# CHAPTER 6

# EXPERIMENTATION ON WASTE HEAT RECOVERY ASSISTED HEAT PUMP DRYER

This chapter describes the design, development, performance, economic and exergoeconomic analysis of the heat pump dryer assisted with the waste heat recovery from the IC engine exhaust. Waste heat recovery from the various power generating system is an interesting area of research these days so in the current study, an open and closed-loop HPD-assisted with WHR from diesel engine exhaust was developed, and thermal (energy and exergy), economic and exergoeconomic performances are experimentally investigated. The main components of the drying system are the heat pump system, dryer system, and the waste heat recovery unit system with the 4-cylinder diesel engine. The coefficient of performance, moisture content, specific moisture extraction rate, specific energy consumption, energy efficiency, energy-saving potential, irreversibility, second law efficiency, and economic and exergoeconomic parameters are compared for simple HPD and WHR assisted HPD. The effects of drying time and engine load are studied as well.

## 6.1. Experimental setup and procedure

A convective compact engine WHR-assisted HPD has been designed and developed to study the performance of different agricultural products and fruit drying. Fig. 6.1 is the symbolic diagram of the HPD-assisted with WHR. The HPD assisted with heat recovery is mainly a combination of several subsystems such as the heat pump system, dryer system, diesel engine system, and WHR system. The photograph of the developed experimental facility for the WHR-assisted HPD system is shown in Fig. 6.2.

Detailed descriptions of the heat pump and dryer system have been provided in Table 3.1.

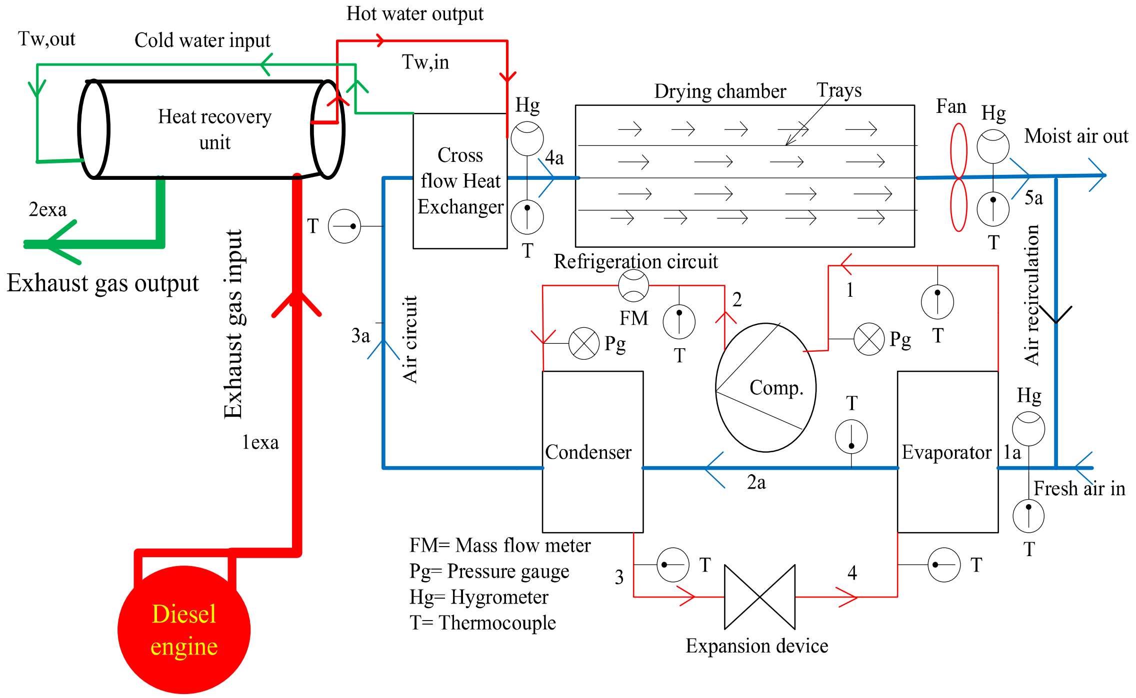

**Fig. 6.1:** Graphical representation of diesel engine exhaust heat recovery assisted HPD

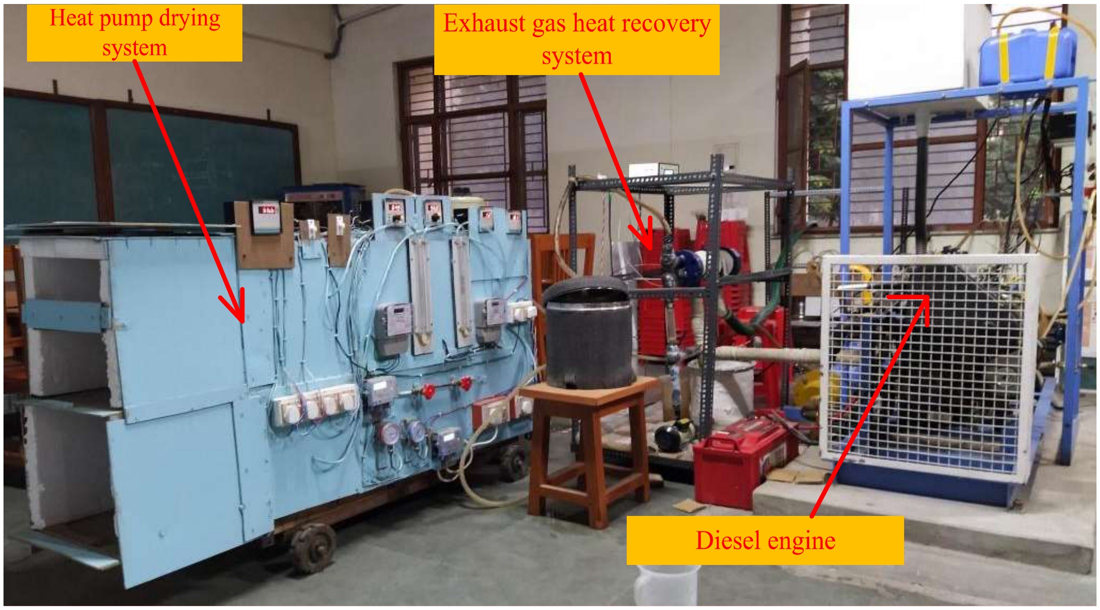

**Fig. 6.2:** Laboratory prototype of WHR assisted HPD

The heat pump system consists of a condenser, compressor, expansion device, and evaporator. The batch-type drying chamber has an inside dimension of 0.35 m×0.4 m×0.7

m, consisting of several trays inside it. The fan is used to maintain the flow of air in the HPD system.

