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Modelling and Simulation of Chemical Adsorption Heat Pump for Drying and Heating Applications

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: *The performance of a chemical adsorption heat pump drying system is largely influenced by the selection of working fluid, operating conditions, and system configuration and design. In this study, tomato slices were dried at five different air temperatures (35 °C, 40 °C, 45 °C, 50 °C, and 55 °C) with a tomato slice flow rate of 400 kg/hr and an air flow rate of 200 kg/hr using a modelled and simulated chemical adsorption heat pump drying system. Four adsorbent-adsorbate pairs were used: magnesium chloride-methanol, calcium chloride-ethanol, calcium chloride-water, and aluminium trifluoride-dimethyl ether, at evaporating and condensing temperatures of 10 °C and 15 °C, respectively. The specific moisture extraction rate ranged from 0.116 kg/kWh to 0.149 kg/kWh. The coefficient of performance (COP) of the heat pump drying (HPD) system ranged from 0.960 to 0.987, and the overall exergy efficiency at the highest ambient air temperature (30 °C) ranged from 3.84% to 20.29%. Exergy analysis of the system's components revealed that the condenser and evaporator contributed significantly to exergy destruction, exhibiting low exergy efficiency.*

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

1. INTRODUCTION

Tomatoes have a high-water content of 93–95 percent. It is highly perishable, with post-harvest losses ranging from 25 to 50 percent (Correia *et al.*, 2015). Drying is simultaneous heat and mass transfer process through which moisture is removed or reduced from a material. The basic objective of drying is to remove water from the material so as to preserve it and the consequent limitation of microbial activity, longer shelf-life and significant reducing of the volume of finish products (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. 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 utilization of waste heat as a driving energy in an adsorption heat pump not only recovers energy that would otherwise be wasted, but also provides a system with low operating costs. Thermally driven heat pumps can use renewable energy sources such as solar, waste heat and geothermal energy (Chian *et al.*, 2011). In this present study, the performance and efficiency of chemical adsorption heat pump for heating process and drying of tomatoes slices (using four adsorbent-adsorbate pairs) and the drying efficiency at different drying air temperatures were evaluated through energy analysis, exergy analysis, and drying analysis by Aspen Plus simulation model.

2. METHODOLOGY

2.1 Modelling of CSTR adsorber in Aspen Plus

Below are the given steps for modeling CSTR adsorber using Aspen Plus:

a. Specify the operating condition (temperature, pressure, volume and valid phase of the reactor), specify the adsorption kinetics (n (order of reaction), k (kinetic rate reaction constant), e (activation energy), and t (reaction temperature and reaction equation and state). Driving force, concentration exponent and specify the adsorption equilibrium (temperature approach to equilibrium and reacting phase).
b. Specify Generalized-Langmuir-Hinshelwood-Hougen-Watson adsorption parameters (adsorption exponents, adsorption constant, concentration exponent).

Table 1 shows the kinetic parameters of common chemisorption adsorbent-adsorbate pairs.

Table 1: Kinetic parameters obtained from the reaction of the adsorbent-adsorbate pairs for modelling chemisorption adsorber using CSTR reactor (Korhammer *et al.*, 2016; Korhammer *et al.*, 2019)

Parameter	$CaCl_2$- C_2H_5OH	$MgCl_2$- CH_3OH	$CaCl_2$- H_2O	$AlCl_3$- $C_4H_{10}O$
Adsorber pressure (kPa)	680	700	1000	800
Adsorber temperature (°C)	180	120	150	130
k (mg/min)	0.14	0.12	0.18	0.08
n	2	1	2	1
Reaction time(min)	27	33	34	20
$E_{a, ads}$(kJ/mol)	50	46	45	38

