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Thermodynamic Analysis of Modelled and Simulated Heat Pump Drying System Using Azeotropic Mixture of Organic Working Fluids

Abimbola Emmanuel ISOLA*, Michael Sunday OLAKUNLE, Adegboyega Surajudeen OLAWALE

*Department of Chemical Engineering, Ahmadu Bello University, Zaria, Nigeria

isolaabimbola28@gmail.com, msolakunle@abu.edu.ng, asolawale@abu.edu.ng

*Correspondence: isolaabimbola28@gmail.com; Tel.: +2347037624038

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Abstract: *It is well-known that the choice of working fluid significantly impacts the performance, cost estimation, and environmental effect of a heat pump. In this study, the performance of pure working fluids (dimethyl ether and ethanol) was compared with that of azeotropic mixture working fluids used in vapor compression heat pumps. The study also examined the effect of compression ratio and different compressor models on the performance of a vapor compression heat pump for heating processes and drying tomato slices at an air temperature of 40 °C and an air flow rate of 200 kg/hr. Using ethanol as the working fluid at evaporating and condensing temperatures of 10 °C and 15 °C, respectively, the specific moisture extraction rate was 0.2112 kg/kWh, and the Carnot coefficient of performance was 57.60. The study demonstrated a COP improvement of more than 15% for azeotropic mixtures compared to a pure working fluid. The maximum overall energy efficiency and exergy efficiency, achieved with Mixture II, were 5.68% and 27.32%, respectively. As suction pressure increased while maintaining constant discharge pressure, the compression ratio and work done by the compressor decreased, while the system's* $\mathrm{COP}_{\mathrm{energetic}}$, $\mathrm{COP}_{\mathrm{exergetic}}$, *overall energy efficiency, and overall exergy efficiency improved under the given conditions.*

Keywords: Coefficient of performance, overall exergy efficiency, specific moisture extraction rate, specific energy consumption, azeotropic mixture.

1. INTRODUCTION

Due to its commercial importance, tomato is one of the most scientifically studied vegetables. It is highly perishable, with post-harvest losses ranging from 25 to 50 percent. From harvesting to consumption, there is a 20–50% loss in tropical regions (Correia *et al.*, 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 are an example of such a heating technology. Heat pumps are devices that extract and transfer heat from one place to another. They are devices that, when compared to other traditional heating techniques, offer a higher efficiency and the potential to meet the needs of both an environmentally and economically sustainable future in terms of residential energy use (Arif and Kuntal, 2014). Heat pumps have long been recognized as an effective means of drying and energy recovery. During the operation, a heat pump will be used to dry the difference between the hot heat produced by the condenser and the cold heat produced by the evaporator. The hot heat produced by the condenser will be supply heat require for drying of the material (Yang, 2020).

The economic benefits resulting from high coefficient of performance (COP) value of mechanical heat pump system makes it more convenient device for heating and cooling purposes though with low primary energy efficiency (Chian *et al.*, 2011). Mixture of refrigerants give another possibility for efficient refrigerants. Studies have shown a COP improvement of more than 25% for zeotropic mixtures, compared with a pure refrigerant (Pieter and Visagie, 2008).

In this present study, the performance of pure working fluids (dimethyl ether and ethanol) was compared with azeotropic mixture working fluids and the effect of compression ratio and different compressor models on the performance of vapour compression heat pump for heating process and drying of tomatoes slices were investigated through energy analysis, exergy analysis and drying analysis using Aspen Plus simulation model**.**

Compression Heat Pump Drying System

The HPD system consists mainly of two subsystems: a compression heat pump and a drying chamber. Through the evaporator, the heat pump extracts and transfers heat from natural heat sources in the environment, industrial or residential waste, a chemical reaction, or dryer exhaust air. The heat-pump evaporator absorbs waste heat and vaporizes the heat-pump working fluid. The Closed HPD (as illustrated in Figure 1) operates on the principle that the dryer's exhaust air enters the evaporator of heat pump, where it is cooled and the moisture in the air is condensed and removed. 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 tomato slices placed in the drying chamber 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).