In experimental setup, 4-stroke 4-cylinder diesel engine (cylinder volume = 1396cc, water-cooled, number of cylinders = 4, bore × stroke = 75mm×79mm, compression ratio = 21) is used. The heat recovery from the diesel engine exhaust system consists of a shell and tube liquid to the air heat exchanger, water pump, and a wavy fin cross-flow heat exchanger (HE). The shell and tube air to liquid HE contains the total no. of tubes = 12, length of tube = 400mm, size of shell = 100 mm×400 mm, no. of baffles = 2, and no. of pass (water side) = 2. The effectiveness of the shell and tube heat exchanger is 70 %. The hot water from the shell and tube HE is circulated in the HE (Wavy fin, Cross-sectional dimension = 30.48cm×33.02cm, length of tube = 15.85m, diameter = 9.7mm) with the help of a water pump (rated power=1/12hp, 220V, 50Hz, RPM=6500). The cross-flow heat exchanger is located just before the inlet of the drying cabin because the air coming from the condenser at a lower temperature is heated in the cross-flow HE.

The heat pump drying system with waste heat recovery from diesel engine exhaust was operated for the drying of the radish chips at the Indian Institute of Technology (BHU), Varanasi. The fresh white color radish was bought from the market and washed with clean water and the chips of 2mm size were prepared. The chips were made by a chip cutting instrument that can cut all chips of the same size. In this instrument, the size of the chips can be also adjusted from 1mm to 10mm size. The initial and the final MC of the radish chips were obtained by using the oven method at 105°C±3 A sample of 5.0 kg of radish chips was dried in the simple-HPD and the HPD-assisted with WHR. The capacity of the dryer is 5 kg and the experiment was performed at the full capacity of the drying system. The radish chips were spread with a similar pattern for all the experiments on trays for homogeneous drying. Three hygrometers and five thermocouples (PT100) were installed at different locations in the HPD system to estimate the heat exchange in the evaporator, condenser, and the cross-flow HE and also to control the drying temperature of the air. The thermocouples and the pressure gauge were installed to obtain the temperature and the pressure of the refrigerant in the heat pump cycle.

The experiment was carried out to investigate the thermal performance of the HPD-assisted with waste heat recovery (WHR). The diesel engine was started, and the exhaust gas was connected with the inlet to the shell and tube HE. The velocity of air was 1.0 m/s and the temperature was adjusted to the desired values. In many works of literature, many people have conducted experiments between the velocity range of 0.5 to 2.5m/s. So it was decided to experiment with this range of velocity but due to the limits of the fan speed installed in the setup, the maximum velocity of 1.2m/s were measured in the system that's why the experiments were performed at the velocity of 1.0m/s. The drying temperature was adjusted by controlling the flow rate of the air in the system. After that, the heat pump system is switched on and waited until the steady-state condition is achieved at the desired air temperature. The air volume flow rate was kept the same for the drying with HPD and assisted with the WHR. Then the radish chips were loaded inside the drying cabin after weighing in a digital balance and the desired air mass flow rate was obtained by controlling the speed of the fan, and the water pump was switched on to circulate the heated water in the cross-flow heat exchanger (HE) which was installed just before the drying cabin. The humidity and temperature of the air at the inlet and outlet to the evaporator, drying cabin, condenser outlet, and inlet, and the cross-flow heat exchanger were periodically recorded at the interval of 15minutes until the end of the experiment.

The energy meters were used to measure the supplied energy for the pump, compressor, and fan. The average air temperature at the drying cabin inlet was between 65-70°C for the closed system drying with HPD-assisted waste heat recovery (WHR). The experiment was conducted for the HPD-assisted with WHR and moisture reduction, moisture extraction rate (MER), specific moisture extraction rate (SMER), total energy input, coefficient of performance (COP), exergy loss, exergy efficiency, specific energy consumption (SEC), drying efficiency, payback period, exergoeconomic factor, cost of drying and the cost related to the exergy destruction were investigated.

## 6.2 Data analysis

The performance parameters of the simple HPD and WHR-assisted HPD have been evaluated. It is assumed that there is no pressure drop of refrigerant and heat loss in the heat pump drying system (Gungor et al., 2011).

The performance parameters such as COP, MER, SMER, drying efficiency, energy efficiency, and the SEC are calculated using the equations as discussed in Chapter 3. The Overall heating coefficient of performance (OHCOP), the ratio of the total heat gained in the condenser and cross-flow HE to the total energy input to the system, is given as,

$$\mathrm{OHCOP} = \frac{Q_{Cond} + Q_{HE}}{W_{comp} + W_{fan} + W_{pump}} \tag{6.1}$$

Where, $\dot{Q}_{HE} = \dot{m}_{air} c_{pam} (T_{4a} - T_{3a}) = \dot{m}_{hw} c_{pw} (\mathrm{T}_{w,in} - T_{w,out})$ (6.2)

The exergy destruction (or irreversibility) can be estimated by,

$$Ex_{dest} = Ex_{in} - Ex_{out} \tag{6.3}$$

Exergy destruction and exergy efficiency of different components of simple HPD and WHR assisted HPD is given as,

$$Ex_{\text{dest},comp} = W_{comp} + \dot{m}_r\left(e_{x1} - e_{x2}\right) \qquad \eta_{ex,comp} = \frac{\dot{m}_r\left(e_{x2} - e_{x1}\right)}{\dot{W}_{comp}} \tag{6.4}$$

$$Ex_{\text{dest},cond} = \dot{m}_r\left(e_{x2} - e_{x3}\right) + \dot{m}_a\left(e_{x3a} - e_{x2a}\right) \qquad \eta_{ex,cond} = \frac{\dot{m}_a\left(e_{x3a} - e_{x2a}\right)}{\dot{m}_r\left(e_{x2} - e_{x3}\right)} \tag{6.5}$$