2.2 Adsorption Hybrid Heat Pump Drying System

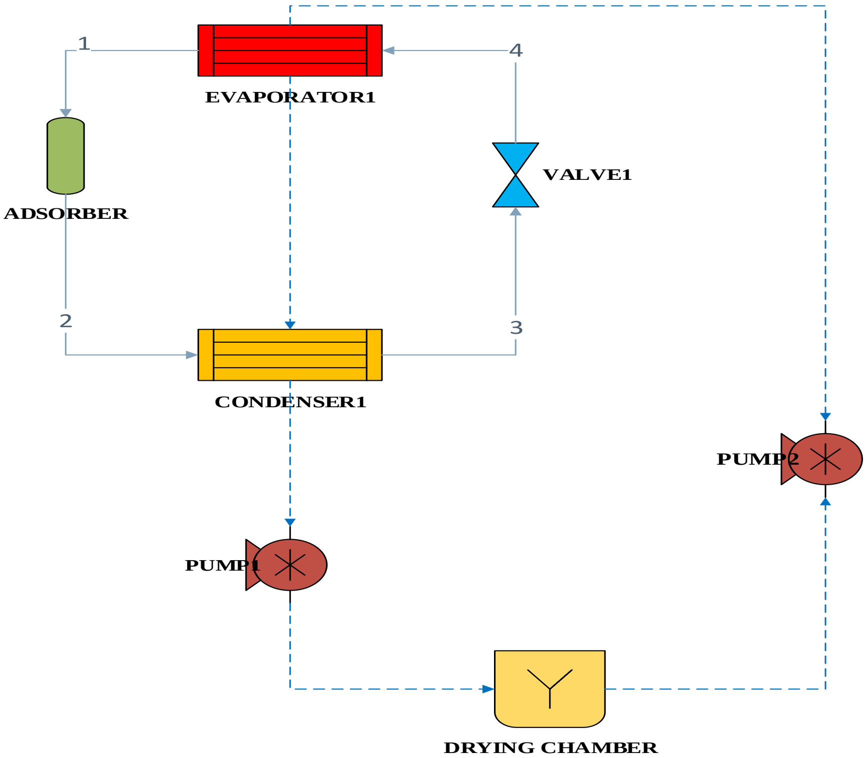

Figure 1: Schematic diagram of adsorption heat pump drying system

Through the adsorber and evaporator, the heat pump extracts and transfers heat from the surrounding air, industrial or home waste, or dryer exhaust air. The heat pump drying system is made up of a heat pump (which includes an adsorber, condenser, expansion valve, and evaporator), a dryer, and air cycling circuits that connect the heat pump and the dryer (Figure 1). Closed HPD (as illustrated in Figure 1) operates on the principle that the exhaust air from the dryer enters the evaporator of the 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, dry air then enters the dryer, absorbs the moisture in the tomato slices in the drying chamber, and exits the dryer as exhausted air, and the cycle repeats. The heat pump provides a high energy efficiency in the drying of tomato slices that are thermally and oxygen sensitive because it retrieves the heat from the exhausted air to heat the air entering the dryer while removing the moisture from the exhausted air (Kivevele and Huan, 2014).

Coefficient of performance for heating ($COP_{heating}$) is given as shown in Equations (2) and (3):

$$COP_{heating} = \frac{heating\ effect}{Work\ input} = \frac{Q_{condenser}}{W_{ad}} \quad (1)$$

For Carnot cycle,

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

2.3 Exergy Analysis of Chemical Adsorption Heat Pump Drying System

The exergy destruction was calculated using Equation (3) (Antonijevi *et al.*, 2011) and exergy efficiency using Equation (4).

The exergy destruction $Exdest, HE = Exin - Exout$ (3)

$$\text{Exergy efficiency} = \frac{net\ output\ exergy\ flow}{net\ input\ exergy\ flow} \quad (4)$$

The total exergy destruction was calculated using Equation (5):

$Ex_{dest,\ total} =$ Exdest, comp + Exdest, cond + Exdest, evap + Exdest, valve + Exdest, dryer (5)

The exergy efficiency of the heat pump drying system was evaluated using Equation (6):

$$\eta_{ex} = 1 - \frac{E_{xloss\ total}}{Wcomp + Ex\ Q,evap} \quad (6)$$

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

$$\text{Exergetic coefficient of performance} = \frac{\left(Q_{cond}\left(1 - \frac{To}{T_{cond}}\right)\right)}{Wcompression} \quad (7)$$

Table 2 shows the exergy calculation of the components used.