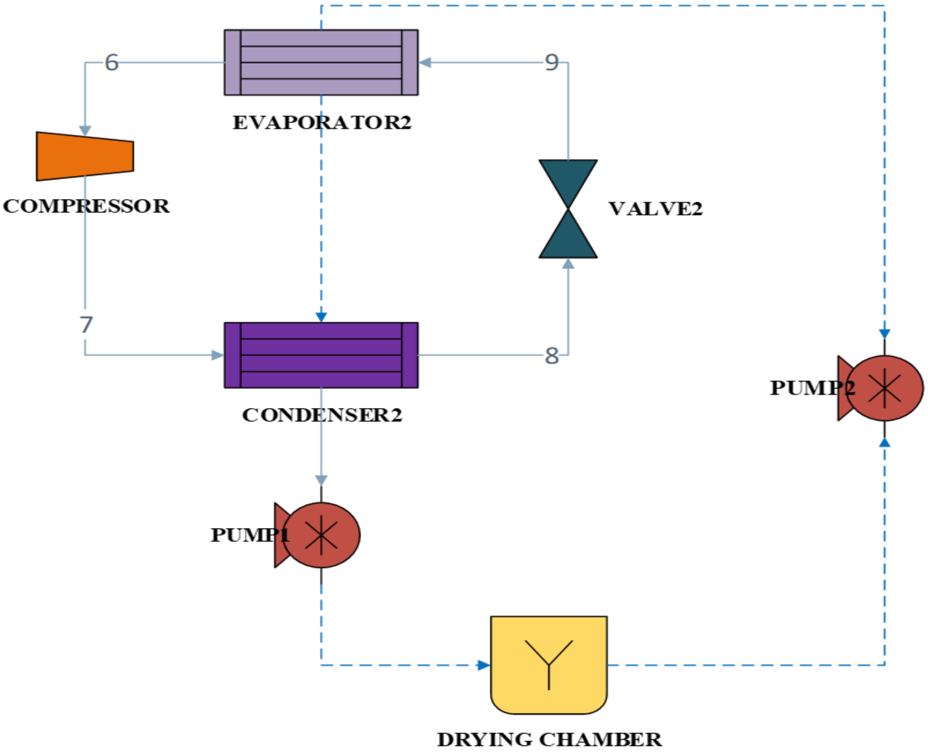

Figure 1: Schematic diagram of compression heat pump drying system

Coefficient of performance for heating COP $_{heating}$ is given as shown in Equation (1):

$$COP_{heating} = \frac{heating\ effect}{Work\ input} = \frac{Q_{condenser}}{W_{comp}} \tag{1}$$

The $Wcomp$ is calculated using Equation (2):

$$Wcomp = \frac{W\ insentropic}{\eta\ \text{isentropic}} \tag{2}$$

For Carnot cycle, Equations (3) and (4) are used.

$$COP_{heating} = \frac{T_H}{T_H - T_C} \tag{3}$$

$$\eta\ \text{Overall energy efficiency} = \frac{\text{COPenergetic}}{\text{COPCarnot}} \tag{4}$$

Equation (5) was used to calculate the percentage increase in $\text{COP}_{\text{energetic}}$

$$\text{Percentage increase in } \text{COP}_{\text{energetic}}\ (\%) = \frac{Final\ \text{COP}_{\text{energetic}} - intial\ \text{COP}_{\text{energetic}}}{Initial\ \ \text{COP}_{\text{energetic}}} \tag{5}$$

Exergy analysis and drying analysis of vapour compression heat pump drying system were calculated in Equations (6) to (10).

$$\text{Exdest, HE} = \text{Exin} - \text{Exout} \tag{6}$$

The total exergy destruction was calculated using Equation (7) (Antonijevi *et al.*, 2011):

$$\text{Ex}_{\text{dest, total=}} \text{ Exdest, comp + Exdest, cond + Exdest, evap + Exdest, valve + Exdest, dryer} \tag{7}$$

The exergy efficiency of the heat pump drying system was evaluated as shown in Equation (8):

$$\eta\text{ex} = 1 - \frac{E_{xloss\ total}}{Wcomp + \text{Ex Q, evap}} \tag{8}$$