$$Ex_{\text{dest},evap} = \dot{m}_r\left(e_{x4} - e_{x1}\right) + \dot{m}_a\left(e_{x1a} - e_{x2a}\right) \qquad \eta_{ex,evap} = \frac{\dot{m}_a\left(e_{x2a} - e_{x1a}\right)}{\dot{m}_r\left(e_{x4} - e_{x1}\right)} \tag{6.6}$$

$$Ex_{\text{dest,exp}} = \dot{m}_r\left(e_{x3} - e_{x4}\right) \qquad \eta_{ex,\text{exp}} = \frac{e_{x4}}{e_{x3}} \tag{6.3}$$

$$Ex_{\text{dest,HE}} = \dot{m}_{hw}\left(e_{xw,in} - e_{xw,out}\right) + \dot{m}_a\left(e_{x3a} - e_{x4a}\right) + W_{pump} \qquad \eta_{\text{ex,HE}} = \frac{\dot{m}_a\left(e_{x3a} - e_{x4a}\right)}{\dot{m}_{hw}\left(e_{xw,in} - e_{xw,out}\right) + W_{pump}} \tag{6.7}$$

$$Ex_{\text{dest,WHR}} = \dot{m}_{hw}\left(e_{xw,in} - e_{xw,out}\right) + \dot{m}_{exa}\left(e_{x,1exa} - e_{x,2exa}\right) \qquad \eta_{\text{ex,WHR}} = \frac{\dot{m}_{exa}\left(e_{x,1exa} - e_{x,2exa}\right)}{\dot{m}_{hw}\left(e_{xw,in} - e_{xw,out}\right)} \tag{6.8}$$

Economic investigation depends on initial investment cost and running cost. The total running cost of dried products can be presented as (Yahya et al., 2018),

$$C_{RU} = C_{RM} + C_P + C_L + C_m \tag{6.9}$$

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),

In the present economic analysis, the Simple HPD system is compared with the HPD with waste heat recovery in a closed system. The raw material cost and the labor cost is the same for both the system and cancel out, thus the economic analysis can be carried out based on energy consumption cost and the maintenance cost, and the equation can be written as,

$$C_{RU} = C_P + + C_m \tag{6.10}$$

The total cost of drying is given as

$$C_{Total} = C_{IC} + C_{RU} \tag{6.11}$$

Total profit from using WHR assisted HPD over simple HPD is the difference between the cost of WHR assisted HPD and simple HPD and given as,

$$C_F = C_{Total,HPD,HR} - C_{Total,HPD} \tag{6.12}$$

The payback period (which indicates the period to recover the capital investment, which is the initial investment cost per average profit) is given as (Atalay, 2019),

$$P_P = \frac{C_{IC}}{C_F} \tag{6.13}$$

Exergoeconomic analysis aims to estimate the cost related to the exergy destruction and component inefficiencies. Exergy cost balance for the different components of the system is given (Ganjehsarabi et al., 2014),

$$\sum_{out} C_{x,out,k} + C_{x,w,k} = C_{x,\mathrm{q},k} + \sum_{in} C_{x,\mathrm{in},k} + C_k \tag{6.14}$$

The overall cost of the WHR-assisted HPD can be determined by equation (17). The cost rate of exergy flow through the system at the exergy inlet, exergy outlet, and the exergy destruction can be estimated by the followings (Ganjehsarabi et al., 2014)

$$C_{x,input} = c_{input} E_{x,input} \tag{6.15}$$

$$C_{x,\mathrm{output}} = c_{output} E_{x,\mathrm{output}} \tag{6.16}$$

$$C_{x,\mathrm{dest}} = c_{dest} E_{x,\mathrm{dest}} \tag{6.17}$$

The following equation can give the total exergy cost rate,

$$C_{x,\mathrm{T}otal} = C_{x,\mathrm{dest}} + C_{Total} \tag{6.18}$$

The system recovery factor can be estimated by applying the initial investment cost, annual running and maintenance cost of the system which depends on the annual interest rate and the repayment period in years and given as (Abuska and Sevik, 2017),

$$CRF = \frac{i\left(i+1\right)^{n}}{\left(i+1\right)^{n}-1} \tag{6.19}$$

The initial investment cost can be calculated by,

$$C_{IC} = \frac{CRF}{t_{op}}PEC \tag{6.20}$$

Where PEC is the cost of the purchased equipment that is the cost of the components of the drying system as given in Table 6.3.

And the running cost is given by the following,

$$C_{RU} = C_{IC}\phi \tag{6.21}$$

In the present study, n, i, $t_{op}$, and φ values are taken as 2, 0.12, 3150 (HPD) and 2025 (WHR assisted HPD), and 0.8. Exergoeconomic factor is used to estimate the effect of non-exergy cost on the total cost of a system component and is given (Erbay and Hepbasli, 2017) by,

$$f_{ex} = \frac{C_{Total}}{C_{x,Total}} \tag{6.22}$$

The ratio of the exergy destruction cost to the equipment purchased cost is also an important parameter given by (Ganjehsarabi et al. 2014),

$$R_{ex} = \frac{E_{x,\mathrm{dest}}}{PEC} \tag{6.23}$$

The cost ratio of any component of closed-loop simple-HPD and WHR assisted HPD can be estimated by,

$$(CR)_k = \frac{(PEC)_k}{(PEC)_{Total}} \tag{6.24}$$

## 6.3. Results and discussion

The radish chips were dried in the simple-HPD and HPD-assisted with the WHR from the engine exhaust, and the performance of the system is estimated with and without recirculation of air. The results obtained from the experiment for the simple-HPD and HPD-assisted with WHR are listed in Table 6.1. The energy requirement is highest for the simple-HPD drying in the open-loop and lowest for the WHR-assisted HPD in the closed-loop system. The drying period is found dependent on mass transfer coefficient, diffusivity, drying air humidity, velocity, and temperature. In many works of literature, authors have concluded that the temperature affects the more on chemical and physical parameters (Silva et al., 2017). In the present study, the drying temperature is the parameter that changes highly in all four types of drying systems because velocity and material were fixed for all four types of systems. Total drying time is highest for the simple-HPD in the open system and lowest for the HPD-assisted with WHR in closed system drying.