Table 2: Calculation of exergy parameters of the components

Compartments	Exergy Loss	Exergy efficiency
Condenser	$Ex7 - Ex8 - Q_{cond} \left\lvert \left(1 - \frac{To}{T_{cond}}\right) \right\rvert$	$\frac{E_{X8} + Q_{cond} \left\lvert \left(1 - \frac{To}{T_{cond}}\right) \right\rvert}{E_{X3}}$
Evaporator	$Ex9 - Ex6 + Q_{evap} \left\lvert \left(1 - \frac{To}{T_{evap}}\right) \right\rvert$	$\frac{E_{X6}}{E_{X9} + Q_{evap} \left\lvert \left(1 - \frac{To}{T_{evap}}\right) \right\rvert}$
Adsorber	$(Ex_1 - Ex_2) + Q_{adsorber} \left\lvert \left(1 - \frac{To}{T_{ads}}\right) \right\rvert$	$\frac{E_{x1} - E_{x2}}{Q_{adsorber} \left\lvert \left(1 - \frac{To}{T_{adsorber}}\right) \right\rvert}$
Valve	$Ex_8 - Ex_9$	$\frac{E_{X9}}{E_{X8}}$
Dryer	$(EX_{Air}^{in} + EX_{To}^{in}) - (EX_{Air}^{out} + EX_{To}^{out})$	$\frac{\text{exergy output}}{\text{exergy input}}$

2.4 Drying Analysis of Chemical Adsorption Heat Pump Drying System

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

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

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

2.5 Properties of Tomato Components

The main components of fresh tomato are protein, crude fibre, ascorbic acid, phenolic compound, moisture, carotene and antioxidant (lycopene). The main components of tomato and their percentage composition are shown in the 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

2.6 Simulation Methodology

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 3.

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 flowrate of tomato slices and air are assumed to be 400 kg/hr. and 200 kg/hr. Flowrate of the working fluid is 1kmol/hr. and isentropic efficiency of compressor is 85%. The exergy reference temperature and pressure were assumed to be 30 °C and 1 atm respectively. Magnesium chloride-methanol, calcium chloride-ethanol, calcium chloride-water and aluminium trifluoride -dimethyl ether

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were used as adsorbent-adsorbate pair for adsorption heat pump drying system.

3. RESULTS AND DISCUSSION

Table 4 shows the results of energy analysis, exergy analysis and drying analysis.

Table 4: Results of energy analysis, exergy analysis and drying analysis

S/N	Parameters	$CaCl_2$-C_2H_5OH	$CaCl_2$-H_2O	$MgCl_2$-CH_3OH	$AlCl_3$-C_4H_{10}
1	Specific moisture extraction rate (kg/kWhr)	0.116	0.280	0.282	0.149
2	Specific energy consumption (kWhr/kg)	2.49	2.37	2.45	2.28
3	Pressure ratio	3.40	3.33	2.00	6.67
4	$COP_{energetic}$	0.987	0.960	0.957	0.980
5	$COP_{energetic}$ (%)	15.5	17.6	21.8	20.57
6	Exergy efficiency of condenser (%)	24.51	42.9	52.17	33.19
7	Exergy efficiency of evaporator (%)	93.85	6.47	94.24	93.94
8	Exergy efficiency of compressor (%)	64.78	43.05	44.52	64.72
9	Exergy efficiency of dryer (%)	98	97	95	96
10	Exergy efficiency of valve (%)	65.23	69.25	75.66	55.22
11	Overall exergy efficiency of the system (%)	15.4	3.84	20.14	20.29

