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Evaluation of the Performance of Modeled and Simulated Hybrid Heat Pump Drying Systems for Industrial Applications

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Abstract: *System configuration and design is one of the major factors that influence the performance of heat pump drying system. This study aimed to evaluate the performance and drying efficiency of two different configuration of hybrid heat pump drying system for heating process and drying of tomatoes slices at condensing temperature 15 ℃ and evaporating temperature 10 ℃ using calcium chloride-ethanol as adsorbate-adsorbent pair. The energetic coefficient of performance, and exergetic coefficient of performance and overall exergy efficiency of the system are 2.03, 15.6% and 17% respectively for simple adsorption-compression hybrid heat pump drying system while its specific moisture extraction rate is 0.234 kg/kWhr and specific energy consumption is 4.27 kg/kWhr. The energetic coefficient of performance, and exergetic coefficient of performance and overall exergy efficiency of the system are 2.18, 22.6% and 16% respectively for cascaded adsorption-compression hybrid heat pump drying system and its specific moisture extraction rate is 0.457 kg/kWhr and specific energy consumption is 3.17 kg/kWhr.*

Keywords*:* Coefficient of performance, exergy efficiency, specific moisture extraction rate, specific energy consumption, chemisorption.

1. INTRODUCTION

Due to its commercial importance, the tomato is one of the most scientifically studied vegetables. It is highly perishable, with post-harvest losses ranging from 25 to 50 percent. (Correia *et al.*, 2015). Dried tomatoes products have main attributes of quality-nutritional value, acceptability, usability and safety of products the most important quality parameters that determine the acceptation of dried tomatoes by consumers are their color and flavor (Fayose and Huan, 2015). The rapid rise in energy costs, supply security concerns, pollutant emissions, and global climate change have all rendered heating systems unsustainable in their existing forms, both now and in the future. To tackle these issues, alternative heating solutions that focus on reducing energy consumption and improving heating performance while reducing negative impacts or negative influence on the environment must be investigated. Heat pumps have long been recognized as an effective means of drying and energy recovery (Yang, 2020).

The hybrid adsorption-compression heat pump concept allows a thermally activated sorption heat pump to operate at lower waste heat temperatures, extending its operating range to improve system performance and efficiency. The cascade heat pump system, which consists of two independent refrigerant cycles, was developed to overcome the disadvantages of single-stage heating processes in low-temperature heat pump systems, such as high-pressure ratio and low COP (Kim *et al.*, 2012).

In this present study, the performance of adsorption-compression hybrid heat pump systems for industrial applications were evaluated through energy analysis, exergy analysis, and drying analysis using Aspen Plus simulation.

2. MATERIALS AND METHODS

The engineering calculations and simulation of adsorption heat pump drying system using ASPEN PLUS (Version 10) requires availability of numerical information and mathematical approach for the evaluation of efficiency of the heat pump drying systems. The tomato slices at room temperature are assumed to be a solid mixture of the components in Table 2.

The physicochemical properties of the tomato were created in Aspen Plus environment (Ursula and Khan, 2015). The drying air temperature is assumed to be 40 ℃. The initial and critical moisture content are assumed to be 0.1 and 0.01 respectively. Thickness and radius of tomato slices are assumed to be 2 mm and 2 cm respectively (Hany *et al.*, 2013). The number of tomato slices dried per turn (N) is assumed to be 12,000 slices. Dimension of the dryer is assumed to be 61 cm x 61 cm x 61 cm (with a modified drying chamber). The flowrate of tomato slices and air are assumed to be 400 kg/hr. and 200 kg/hr. Flowrate of the working fluid is 1 kmol/hr. and isentropic efficiency of compressor is 85%. The exergy reference temperature and pressure were assumed to be 30 ℃ and 1atm respectively.

2.1 Tomato Components

The main components of tomato are their percentage composition are shown in the Table 1.