**Table: 6.1. Comparison of various performance parameters of HPD with WHR**

| Performance parameter | Types of the drying system | | | |
|---|---|---|---|---|
| | Closed-HPD | Open-HPD | Closed-HPD with WHR | Open-HPD with WHR |
| Moisture content (% w.b), initial-final | 93.5-10.5 | 93.5-10.5 | 93.5-10.5 | 93.5-10.5 |
| Total drying time (min) | 210 | 300 | 135 | 180 |

| | | | | |
|---|---|---|---|---|
| Average dryer inlet temperature (°C) | 40.82 | 54.6 | 59.3 | 69.4 |
| Energy consumption (kWh) | 2.775 | 2.95 | 1.728 | 2.52 |
| Average $COP_{hp}$ | 4.25 | 5.34 | 3.48 | 5.18 |
| Average OHCOP | 3.269 | 4.204 | 5.58 | 6.72 |
| Average MER (kg/h) | 1.524 | 0.82 | 2.322 | 1.58 |
| $SMER_{average}$ (kg/kWh) | 1.6436 | 1.39 | 2.4 | 2.158 |
| $SEC_{average}$ (kWh/kg) | 0.6084 | 0.719 | 0.4166 | 0.4634 |
| Average Drying efficiency (%) | 32.42 | 24.5 | 49.18 | 42.79 |
| Energy efficiency (%) | 43.49 | 33.25 | 56.26 | 48.56 |
| Total Exergy destruction (kW) | 0.7249 | 0.5513 | 0.9044 | 0.7957 |

The total energy consumption is highest for the simple-HPD due to the consumption of energy by the compressor and fan in long drying time due to low drying temperature, and the energy consumption is lowest for the HPD-assisted with WHR in closed-loop loop system due to the very low power consumption by the water pump (50 W) and getting drying air at high temperature. In closed-loop WHR-assisted HPD, the high rate of drying is obtained by just heating the drying air from the high-temperature water coming from the engine exhaust WHR system (with a very less amount of the energy input to the pump).

Fig. 6.3 shows the dependency of the exhaust gas temperature and the water temperature on the engine load, and these parameters increase with applied load because as the load increases, the amount of fuel burning in the engine increases, and exhaust gas temperature increases. The exhaust gas temperature in the heat recovery system decreases from the value 297°C to 162°C and the heating water average temperature increases from the 55°C to 76°C (Shah et al., 2016).

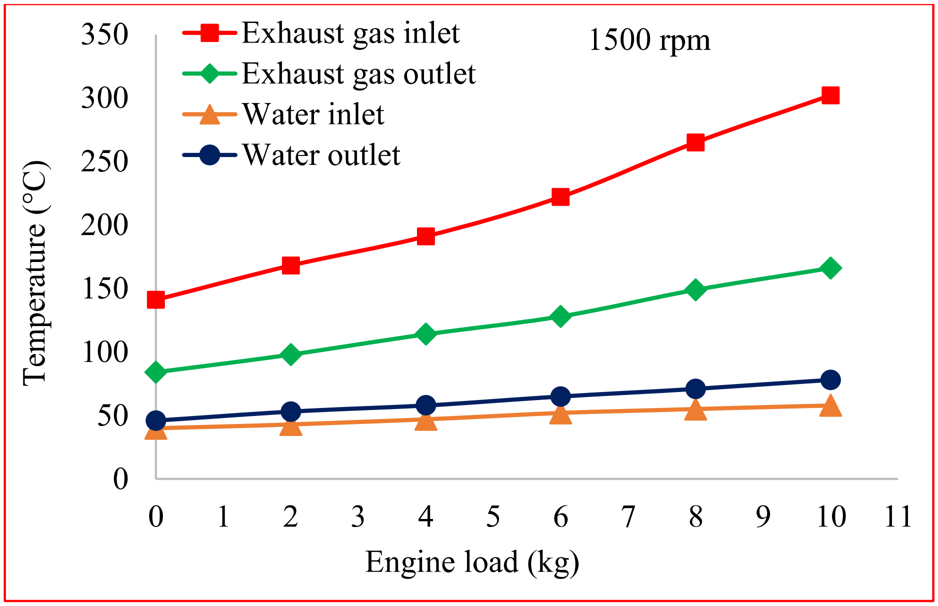

**Fig. 6.3:** Variation of exhaust gas and water temperature in the WHR system

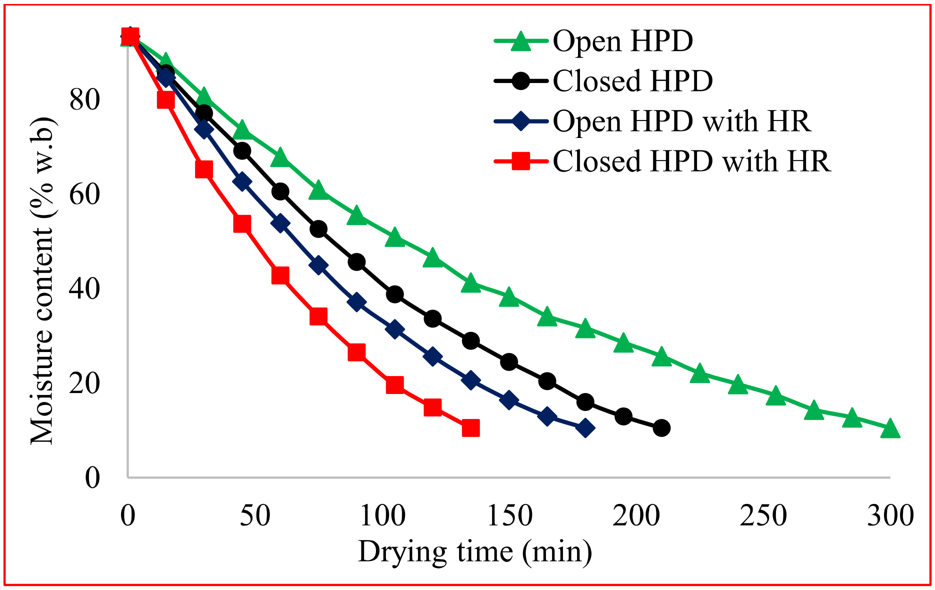

**Fig. 6.4:** Moisture content with drying time

The performance of the HPD system depends on the humidity, airflow rate, temperature, and effective diffusivity of the material. In literature, people have dried the product up to the 10% (Coogan and Wills, 2008). The drying process was carried out until the final MC of the material reached 10.5% from an initial value of 93.5% on a wet basis. As shown in Fig. 6.4, the MC of the material reduces with the drying time because of the removal of the moisture from the material by drying air. The MC reduces quickly for HPD-assisted with WHR in closed-loop drying as the greater drying temperature enhances the moisture extraction. For the time being, the diffusion of moisture from the inside of the product to the outer surface decreases, which decreases the moisture extraction rate from the surface of the product.

