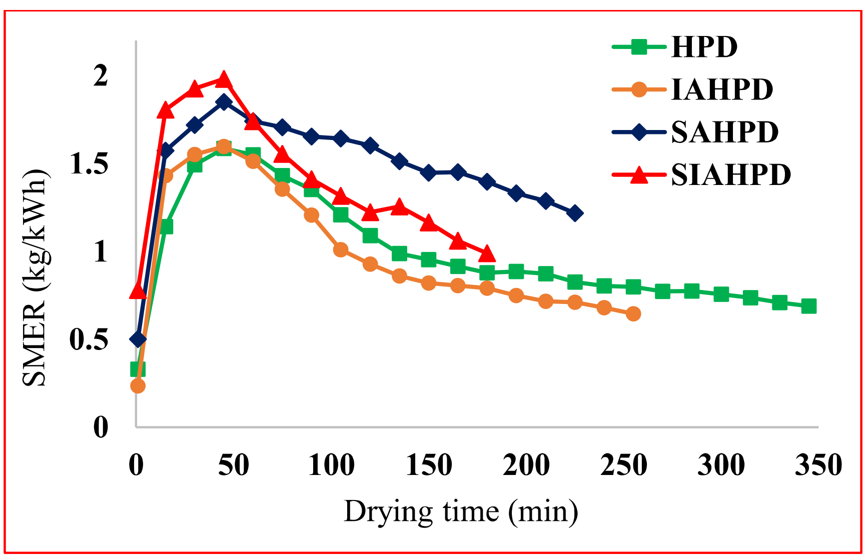

Fig. 5.9: Variation of specific moisture extraction rate with drying time

The drying efficiency depends on the drying chamber outlet humidity and temperature, inlet humidity and temperature, and the saturation temperature and humidity at dryer inlet wet-bulb temperature (Aktas et al., 2016). Fig. 5.10 shows the variation of drying efficiency with time. Its average value was better for the SIAHPD due to the getting of higher drying temperature and higher moisture extraction from the product due to the infrared radiation. The drying efficiency first increases with time due to the decreases in dryer outlet temperature and increase in humidity, but it starts to decrease after some time due to the increase in the temperature of the dryer and decrease in air humidity at the dryer outlet. The drying efficiency is higher for the SIAHPD as compared to other drying systems due to higher temperature drying and humidity extraction. The average drying efficiency of simple HPD, IAHPD, SAHPD, and SIAHPD are 31.8, 39.44, 50.49, and 60.92%, respectively. The drying efficiency of SAHPD (50.49%) was found better than the conventional solar dryer (33.5%) presented in the literature (Lakshmi et al., 2019)

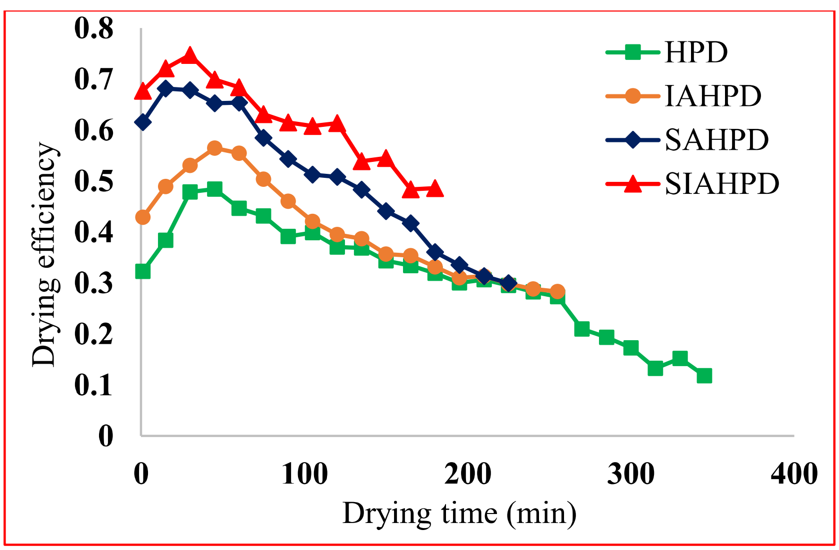

Fig. 5.10: Variation of drying efficiency with drying time

Fig. 5.11 shows the MER variation with the MC of the product. The MER was lower when the MC of the product is low, but the MER increased with an increase in the MC of the material. The MER rate was maximum in between the MC of 40-70%, and after that, its value was low because at that time, the experiment was in the initial stage. Initially, the MC of the product is high, but the MER is low due to the establishment of the mass transfer and heat exchange between the product and the air.