Table 1: Main components of tomatoes (Jimenez, 2015)

Components	Composition
Protein (%)	2.01
Fibre (%)	2.50
Ascorbic acid (mg/100)	19.33
Phenolic compound (mg/100)	30.50
Carotene (mg/100)	13.56
Lycopene (mg/100)	0.51
Moisture (%)	94.60

2.2 Modelling of CSTR Adsorber in Aspen Plus

Table 2 gives the kinetic parameters for modeling CSTR adsorber using Aspen Plus.

Table 2: Kinetic parameters obtained from the reaction of the adsorbent-adsorbate pair for modeling chemisorptions adsorber using CSTR reactor (Korhammer *et al.*, 2016; Korhammer *et al.*, 2019)

Parameter	$CaCl_2$- C_2H_5OH
Adsorber pressure (kPa)	680
Adsorber temperature (℃)	180
k (mg/min)	0.14
n	2
Reaction time(min)	27
$E_{a,\ ads}$(kJ/mol)	50

The simple adsorption-compression hybrid heat pump drying system simulated using calcium chloride-ethanol as adsorbent-adsorbate pair and ethanol as working fluid at 680 kPa and 150 ℃ adsorber temperature and pressure respectively and 120 kPa valve pressure, 700 kPa compressor discharge pressure and 15 kPa valve pressure respectively. Water and ethanol are used as working fluids for the upper circuit and lower circuit respectively for cascaded adsorption-compression hybrid heat pump drying system. The energy, exergy and drying analysis were done using Equations (1) to (9).

2.3 Process Description

2.3.1 Adsorption-Compression hybrid heat pump drying system

The hybrid heat pump drying system consists mainly of two subsystems: adsorption-compression hybrid heat pump and a drying chamber. The hybrid heat pump extract and transfer heat from natural heat sources in the surroundings (such as the air, ground or water), or from industrial or domestic waste, or from a chemical reaction or dryer exhaust air through adsorber and evaporator (Jensen, 2014). The heat from exhausted air from the dryer that is cooled and dried is recirculated back to first evaporator of the heat pump where it is cooled and the moisture in the air is condensed and removed.