The SEC is highest for the simple open-loop HPD because of getting the low air temperature for the same air mass flow rate and lower moisture removal rate with high-energy input. SEC is lowest for the HPD-assisted with WHR in the closed-loop system due to the high-temperature drying and lower energy consumption. The result of SEC is listed in Table 6.2, and the SEC is nearly 72.6% more in simple-HPD in the open-loop system as compared to the HPD-assisted with WHR in the closed-loop drying system.

But in terms of COP, the simple-HPD in the open-loop loop is best (Aktaş et al., 2017). The COP of the heat pump decreases with an increase in moisture ratio and the temperature of the air inlet to the evaporator. So in simple-HPD with an open system, the moisture and temperature are minimum as compared to the closed system because in the open system the fresh air inlet, and closed system the drying air is recirculated which has high temperature and moisture. The average values of the COP for the simple-HPD with open loop, simple-HPD with closed-loop, HPD-assisted with WHR in open and HPD-assisted with WHR in closed systems are 5.34, 4.25, 5.18, and 3.48 respectively (Ismaeel and Yumrutas, 2020).

Fig. 6.5 shows the variation of OHCOP with drying time. The OHCOP is found highest for the HPD-assisted with WHR in a closed open system and lowest for the simple-HPD in the closed-loop system because in HPD-assisted with WHR, the energy input to the system is very low to get heat gain in the cross-flow HE due to the lower power consumption to pump. The average values of the OHCOP for the simple-HPD with open loop, simple-HPD with closed-loop, HPD-assisted with WHR in open, and HPD-assisted with WHR in closed systems are 4.204, 3.269, 6.27, and 5.58, respectively.

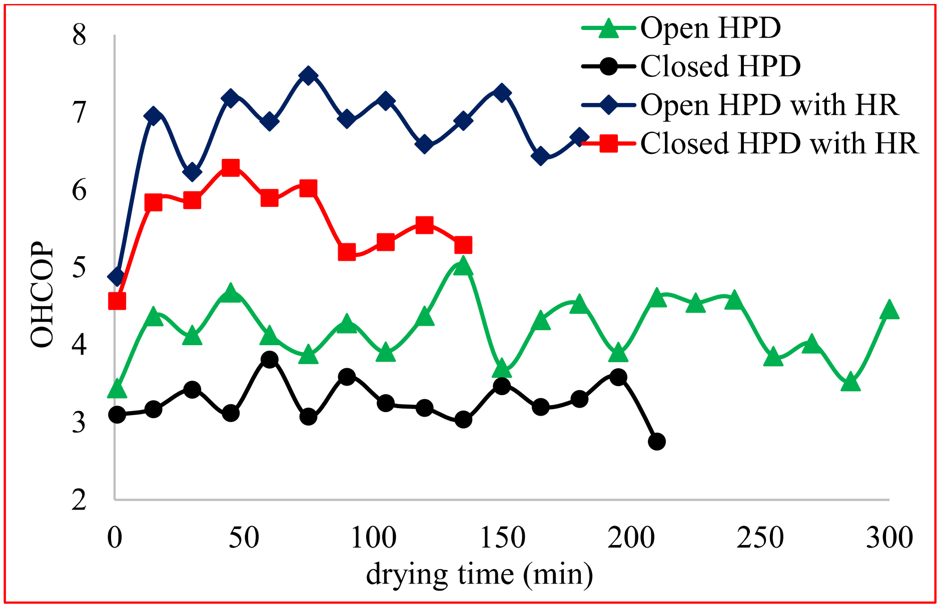

**Fig. 6.5:** OHCOP variation according to drying time

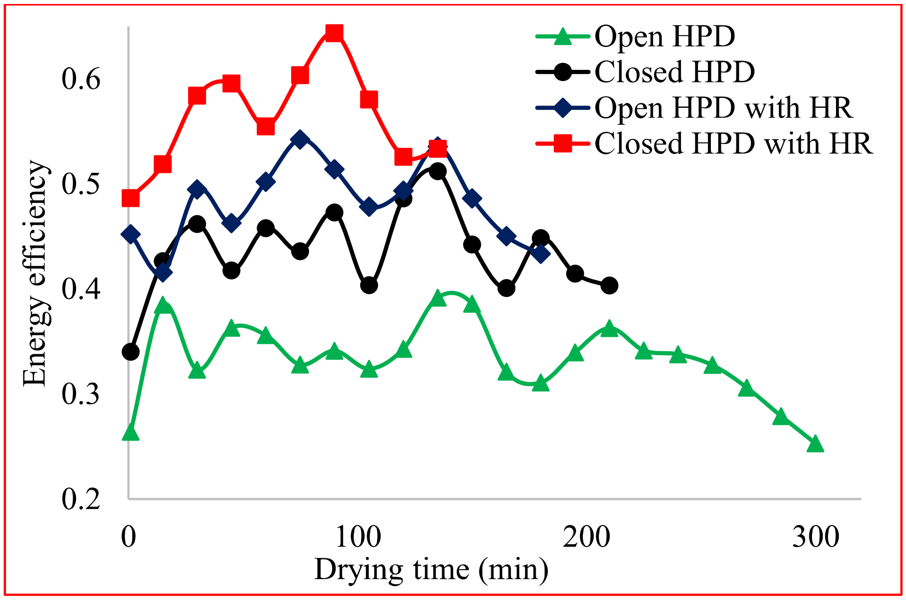

**Fig. 6.6:** Variation in energy efficiency with drying time

The parameter which gives the information about the utilization of the energy input to the drying system for the moisture extraction from the product is known as energy efficiency. Fig. 6.6 predicts energy efficiency for simple-HPD and HPD-assisted with the WHR according to drying time. The energy efficiency initially enhances and then decreases due to decreases in the MC of the material. The energy efficiency is highest for the HPD-assisted with WHR drying in a closed cycle because of the lowest energy consumption. The average values of the energy efficiency with simple-HPD in the open and closed cycles are 33.25% and 43.49%, and for the HPD-assisted with the waste heat recovery in the open and closed-loop are 48.56% and 56.26% respectively.