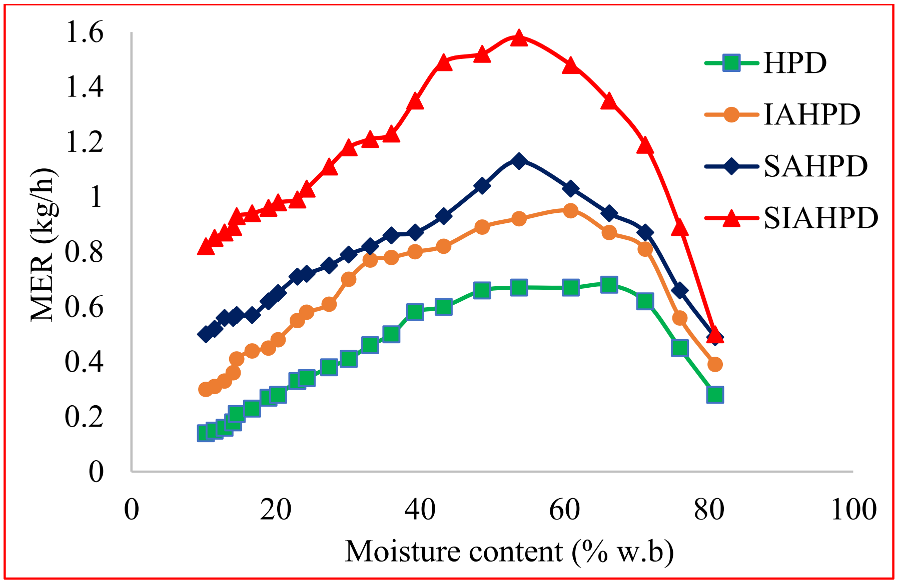

Fig. 5.11: Variation in MER with the moisture content of the product

The component-wise exergy efficiency and exergy destruction are given in Table 5.2. It gives the irreversibility in the components of the drying system due to the energy transfer between air and the refrigerant, between product and hot air, and water and the drying air. The exergy destruction was also highest in the compressor due to the moving part (dissipating more energy due to friction) and a higher degree of superheat. In the evaporator, the exergy destruction was due to the moisture condensation. The infrared heater is also a significant contributor to exergy destruction due to its higher temperature difference.

Table: 5.2. Irreversibility (kW) and exergy efficiency of different components

Type of system/ component	HPD		IAHPD		SAHPD		SIAHPD	
	Ex_{dest}	η_{ex}	Ex_{dest}	η_{ex}	Ex_{dest}	η_{ex}	Ex_{dest}	η_{ex}
Compressor	0.1559	0.659	0.164	0.58	0.2221	0.602	0.296	0.52
Condenser	0.0508	0.868	0.0457	0.907	0.0518	0.925	0.0308	0.912
Expansion device	0.047	0.751	0.0448	0.757	0.0358	0.741	0.0343	0.744
Evaporator	0.1311	0.57	0.112	0.631	0.122	0.71	0.0616	0.743
Drying chamber	0.0196	0.153	0.0213	0.134	0.017	0.24	0.025	0.203
Solar heat exchanger	…….	…….	………	……..	0.071	0.681	0.069	0.711
Infrared heater	…….	…….	0.0766	0.861	………	………	0.0813	0.848
Total Exergy destruction (kW)	0.4044		0.4644		0.5197		0.598	