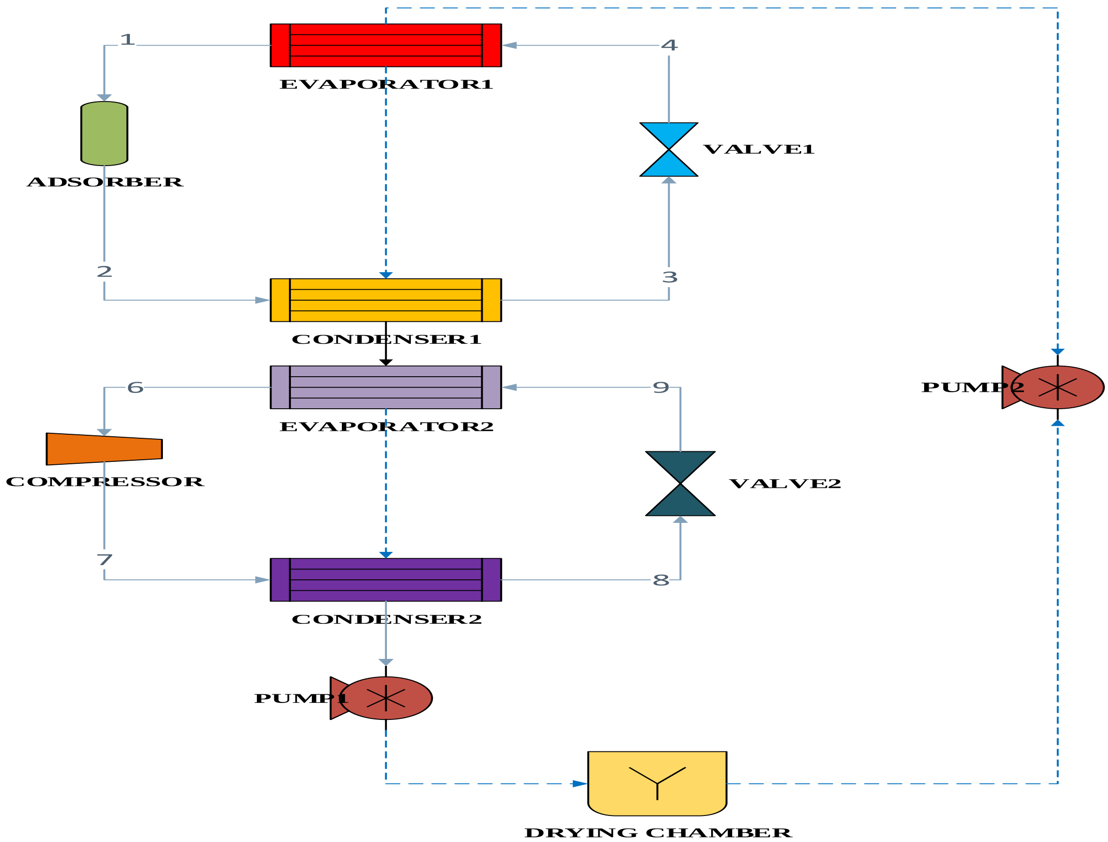

Figure 1: Schematic diagram of adsorption-compression hybrid heat pump drying system

The cool and dry air from the evaporator then goes into the condenser of the heat pump and is heated. The hot and dry air then enters the dryer and absorbs the moisture in the materials being dried in the dryer and becomes exhausted air at the outlet of the dryer, and the cycle repeats. Because the heat pump retrieves the heat in the exhausted air to heat the air entering the dryer while it removes the moisture in the exhausted air, it achieves a high energy efficiency in the drying of biological materials such as tomato slices which are thermally and oxygen sensitive (Kivevele and Huan, 2014).