The Exergetic coefficient of performance was calculated using Equation (9).

$$\text{Exergetic coefficient of performance} = \frac{\left(Q_{cond}\left(1 - \frac{To}{T_{cond}}\right)\right)}{Wcompression} \tag{9}$$

Specific moisture extraction rate (SMER) was calculated using Equation (10) (Sannan *et al.*, 2017).

$$\text{Specific moisture extraction rate (SMER)} = \frac{Moisture\ removed\ in\ kg}{energy\ input\ in\ kwh} \tag{10}$$

2. MATERIALS AND METHODS

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 °C. 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 drying space of the drying chamber can be increased as number of tomato slices increases. The flowrate of tomato slices and air are assumed to be 400 kg/hr. and 200 kg/hr. Flowrate of the working fluid is 2 kmol/hr. and isentropic efficiency of compressor is 85%. The exergy reference temperature and pressure were assumed to be 30 °C and 1 atm respectively. Table 1 shows the working conditions of the heat pump drying system.

Table 1: Parameters and working condition of the heat pump drying systems

Parameter	Value
Condenser temperature	15 °C
Evaporator temperature	10 °C
Pressure of compressor	700 kPa
Valve pressure	15 kPa

Table 2: Working fluids and their components

Working fluids	Mole fraction of ether	Mole fraction of ethanol
Mixture I	0.5	0.5
Mixture II	0.4	0.6
Mixture III	0.6	0.4

2.1 Tomato Components

The main components of tomato are their percentage composition are shown in Table 3.

Table 3: 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

3. RESULTS AND DISCUSSION

Using ethanol as working fluid at 700 kPa discharge pressure of compressor and 15 kPa valve pressure

$$\text{Specific Moisture Extraction Rate (SMER)} = \frac{moistured\ removed}{Qsupplied} = \frac{Mw}{Wcomp}$$

$$SMER = \frac{1.81269\ kg/hr}{8.5828\ kW} = 0.2112\ kg/kWhr$$

Figure 2 shows the performance and energy efficiency of heat pump drying system using different working fluids. Figure 3 shows the exergy efficiency of different working fluids used in heat pump drying system. Table 4 shows the energy and exergy analysis.

Table 4: Results of energy and exergy analysis

S/N	Parameters	Ether	Ethanol	Mixture I	Mixture II	Mixture III
1	Qevap (kW)	15.01730	24.1914	18.6331	19.5472	17.793
2	Qcond (kW)	21.4842	31.4866	25.4098	26.4052	24.4962
3	Wisentropic (kW)	6.4670	7.2952	6.7767	6.85788	6.70321
4	$\mathrm{COP_{energetic}}$ (%)	2.82	3.67	3.19	3.27	3.11
5	Percentage increase in $\mathrm{COP_{energetic}}$ (%)	-	-	13.12	15.96	10.28
6	$\mathrm{COP_{energetic}}$ (%)	14.69	19.11	16.61	17.03	16.20
7	Overall energy efficiency of the system (%)	4.90	6.37	5.54	5.68	5.40
8	Exergy destruction of condenser (kW)	2.1537	5.3108	3.3098	3.6219	3.0296
9	Exergy destruction of evaporator (kW)	3.3210	1.2976	2.6172	2.41316	2.7975