The MER of the HPD first increases, but later some time, it starts to decrease due to the loss in the MC of the material, as shown in Fig. 6.7. The MER was highest for the HPD-assisted with WHR in closed-loop drying of radish chips due to greater drying air temperature. The MER from the drying product depends on the drying temperature, the humidity of the air, diffusivity of the material, and the airflow rate. The MER is found to be the lowest for the simple-HPD in the open-loop system due to the low drying temperature and was highest for the HPD-assisted with WHR. The average MER for simple-HPD in the open and closed-loop system is 0.82kg/h and 1.524kg/h, and for HPD-assisted with WHR in the open and closed-loop system are found to be 1.58kg/h and 2.322kg/h respectively.

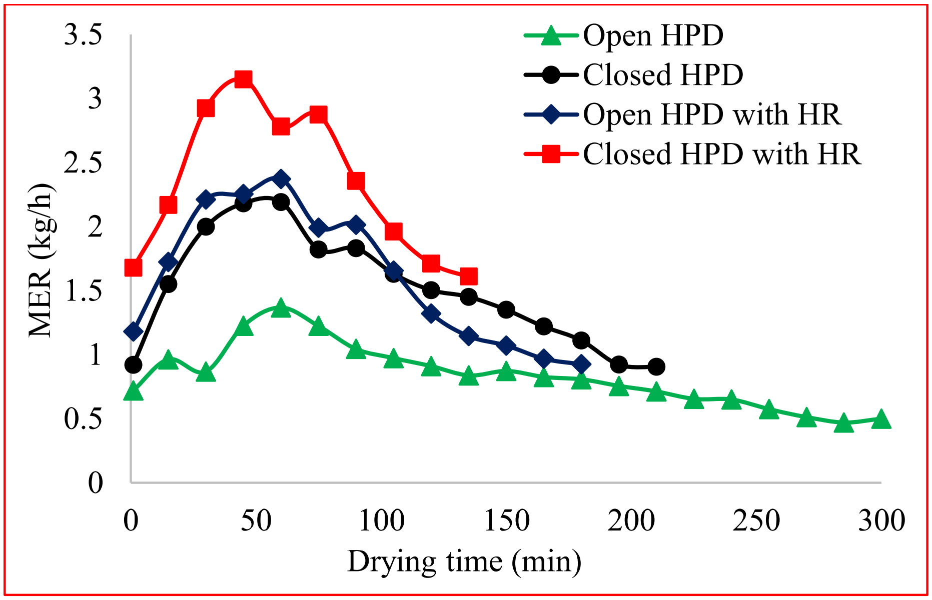

**Fig. 6.7:** Variation in MER with drying time

Fig. 6.8 shows the variation of the SMER with the drying time for the four different types of drying systems. The SMER initially increases with time because of the initiation of the mass and heat exchange between the drying air and product and the high MC of the product, but after some time, it started to decrease due to the loss in the MC of the product. The SMER is highest for HPD-assisted with WHR in a closed-loop as compared to the simple-HPD with a mean value of 2.4kg/kWh and the lowest is for the simple-HPD in the open-loop system with a mean value of 1.39kg/kWh (Lee and Kim, 2009).