2.3.2 Cascaded adsorption-compression hybrid heat pump drying system

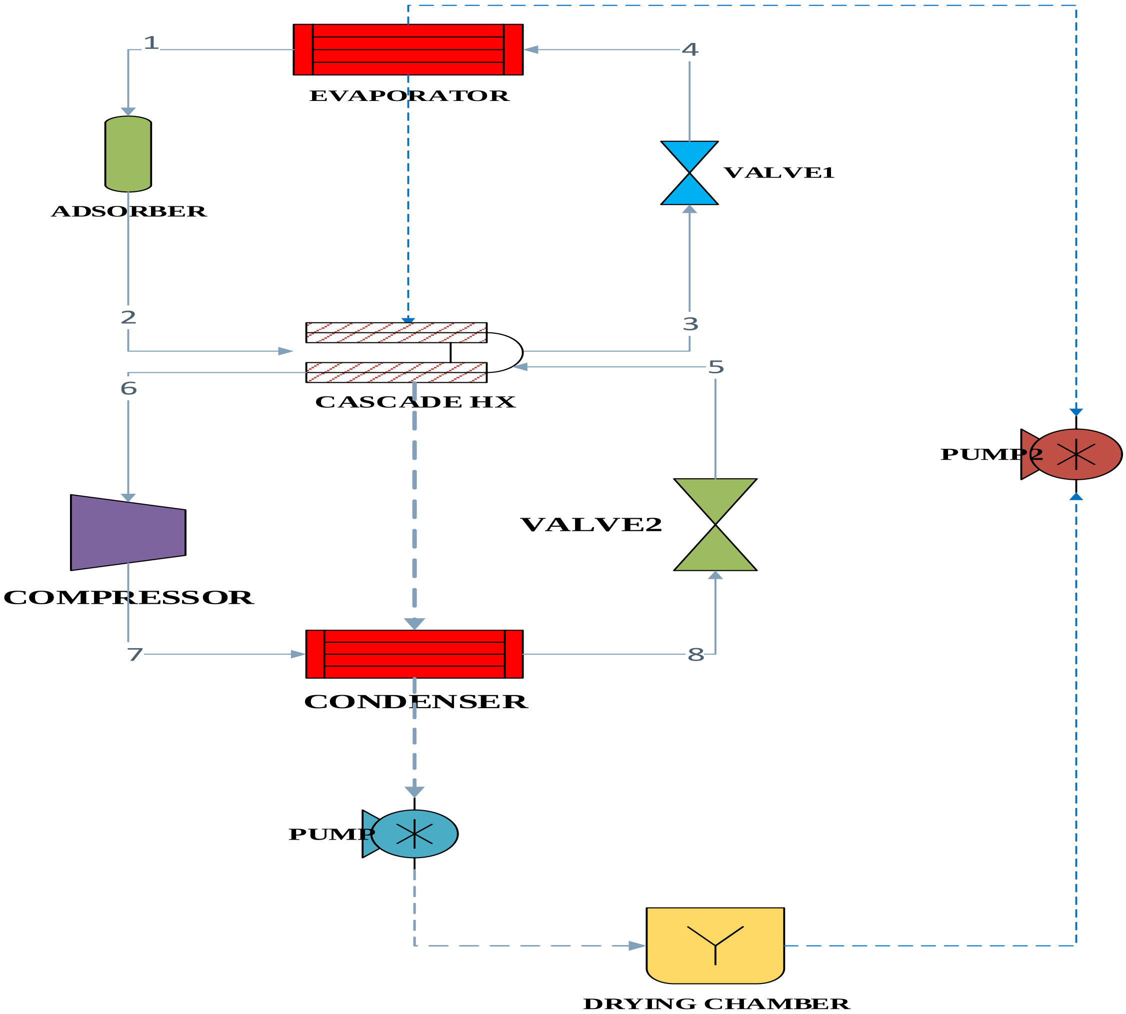

Figure 2: Schematic diagram of cascaded adsorption-compression hybrid heat pump drying system

The A HPD system consists mainly of two subsystems: cascaded adsorption-compression hybrid heat pump and a drying chamber. The working fluid in the high cycle (lower circuit) evaporates, whilst the working fluid in the low stage cycle condenses, before being mechanically compressed by the compressor and condensing during heating or heat being released for drying. For each temperature level, each circuit uses a different working fluid. This indicates that the lower temperature unit (upper circuit) uses a working fluid with a lower boiling point temperature and a higher saturation pressure at low temperatures. In a cascade heat exchanger, the temperature difference is 5 ℃ (Zhang *et al.*, 2018). Water and ethanol are used for the upper circuit and lower circuit respectively.

The working principle of closed HPDs (as shown in Figure 4) that the heat from exhausted air from the dryer that is cooled and dried is recirculated back to evaporator of the heat pump and is heated. The hot and dry air that is released from the condenser then enters the dryer and absorbs the moisture in the tomato slices placed in the dryer and becomes exhausted air at the outlet of the dryer, and the cycle repeats. Because the heat pump retrieves the heat in the exhausted air to heat the air entering the dryer while it removes the moisture in the exhausted air, it achieves a high energy efficiency in the drying of tomato slices which are thermally and oxygen sensitive (Kivevele and Huan, 2014).

Coefficient of performance for heating $COP_{heating}$ is given as shown in Equation (1) and for Carnot cycle calculated using Equation (2).

$$COP_{heating} = \frac{heating\ effect}{Work\ input} = \frac{Q_{condenser}}{W_c + QAD} \quad (1)$$

For Carnot cycle,

$$COP_{heating} = \frac{T_H}{T_H - T_C} \quad (2)$$

2.4 Exergy analysis of the hybrid heat pump drying systems

The total input exergy was calculated using Equation (3).

$$\text{Total input exergy} = \text{Wc} + Q_{evap} \left| \left(1 - \frac{To}{T_{evap}}\right) \right| + Q_{adsorber} \left| \left(1 - \frac{To}{T_{adsorber}}\right) \right| \quad (3)$$

The total exergy destruction adsorption-compression hybrid heat pump drying system is calculated using Equation (4).