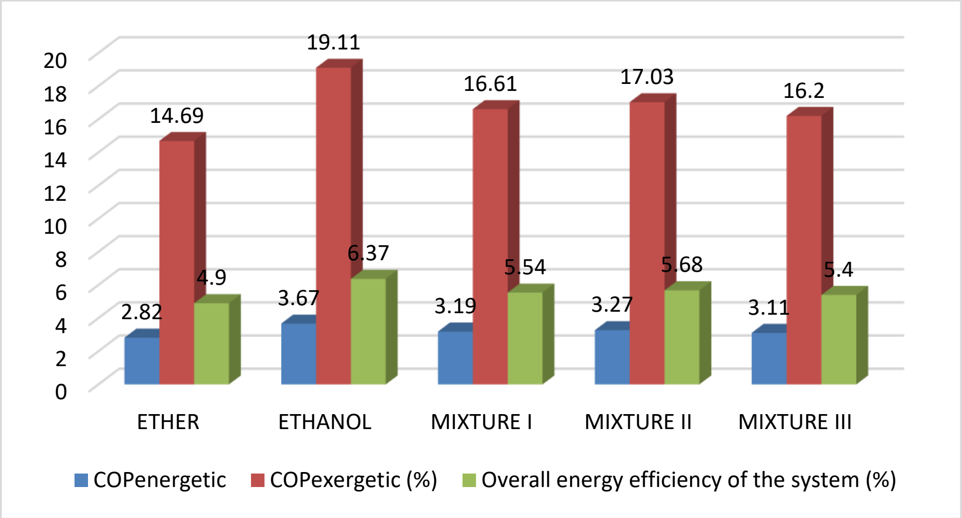

Figure 2: Performance and energy efficiency of heat pump drying system using different working fluids

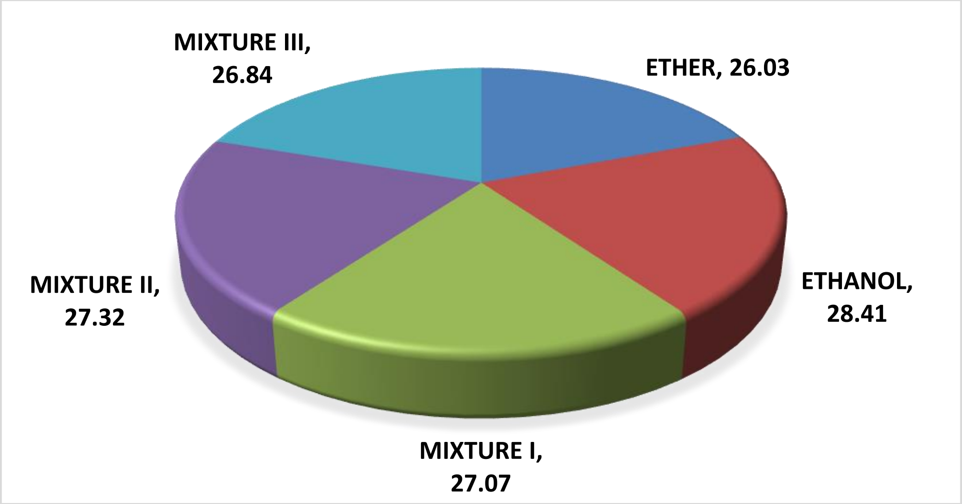

Figure 3: Exergy efficiency of different working fluids used in heat pump drying system

Results of energy and exergy analysis for different compression ratio and compressor models using diethyl-ether as working fluid at 700 kPa discharge pressure of compressor and 120 kPa valve pressure are shown in Tables 5 and 6.

Table 5: Energy and exergy analysis results for different compression ratio

S/N	Parameter	Value				
1	Suction pressure (kPa)	120	140	160	180	200
2	Compression Ratio	5.83	5.00	4.38	3.89	3.50
3	W_c (kW)	1.4920	1.3364	1.2038	1.0888	0.9876
4	$COP_{energetic}$	5.83	6.39	6.99	7.62	8.30
5	$COP_{energetic}$ (%)	30.2	33.3	36.4	36.4	43.21
6	Overall energy efficiency of the system (%)	10.12	11.09	12.14	13.22	14.40
7	Overall exergy efficiency of the system (%)	33.3	34.5	35.5	36.7	33.27

Table 6: Energy and exergy analysis results for different compressor models

S/N	Parameter	Polytropic using ASME method	Isentropic using ASME method
1	Q_{cond} (kW)	16.78	16.4019
2	W_c (kW)	6.506	5.9809
3	$COP_{energetic}$	2.58	2.74
4	$COP_{energetic}$ (%)	13.44	14.28

S/N	Parameter	Polytropic using ASME method	Isentropic using ASME method
5	Overall energy efficiency of the system (%)	4.48	4.83
6	Overall exergy efficiency of the system (%)	36.36	36.93
7	Exergy efficiency of condenser (%)	23.14	23.52
8	Exergy efficiency of compressor (%)	78.30	81.77
9	Exergy efficiency of evaporator (%)	25.23	25.23
10	Exergy efficiency of valve (%)	51.05	51.05
11	Exergy efficiency of dryer (%)	96.00	98.00