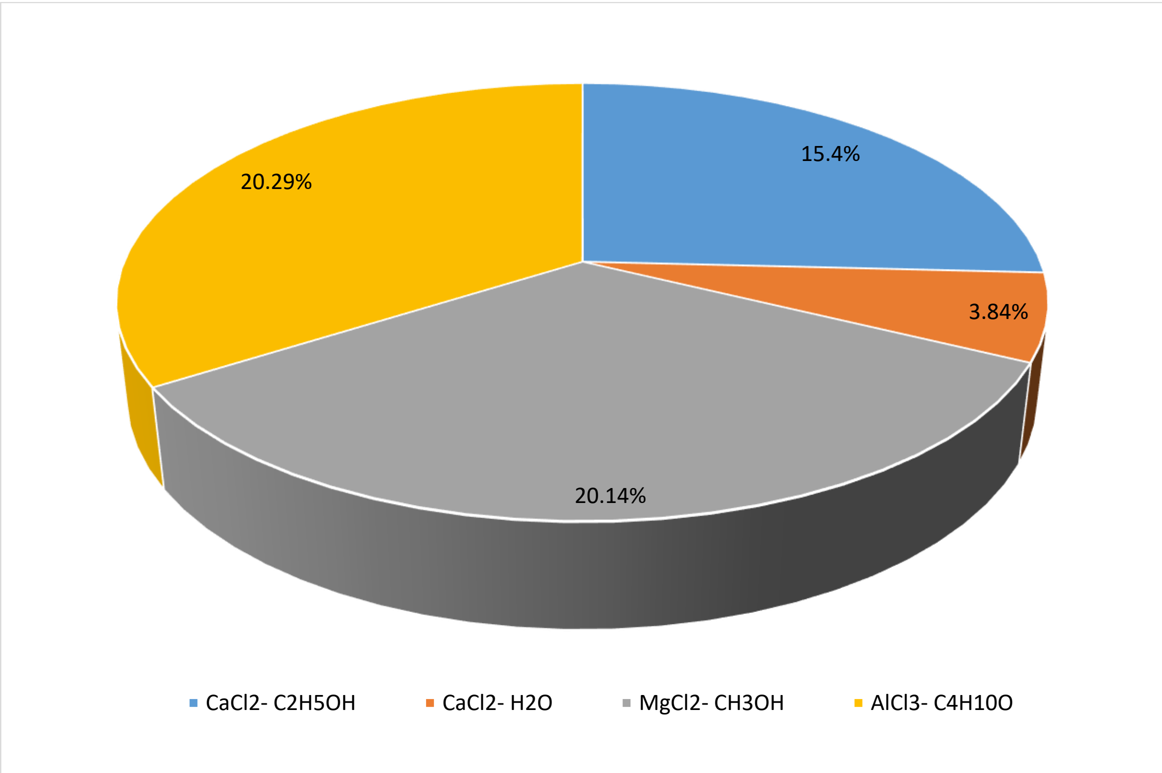

Figure 1: Overall exergy efficiency for four working fluids

Table 5 gives the results of varying drying air temperature on the drying efficiency using calcium chloride-ethanol as adsorbent-adsorbate pair at 680 kPa and 180 °C adsorber temperature and pressure respectively and 120 kPa valve pressure.

Table 5: Effect of drying air temperature on drying efficiency using Calcium chloride-ethanol, as adsorbent-adsorbate pair for adsorption heat pump drying system

Air Temperature (°C)	Water Removed (kg/hr)	SMER (kg/kWhr)	SEC (kWhr/kg)
35	0.18489	0.0994	10.060
40	0.19840	0.1067	9.3721
45	0.21192	0.1140	8.7719
50	0.22539	0.1212	8.2501
55	0.23882	0.1284	7.7862

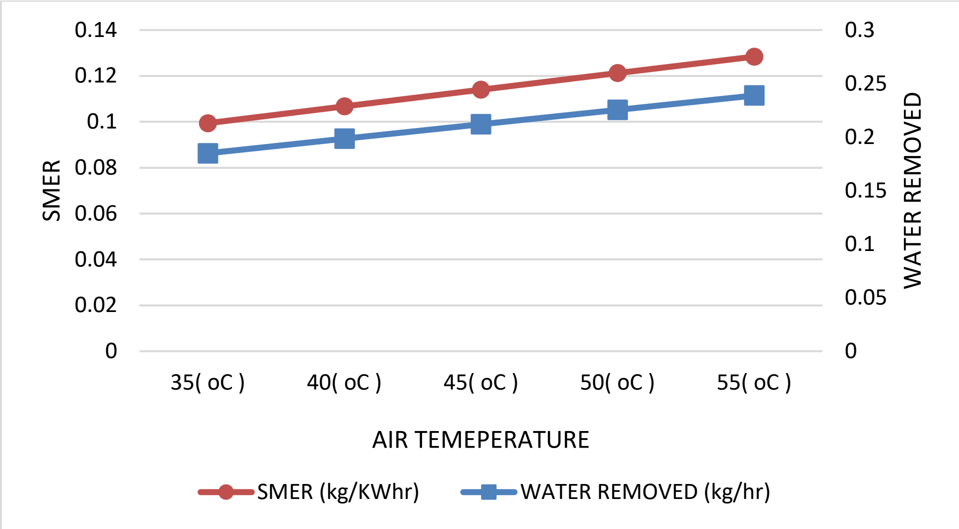

Figure 2: Effect of drying air temperature on specific moisture extraction rate (drying efficiency)