$Ex_{dest,total=}$ Exdest, comp + Exdest, adsorber + Exdest, cond1+ Exdest, cond2 + Exdest, evap1+ Exdest, evap2 + Exdest, valve1+ Exdest, valve2 + Exdest, dryer (4)

The total exergy destruction is cascaded adsorption-compression hybrid heat pump drying system is calculated using Equation (5).

$Ex_{dest,total=}$ Exdest, comp + Exdest, adsorber + Exdest, cond + Exdest, cascade + Exdest, evap + Exdest, valve1+ Exdest, valve2 + Exdest, dryer (5)

The exergy efficiency of the heat pump drying system is evaluated using Equation (6).

$$\eta_{ex} = 1 - \frac{E_{xloss\ total}}{\text{Wc} + Q_{evap} \left| \left(1 - \frac{To}{T_{evap}}\right) \right| + Q_{adsorber} \left| \left(1 - \frac{To}{T_{adsorber}}\right) \right|} \quad (6)$$

The energetic coefficient of performance was calculated using Equation (7) (Soni and Gupta, 2012).

$$\text{Energetic coefficient of performance (COPex)} = \frac{\text{Qcond}_2\ (1 - \frac{To}{Tcond})}{Wad\ (1 - \frac{To}{Tads}) + Wcomp} \quad (7)$$

The specific moisture extraction rate and specific energy consumption were calculated using Equations (8) and (9) (Sannan *et al.*, 2017).

$$\text{Specific moisture extraction rate (SMER)} = \frac{Moisture\ removed\ in\ kg}{energy\ input\ in\ kwh} \quad (8)$$

$$\text{Specific Energy Consumption} = \frac{energy\ input\ in\ kwh}{moistured\ removed\ in\ kg} \quad (9)$$

3. RESULTS AND DISCUSSION

In general, the drying efficiency key factors such as specific moisture extraction rate (SMER) and specific energy consumption (SEC) of the dryer depend profoundly on drying air temperature energy input of the heat pump. Interestingly, the specific moisture extraction rate of simple adsorption-compression hybrid heat pump drying system is 0.234 kg/kWhr and specific energy consumption is 4.27 kg/kWhr. For cascaded adsorption-compression hybrid heat pump drying system, the specific moisture extraction rate is 0.457 kg/kWhr and specific energy consumption is 3.17 kg/kWhr as shown in Table 4.

The energetic coefficient of performance, and exergetic coefficient of performance and overall exergy efficiency of the system are 2.03, 15.6% and 17% respectively for simple adsorption-compression hybrid heat pump drying system. The energetic coefficient of performance, and exergetic coefficient of performance and overall exergy efficiency for cascaded adsorption-compression hybrid heat pump drying system are 2.18, 22.6% and 16% respectively. Cascaded adsorption-compression hybrid heat pump drying system has greater energetic coefficient of performance, exergetic coefficient of performance but lower overall exergy efficiency than simple adsorption-compression hybrid heat pump drying system.

Table 4: Results of simple and cascaded adsorption-compression hybrid heat pump drying system

Parameters	Cascaded Hybrid Heat Pump Drying System	Simple hybrid heat pump drying system
Specific Moisture Extraction Rate (kg/kWhr)	4.27	3.17
Specific Energy Consumption (kWhr/ kg)	0.234	0.457
Energetic coefficient of performance	2.18	2.03
Exergetic coefficient of performance (%)	22.6	15.6
Overall exergy efficiency (%)	16	17
Exergy efficiency of compressor (%)	86.31	89.97
Exergy efficiency of adsorber (%)	96.4	64.8
Exergy efficiency of evaporator1 (%)	76.19	46.7
Exergy efficiency of condenser2 (%)	36.76	24.14