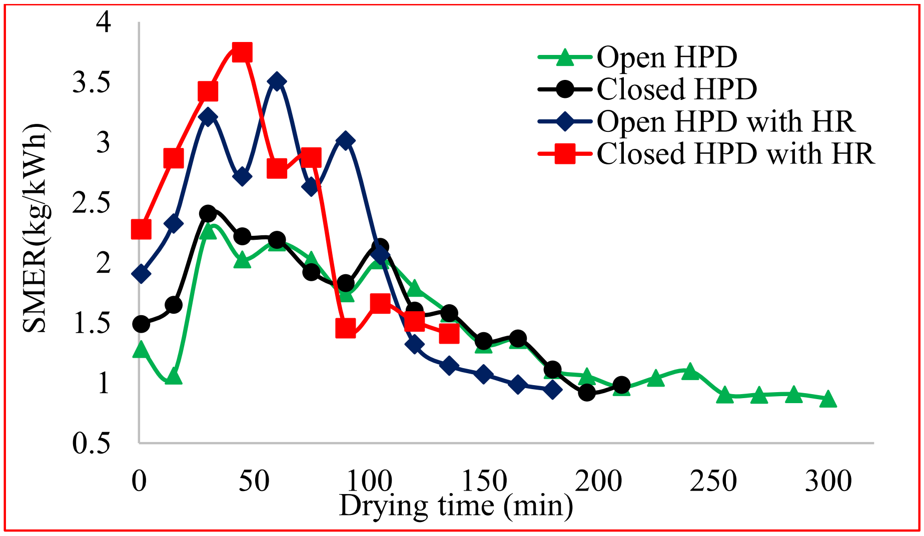

**Fig. 6.8:** Variation of SMER with drying time

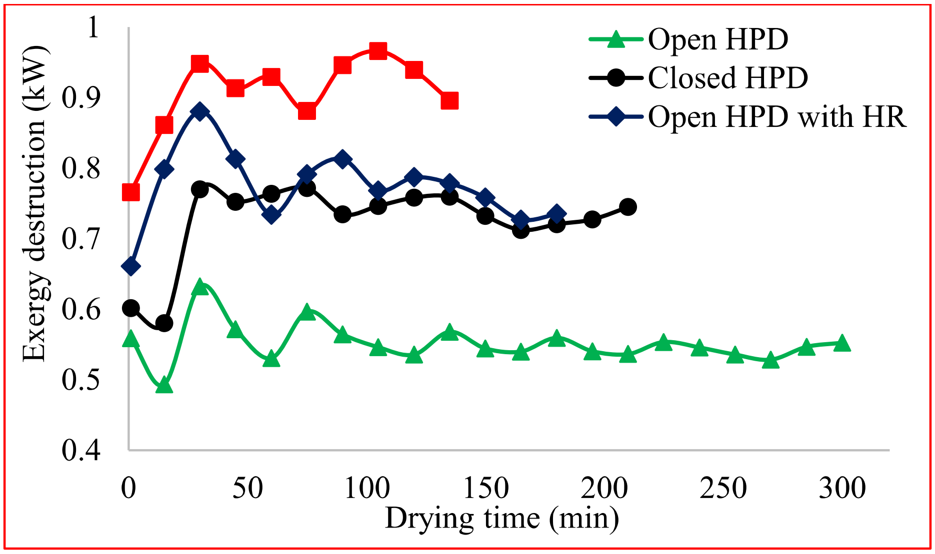

**Fig. 6.9:** Variation in exergy destruction with drying time

Exergy analysis is an important method to investigate the performance and utilization of energy in any system. It gives the irreversibility in the components of the HPD system. Fig. 6.9 predicts the exergy destruction and is found highest for the HPD-assisted with WHR due to high-temperature water and the very high-temperature exhaust gas. The exergy destruction in the evaporator is due to moisture condensation. Exergy analysis is an important method to investigate the performance and utilization of energy in any system and component-wise is given in Table 6.2. It gives the irreversibility in the components of the HPD system

**Table. 6.2: Irreversibility (kW) and exergy efficiency of different components**

| Type of system / component | Open-HPD | | Closed-HPD | | Open-HPD with HR | | Closed-HPD with HR | |
|---|---|---|---|---|---|---|---|---|
| | $Ex_{dest}$ | $\eta_{ex}$ | $Ex_{dest}$ | $\eta_{ex}$ | $Ex_{dest}$ | $\eta_{ex}$ | $Ex_{dest}$ | $\eta_{ex}$ |
| Compressor | 0.1659 | 0.679 | 0.194 | 0.63 | 0.1921 | 0.612 | 0.236 | 0.52 |
| Condenser | 0.1208 | 0.858 | 0.1657 | 0.897 | 0.1318 | 0.905 | 0.1408 | 0.912 |
| Expansion device | 0.062 | 0.771 | 0.0848 | 0.747 | 0.0818 | 0.761 | 0.0843 | 0.744 |
| Evaporator | 0.1411 | 0.61 | 0.155 | 0.621 | 0.132 | 0.731 | 0.1416 | 0.743 |
| Drying chamber | 0.0616 | 0.1574 | 0.1243 | 0.234 | 0.093 | 0.306 | 0.105 | 0.359 |
| Cross-flow heat exchanger | ……. | ……. | ……… | …….. | 0.071 | 0.691 | 0.089 | 0.711 |
| Exhaust gas heat recovery system | …….. | …….. | ……… | …….. | 0.094 | 0.783 | 0.112 | 0.766 |

The economic analysis of the simple-HPD and the HPD-assisted with WHR in a closed-loop drying system was conducted (because the closed system has better performance as compared to the open system) for the net annual profit of using the HPD-assisted with WHR over the simple-HPD system, return period of investment and payback period. The primary investment cost, annual maintenance, running cost, and the cost of the drying system are listed in Table 6.3. The first stage of the economic analysis of the simple-HPD and the HPD-assisted with WHR is done to determine the total primary investment of the drying system. The daily and annual running costs of the system were presented for the simple-HPD and HPD-assisted with WHR in the closed-loop system. The running cost of both types of the system includes energy consumption, raw material, and labor cost. The energy consumption cost is the most important cost among the running costs for the simple-HPD and the HPD-assisted with WHR. The daily average of 15kg of the radish chips are dried in the simple-HPD and HPD-assisted with WHR, and the daily total cost of the raw material in the Varanasi was specified as \$6.3. The total installation cost of the simple-HPD and HPD-assisted with WHR are estimated at \$130.98 and \$166.04, respectively. The yearly average running cost of the simple-HPD and the HPD-assisted with waste heat recovery in the closed-loop system are given as \$358.41 and \$233.81. The total yearly profit gained by using the HPD-assisted with waste heat recovery instead of the simple-HPD in the closed-loop system is determined as \$124.53, and the total difference in the initial investment between the simple-HPD and the HPD-assisted with WHR is \$343.15. The average payback period of drying the radish chips in the HPD-assisted with WHR over the simple-HPD in the closed-loop system is estimated at 33 months, which is a better result for the radish drying as compared to the other researchers (Qui et al., 2016). It is a better result for the experiment because after

33 months the HPD assisted with WHR will be more economical as compared to simple HPD in the closed-loop. The life guaranteed life of the compressor used in the present HPD system is much more than the payback period. The overall cost of any drying system can be defined by the two types of cost, one is the system's basic cost, and the second is the energy requirement cost of the system. The overall cost of both simple-HPD and the HPD-assisted with WHR in the closed-loop can be obtained by applying the economic investigation.

**Table: 6.3. Economic parameters of different components of HPD with WHR**

| Parameter | Cost of the parameter ($) | |
|---|---|---|
| | HPD | HPD with WHR |
| The cost of the compressor | 136.03 | 136.03 |
| The cost of the condensers | 89.75 | 89.75 |
| The cost of the evaporator | 72.92 | 72.92 |
| The cost of the expansion device | 3.51 | 3.51 |
| The cost of the drying chamber | 46.61 | 46.61 |
| The cost of the refrigerant (R134a) | 24.68 | 24.68 |
| The purchase cost of the fans | 16.83 | 16.83 |
| The cost of the water pump | …….. | 25.24 |
| The cost of the heat recovery system (shell and tube) | ……… | 237.97 |
| The cost of the cross-flow heat-exchanger | ……….. | 44.88 |
| The setup cost of the dryer | 130.98 | 166.04 |
| Total initial cost of the drying system | 521.31 | 864.46 |

| | | |
|---|---|---|
| Total Energy consumption (kWh/day) | 8.265 | 5.184 |
| Total Energy consumption cost (per day) | 1.16 | 0.74 |
| Total running cost of the dryer (daily) | 1.1947 | 0.7796 |
| Maintenance cost (2 % of the initial cost), annual | 10.424 | 17.289 |
| Total running cost of the dryer (annual, 300 days) | 358.41 | 233.88 |