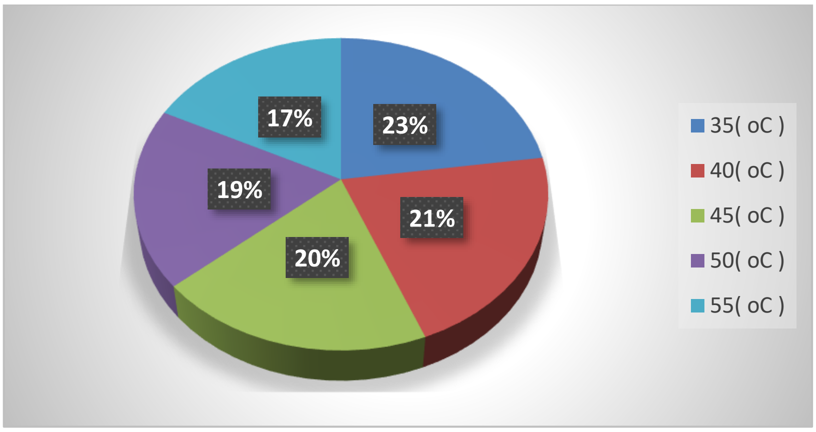

Figure 3: Effect of drying air temperature on specific energy consumption

Table 4 shows that the selection of working fluid, operating conditions and system configuration and design are the major factor that influence the performance of chemical adsorption heat pump drying system. Also, the low value of overall exergy efficiency was 3.84% as shown Figure 1 is due to energy lost in the components of the system as result of pressure drop arising from phase change, the temperature difference between working fluid and heated environment, heat transfer and heat losses due to friction. 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. Interestingly, the specific moisture extraction rate of the drying process increased significantly from 0.0994 kg/kWhr to 0.1284 kg/kWhr as the drying air temperature increases (from 35 °C, to 55 °C) as shown in Table 5. The higher the drying air temperature, the faster the rate of evaporation and the greater the amount of water removed from the slices of tomatoes as shown in Figure 2. Figure 3 shows that as the drying air temperature increases by unit of 5 °C, the percentage increase in the specific energy consumption is between 1% to 2%. The nutritional quality of tomatoes decreases as drying temperature increases. Nutrients retention occurred at low temperature treatments, but not at higher temperature. Maximum nutrients and flavours are retained in tomatoes at 42 °C (Correia *et al.*, 2015). Thus, the drying air temperature must be controlled to meet product requirements.

4. CONCLUSION

The drying efficiency and performance of the heat pump drying system were evaluated under varying air temperature conditions using the Aspen Plus (Version 10) simulation program, thermodynamic models, energy analysis, exergy analysis, and drying analysis. The simulation methodology employed energy, exergy, and drying analysis as predictive tools to assess the performance and drying efficiency of the system under specified conditions. Both experimental and assumed data were used in the analysis.

This study demonstrated that the interactions between the physical or chemical properties of adsorbents and adsorbates, along with the types of adsorbent-adsorbate pairs, significantly influence the performance of the adsorption heat pump drying system. Additionally, system design and operating conditions impacted the system's performance. The specific moisture extraction rate ranged from 0.116 kg/kWh to 0.149 kg/kWh. An increase in drying air temperature led to a higher specific moisture extraction rate and a corresponding decrease in specific energy consumption. The energetic coefficient of performance of the HPD system ranged from 0.960 to 0.987. The overall exergy efficiency at the highest ambient air temperature (30 °C) ranged from 3.84% to 20.29%. The low overall exergy efficiency and low exergetic coefficient of performance are likely due to pressure drops caused by working fluid flow, the temperature gradients needed for heat transfer, or heat losses due to friction.

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