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Table 3: Calculation of exergy analysis of the heat pump drying system

Compartments	Exergy Loss	Exergy loss coefficient	Exergy efficiency
condenser1	Ex2 – Ex3-$Q_{cond} \left\|\left(1-\frac{To}{T_{cond}}\right)\right\|$	$\frac{E_{\times 2} - E_{\times 3} - Q_{cond} \left\|\left(1-\frac{To}{T_{cond}}\right)\right\|}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$	$\frac{E_{X3} + Q_{cond} \left\|\left(1-\frac{To}{T_{cond}}\right)\right\|}{E_{X2}}$
condenser 2	Ex7 – Ex8 -$Q_{cond} \left\|\left(1-\frac{To}{T_{cond}}\right)\right\|$	$\frac{E_{\times 7} - E_{\times 8} - Q_{cond} \left\|\left(1-\frac{To}{T_{cond}}\right)\right\|}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$	$\frac{E_{X9} + Q_{cond} \left\|\left(1-\frac{To}{T_{cond}}\right)\right\|}{E_{X8}}$
evaporator1	Ex4 – Ex1+$Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\|$	$\frac{E_{\times 1} - E_{\times 4} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\|}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$	$\frac{E_{X1}}{E_{X4+}Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\|}$
evaporator2	Ex9 – Ex6+$Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\|$	$\frac{E_{\times 9} - E_{\times 6} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\|}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$	$\frac{E_{X6}}{E_{X9+}Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\|}$
Cascade HX	$(Ex_2 - Ex_3) - (Ex_6 - Ex_5)$	$\frac{(\mathrm{Ex2} - \mathrm{Ex3}) - (\mathrm{Ex6} - \mathrm{Ex5})}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$	$\frac{E_{X6} - E_{X5}}{E_{X2} - E_{X3}}$
compressor	$(Ex_6 - Ex_7) + W_{isentropic}$	$\frac{E_{\times 6} - E_{\times 7} + Wis}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$	$\frac{E_{x6} - E_{x7}}{Wisentropic}$
adsorber	(Ex1 –Ex2) +$Q_{adsorber} \left\|\left(1-\frac{To}{T_{ads}}\right)\right\|$	$\frac{(\mathrm{Ex1} - \mathrm{Ex2}) + Q_{adsorber} \left\|\left(1-\frac{To}{T_{ads}}\right)\right\|}{\mathrm{Ex\ Q,\ adsorber} + \mathrm{Ex\ Q,\ evap}}$	$\frac{E_{x1} - E_{x2}}{Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$
Valve1	$Ex_3 - Ex_4$	$\frac{E_{\times 3} - E_{\times 4}}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$	$\frac{E_{X4}}{E_{X3}}$
Valve2	$Ex_8 - Ex_9$	$\frac{E_{\times 8} - E_{\times 9}}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|}$	$\frac{E_{X9}}{E_{X8}}$
dryer	$(EX_{Air}^{in} + EX_{To}^{in})$ - $(EX_{Air}^{out} + EX_{To}^{out})$	$\frac{E_{xloss} dryer}{\mathrm{Wc} + Q_{evap} \left\|\left(1-\frac{To}{T_{evap}}\right)\right\| + Q_{adsorber} \left\|\left(1-\frac{To}{T_{adsorber}}\right)\right\|} -$	$\frac{\text{exergy output}}{\text{exergy input}}$