The exergy-energy-based cost of both drying methods can be obtained by applying the exergoeconomic investigation of the drying system. When the evaluation of the drying system is estimated based on the exergoeconomic investigation, the parameters that can be analyzed for the simple-HPD and the HPD-assisted with WHR system are the basic purchasing cost of each component, the exergy destruction cost, system recovery factor, the overall cost of the drying system, the ratio of exergy destruction to the total purchase cost of the components, and the exergoeconomic factor. The result obtained from the exergoeconomic analysis of the simple-HPD and HPD-assisted with WHR in a closed system is listed in Table 6.4. The exergy destruction cost is highest for the compressor for both simple-HPD (0.02716$/h) and HPD-assisted with WHR (0.03304 4/h), and lowest for the expansion device for both HPD (0.01187$/h) and the HPD-assisted with WHR (0.0118$/h). The total exergy cost is highest for the compressor for simple-HPD (0.07314$/h) and waste heat recovery unit for the HPD-assisted with WHR (0.05017$/h) and is lowest for the expansion device for the simple-HPD (0.001067$/h) and HPD-assisted with WHR (0.1408 $/h) system. It is estimated that the $R_{ex}$ value was highest for the expansion device for the simple HPD (24.16W/$) and the HPD-assisted with waste heat recovery (24.02W/$) due to the very low purchasing cost of the expansion device, and $R_{ex}$ values were lowest for the compressor for the simple-HPD (1.426W/$) and the waste heat recovery unit for the HPD-assisted with WHR (0.4706W/$) system. It is estimated that the compressor is having the highest value of the exergoeconomic factor for the simple-HPD (0.6286), and the waste heat recovery unit having the highest exergoeconomic factor value for HPD-assisted with WHR (0.888) system followed by the condenser (0.566) for simple-HPD and 0.705 for HPD-assisted with WHR. The exergoeconomic factor values are lowest for the evaporator (0.0918) for simple-HPD and 0.1348 for the HPD-assisted with WHR. The cost ratio (CR) values were highest for the compressor with 0.348 for simple-HPD and the heat recovery unit with 0.3407 for the HPD-assisted with WHR.

**Table: 6.4. Exergoeconomic parameters of HPD with WHR**

| Drying system | | Components | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Compressor | Condenser | Expansion device | Evaporator | Drying chamber | Cross flow HE | Heat recovery Unit |
| HPD | $R_{ex}$ (W/$) | 1.426 | 1.846 | 24.16 | 2.1256 | 2.666 | ………. | ………. |
| | $C_{Total}$ ($/h) | 0.04598 | 0.0303 | 0.0012 | 0.02465 | 0.01575 | ………. | ……….. |
| | $C_{x,dest}$ ($/h) | 0.02716 | 0.0232 | 0.01187 | 0.0217 | 0.0174 | ……….. | ……….. |
| | $C_{x,\text{total}}$ ($/h) | 0.07314 | 0.0535 | 0.01307 | 0.04635 | 0.03315 | ……….. | ………. |
| | $f_{ex}$ | 0.6286 | 0.566 | 0.0918 | 0.5318 | 0.475 | ……….. | ………. |
| | CR | 0.348 | 0.229 | 0.00899 | 0.1868 | 0.1194 | ……….. | ……….. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| HPD with heat recovery | $R_{ex}$ (kW/$) | 1.7348 | 1.568 | 24.02 | 1.942 | 2.2527 | 1.986 | 0.4706 |
| | $C_{Total}$ ($/h) | 0.07153 | 0.0472 | 0.00184 | 0.03834 | 0.0245 | 0.0236 | 0.12513 |
| | $C_{x,dest}$ ($/h) | 0.03304 | 0.0197 | 0.0118 | 0.0198 | 0.0147 | 0.01246 | 0.01568 |
| | $C_{x,total}$ ($/h) | 0.10457 | 0.0669 | 0.01364 | 0.05814 | 0.0392 | 0.03606 | 0.1408 |
| | $f_{ex}$ | 0.668 | 0.705 | 0.1348 | 0.659 | 0.625 | 0.654 | 0.888 |
| | CR | 0.195 | 0.1285 | 0.00502 | 0.1044 | 0.0667 | 0.0642 | 0.3407 |

## 6.4 Highlights

The WHR-assisted HPD has been developed and experimentally investigated in open and closed loops. A comparative study of two different operational modes of the system (with and without WHR) has been carried out for 2mm thin radish chips drying at a constant airflow rate. The following highlights are made from the results:

- For the decrease in the moisture content of radish chips from 93.5% to 10.5% on a wet basis, the drying time is lowest for HPD-assisted with WHR in closed-loop (135 min) and highest for the simple-HPD (300min).
- COP of simple-HPD is better as compared to WHR-assisted HPD. The average COP of simple-HPD in an open loop, simple-HPD in a closed-loop, HPD-assisted with WHR in the open, and HPD-assisted with WHR in a closed loop are 5.34, 4.25, 5.18, and 3.48, respectively.

- OHCOP values are higher for WHR-assisted HPD as compared to simple-HPD. The average values of OHCOP for simple-HPD in open loop, simple-HPD in closed-loop, HPD assisted with WHR in open and HPD-assisted with WHR in closed loops are found to be 4.204, 3.269, 6.72, and 5.58, respectively.
- MER is highest for the HPD-assisted with WHR in the open and closed-loop system. The MER of simple-HPD in open loop, simple-HPD in closed-loop, HPD-assisted with WHR in open loop, and HPD-assisted with WHR in closed-loop are 0.82kg/h, 1.52kg/h, 1.58kg/h and 2.322kg/h, respectively.
- SMER is much higher for WHR-assisted HPD as compared to the simple-HPD. The average values of SMER of simple-HPD in open loop, simple-HPD in closed-loop, WHR assisted HPD in open loop and HPD-assisted with WHR in closed-loop are 1.39kg/kWh, 1.6436kg/kWh, 2.158kg/kWh and 2.4kg/kWh, respectively.
- The payback period of using HPD-assisted with WHR over the simple-HPD in the closed-loop is found to the 33 months.
- The lowest exergoeconomic factor for simple-HPD and HPD-assisted with WHR are 0.0918 and 0.1348, respectively. Thus based on exergoeconomic factors, the HPD-assisted with WHR is better as compared to the simple-HPD in a closed loop.
- The cost of exergy destruction for the simple-HPD and HPD-assisted with WHR in a closed-loop is 0.10148$/h and 0.1266$/h, respectively.
- A compact size batch-type HPD-assisted with WHR from the diesel engine exhaust can be recommended for the food chips drying, where a faster rate of drying is needed with low energy consumption.