The selection of working fluid, operating conditions and system configuration and design are the major factors that influence the performance of heat pump drying system. Though they usually suffer chemical deteriorations and decomposition at high temperatures; organic working fluids which are environmentally friendly and economical such as ethanol and dimethyl ether are capable of producing highly efficient and better performance as natural working fluids. Mixture of working fluids give another possibility for more efficient working fluid. This research has shown a COP improvement of more than 15% for azeotropic mixtures, compared with a pure working fluid. As amount of ethanol presents in the mixture increases, $\mathrm{COP_{energetic}}$, $\mathrm{COP_{exergetic}}$, overall energy efficiency of the system and overall exergy efficiency of the system at the given conditions also increase. Mixture II gives better performance and its more efficiency than pure working fluid (ether) and other mixtures. This does not only improve the performance and efficiency of the heat pump drying system but it also harnesses the advantage of the properties of the constitutents of the mixture (ether and ethanol) such as non-toxicity, non-flammability, easily and cheaply available, zero ozone layer depletion potential, low global warming potential and chemical stability.

The exergy loss in the condenser can be reduced by adopting condenser type of higher coefficient of heat transfer or by removing any scale and heat resistance pipe (Bingje *et al.*, 2015). To reduce exergy losses in evaporator and condenser, enlargement of the surface area and the use of a very good conductive material with high coefficient of heat transfer is a good recommendation. When the pressure of the compressor is high, double stage compressor can be adopted which reduces the inlet temperature and exergy loss and the exergy loss of expansion valve is by using electronic expansion valve which has wider range of flow regulation than thermal expansion valve and can be adapted to the large variation of systematic operation conditions.

Model Validation

In the study: investigation of drying kinetics of tomato slices by using closed loop heat pump dryer by Coskun *et al.* (2016), tomato slices were dried at three different drying air temperatures (35, 40 and 45 °C) and at 1 m/s air velocities by using a closed loop heat pump dryer (HPD) at the end of drying process, the highest mean specific moisture extraction ratio and coefficient of performance of HPD system were obtained as 0.324 kg/kWh and 2.71, respectively.

4. CONCLUSION

The simulation methodology, incorporating comprehensive energy, exergy, and drying analysis, was introduced and used as a predictive tool to assess the performance and efficiency of a drying system. Both experimental and assumed data were utilized in this analysis. Key metrics such as exergy destruction, energy efficiency, exergy efficiency, and drying efficiency of the entire heat pump drying system were evaluated and quantified. The $\mathrm{COP_{carnot}}$ of the system under specified conditions is 57.60. This study demonstrated a COP improvement of over 15% for azeotropic mixtures compared to a pure organic working fluid. The specific moisture extraction rate (SMER) of the drying system under given conditions is 0.2112 kg/kWhr, indicating good drying efficiency. As the ethanol content in the mixture increases, the system's $\mathrm{COP_{energetic}}$, $\mathrm{COP_{exergetic}}$, overall energy efficiency, and overall exergy efficiency also increased. Concurrently, exergy losses in the condenser and valve increased, while those in the evaporator and compressor decreased. The maximum overall energy efficiency and exergy efficiency were 5.68% and 27.32% respectively, which was achieved with Mixture II. The isentropic process using the ASME method yields a 6.20% higher $\mathrm{COP_{energetic}}$ and $\mathrm{COP_{exergetic}}$, than the polytropic process using the ASME method. Additionally, the isentropic process provided a 5.88% higher overall energy efficiency of the system compared to the polytropic process. An increase in suction pressure at constant discharge pressure led to a decrease in compression ratio and compressor work. Consequently, the system's $\mathrm{COP_{energetic}}$, $\mathrm{COP_{exergetic}}$, overall energy efficiency, and overall exergy efficiency increased. Although organic working fluids like ethanol and dimethyl ether can degrade chemically at high temperatures, they are environmentally friendly, economical, and capable of achieving high efficiency and performance, rivalling natural working fluids.

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