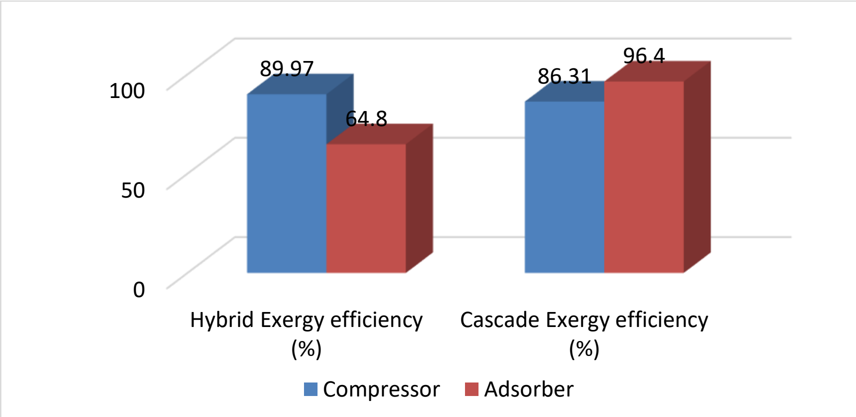

Figure 3: Exergy efficiency of adsorber and compressor

Also, the exergy efficiency of adsorber of simple adsorption-compression hybrid heat pump drying system (64.8%) is lower than that of cascaded adsorption-compression hybrid heat pump drying system (96.4%). The cascade heat exchanger which serves as the condenser for high temperature cycle and evaporator for low temperature cycle has lower exergy efficiency (19.2%) than the individual condenser and evaporator of simple adsorption-compression hybrid heat pump drying system whose exergy efficiency are 59.8% and 29.2% respectively as shown in Figure 4. In cascaded adsorption-compression hybrid heat pump drying system, the low temperature cycle and high temperature cycle operate independently and because there is higher exergy destruction (exergy loss) in the cascaded heat exchanger due to high temperature difference between the two working fluids, heat transfer and heat losses due to friction, it reduces the overall exergy efficiency of cascaded heat pump drying system.

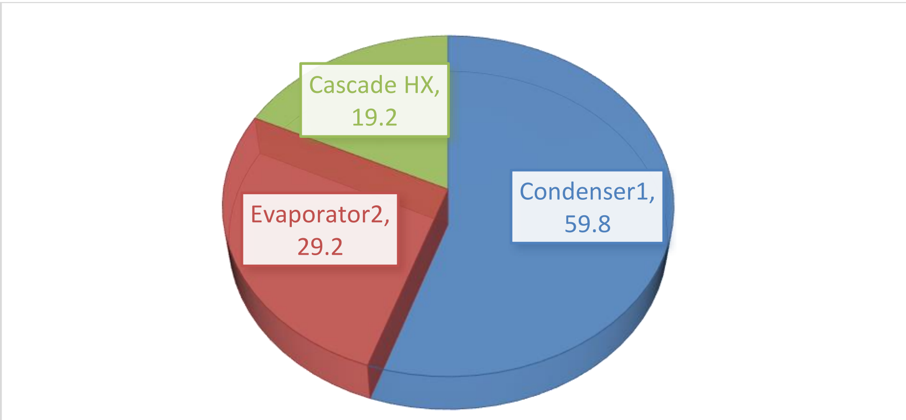

Figure 4: Exergy efficiency cascade heat exchanger of cascaded heat pump, condenser1, and evaporator2 of hybrid heat pump

Low exergy efficiencies, or large exergy losses, in particular, suggest that there is a significant margin for efficiency increase in principle. This efficiency increase requires inventiveness and innovation, as well as choices with other considerations like cost and environmental impact. The breakdown of exergy losses allows for a better understanding of the causes, locations, and magnitudes of exergy losses, allowing efficiency-improvement efforts to focus more directly on those elements likely to be producing efficiency losses.

4. CONCLUSION

The heat pump drying system modeled and simulated serves as predictive tool to determine the performance and efficiency of the drying systems and how to determine the optimum condition. The adsorption-compression cascade heat pump drying system has greater energetic coefficient of performance, exergetic coefficient of performance and overall exergy efficiency than adsorption heat pump drying system. Also, adsorption-compression cascade heat pump drying system has greater energetic coefficient of performance, exergetic coefficient of performance but lower overall exergy efficiency than adsorption-compression hybrid heat pump drying system.

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