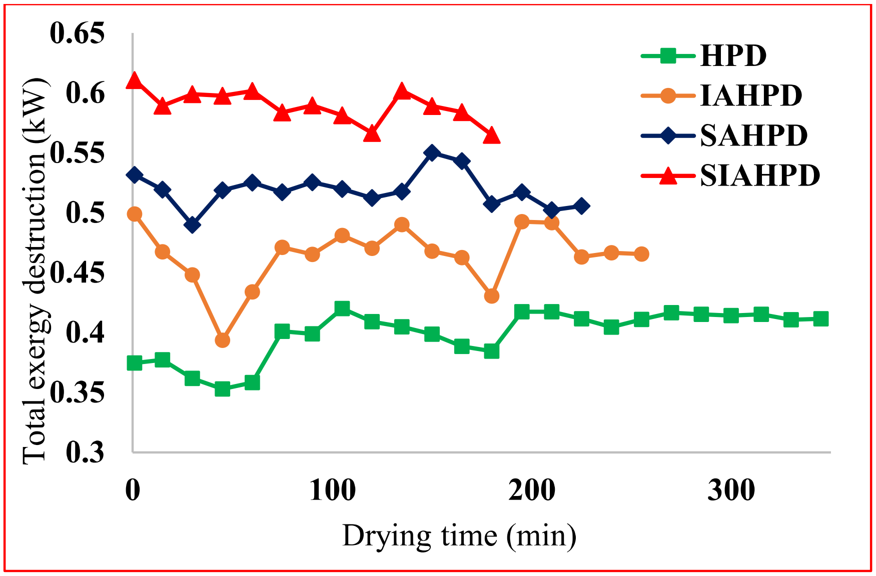

Fig. 5.12: Variation in the total exergy destruction with drying time

Fig. 5.12 shows the destruction of the exergy in the HPD system with drying time. The exergy destruction is highest for the SIAHPD because, at a higher temperature, destruction was also higher and also due to high-temperature water and the infrared heater. The exergy destruction is lowest in the simple HPD system due to the lower drying temperature. The highest exergy destruction was taking place in the first stage of the drying, and after that, it decreases slowly due to the decrease in drying temperature. Total exergy destruction in HPD, IAHPD, SAHPD and SIAHPD for banana chips drying are 0.4001kW, 0.4644kW, 0.5188kW and 0.598kW, respectively.

In the present study, an evacuated tube solar water heater was used to utilize solar energy for the drying of the banana chips. The heating capacity of the solar water heater depends on the available solar radiation, as the radiation incidence on the tubes changes with the daytime, the output temperature of the water may change. Hence, the solar-assisted system may suffer from more fluctuation. The size of the drying system is similar to the simple HPD and IAHPD and smaller as compared to the SAHPD and SIAHPD because the size of the solar water heater with heat exchanger is much larger compared to the infrared heater. Hence, the initial investment cost of the simple HPD is minimum and maximum for the SIAHPD due to the additional cost of solar heating systems and infrared heaters. The investment cost details of the drying system are given in Table 5.3. The running cost was minimum for SAHPD and maximum for IAHPD. The total initial cost of simple HPD, IAHPD, SAHPD, and SIAHPD are 521.31$, 567.9$, 892.94$, and 939.54$, respectively. The running cost of IAHPD is highest due to the high energy consumption by the infrared heater as compared to the water pump in SAHPD. The drying cost per kg of material for the banana chips in simple HPD, IAHPD, SAHPD and SIAHPD are 0.488$/kg, 0.497$/kg, 0.469$/kg and 0.484$/kg, respectively. The payback period of the all studied system was calculated based on the profit gained by selling the dried material and the total cost of the drying (running cost + initial cost). The payback period for the simple HPD, IAHPD, SAHPD, and SIAHPD is calculated as 0.392 years, 0.436 years, 0.633 years, and 0.969 years, respectively.

Table: 5.3. Economic parameters of components of drying system

Parameter	Cost of the parameter ($)			
	HPD	SAHPD	IAHPD	SIAHPD
The cost of the compressor	136.03	136.03	136.03	136.03
The cost of the condensers	89.75	89.75	89.75	89.75
The cost of the evaporator	72.92	72.92	72.92	72.92
The cost of the expansion device	3.51	3.51	3.51	3.51
The cost of the drying chamber	46.61	46.61	46.61	46.61
The cost of the refrigerant (R134a)	24.68	24.68	24.68	24.68
The purchase cost of the fans	16.83	16.83	16.83	16.83
The cost of the water pump	……..	25.24	……..	25.25

The cost of the solar water heater (evacuated tube)	………	266.45	………	266.45
The cost of the solar heat exchanger	………..	44.88	………..	44.88
Infrared heater	…………	………..	46.59	46.59
The setup cost of the dryer	130.98	166.04	130.98	166.04
The total initial cost of the drying system	521.31	892.94	567.9	939.54
Raw material cost ($/day), 13.5 kg/day	5.44	5.44	5.44	5.44
Raw material cost (annual, 300 days)	1632	1632	1632	1632
Labour cost ($/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	10.43	17.86	11.36	18.79
Energy consumption cost ($/day),	1.13	0.84	1.23	1.04
Energy consumption cost (annual)	339	252	369	312
Total running cost of the dryer ($/day)	10.63	10.37	10.74	10.57
Total running cost of the dryer (annual, 300 days)	3190.43	3110.86	3221.36	3171.79
Total cost ($)	3711. 74	4003.8	3789.26	4111.33

Drying cost per kg material ($/kg)	0.488	0.469	0.497	0.484
Total sale of product ($/day)	15.07	15.07	15.07	15.07
Total sale of product (annual, 300 days)	4521	4521	4521	4521
Total profit (annual, 300 days)	1330.57	1410.14	1299.64	1349.21
Payback period (year)	0.392	0.633	0.436	0.696

5.4 Highlights

The solar-infrared-assisted HPD has been developed and experimentally investigated. A comparative study of four different operational modes of the system (simple HPD, IAHPD, SAHPD, and SIAHPD) has been carried out for the drying of the 2 mm thin banana chips at an air mass flow rate of 0.0966 kg/s. The following highlights can be made from the results and discussion:

- For the decrease in the moisture content of banana chips from 83.8% to 11.5% on a wet basis, the drying time is lowest for SIAHPD (180min) followed by SAHPD (225min), IAHPD (255min), and simple HPD (345min).
- The total energy consumption is lowest for SAHPD and highest for IAHPD. The total energy consumption for simple HPD, IAHPD, SAHPD and SIAHPD are 2.75, 2.98, 2.04 and 2.52kW, respectively.
- COP of simple HPD is better as compared to others. Average COP of simple HPD, IAHPD, SAHPD, and SIAHPD are 2.618, 2.303, 2.04 and 1.94, respectively.
- MER is highest for SIAHPD. Average MER values for simple HPD, IAHPD, SAHPD and SIAHPD are 0.4747, 0.7068, 0. 8224 and 1.1618kg/h respectively.

- SMER was best for SAHPD. Average SMER values for chips in simple HPD, IAHPD, SAHPD and SIAHPD are 0.975, 0.968, 1.45, 1.351kg/kWh, respectively.
- Specific energy consumption is maximum for simple HPD system drying and minimum for SAHPD. Average SEC for simple HPD, IAHPD, SAHPD, and SIAHPD are 1.0256, 1.033, 0.6896 and 0.7402kWh/kg, respectively.
- SAHPD is better based on SMER and SIAHPD was better than others based on MER in the given humid and hot atmosphere for drying of banana chips.
- Exergy destruction is highest for the SIAHPD system and minimum for simple HPD and moderate for the SAHPD and IAHPD system drying of banana chips.
- The drying cost of the material per kg is minimum for the solar-assisted heat pump dryer and it was highest for the infrared-assisted heat pump dryer. The drying cost per kg of material for the banana chips in simple HPD, IAHPD, SAHPD and SIAHPD are 0.488$/kg, 0.497$/kg, 0.469$/kg and 0.484$/kg, respectively.
- The payback period for the simple HPD, IAHPD, SAHPD, and SIAHPD is calculated as 0.392 years, 0.633 years, 0.436 years, and 0.696 years, respectively.
- Compact size batch-type SIAHPD can be recommended for food chip drying, where a faster rate of drying is needed.