Exergy Analysis of Heat Pump Dryer

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Abstract. *Exergy analysis was based on five components; exergy calculation of the drying medium cycle, vaporization at ginger and evaporator, refrigeration cycle and electricity. Drying medium temperature plays the important role in calculation of exergy, therefore the measured inlet and outlet temperatures for the system was used for the drying medium cycle exergy calculation. The inlet and outlet refrigerant temperatures were used for exergy calculation of the refrigeration cycle based on the R-22 pressure-enthalpy diagram. The refrigerant was cycled through evaporator to compressor, condenser and expansion valve. Exergy of the electricity was found from the energy irrespective of drying time at heater, compressor and blower: only system exergy inflow was considered. Exergy inflow, outflow and loss were determined for the whole system and exergy efficiency then calculated. Ginger drying by 50˚C air had the highest exergy efficiency at 28 %, followed with 60˚C air at 24 %.*

Keywords: Availability, exergy efficiency, ginger, irreversibility

1. Introduction

Drying is an important process for preserving agricultural products: it reduces the moisture content to a level that allows safe storage over an extended period [1]. It is an energy-intensive operation consuming 9-25% of national energy in the developed countries [2]. Agricultural products could be dried by many types of dryers such as electrical resistance dryer, conventional hot air dryer, fluidized bed dryer and heat pump dryer.

Energy savings of about 40% were reported using heat pump dryers as compared to electrical resistance dryers [3]-[4]. The heat pump drying technology is suitable for high value products. Its ability to produce controlled transient drying conditions in terms of temperature, humidity and air velocity has been investigated in order to improve product quality and reduce drying cost [5]. Many researchers have agreed on using heat pump dryer help improve drying quality and produce a range of precise condition [6]-[7].

Exergy is defined as the maximum amount of work as it comes to equilibrium with a reference environment. Exergy is consumed or destroyed, due to irreversibilities in any process. Exergy analysis is usually aimed to determine the maximum performance of the system and identify the sites of exergy destruction [8]. Using the second law of thermodynamics, the exergy analysis, is useful to identify the location, magnitude and sources of exergy destruction [9]. In this study, exergy analysis by heat pump dryer to dried agricultural product could be investigated to access the exergy flow and increment of exergy efficiency.

2. Experimental Setup

The closed system of the heat pump dryer consisted of R22 refrigerant, a 0.5 m x 0.5 m x 1.0 m drying chamber and its air velocity was measured at 0.4 m/s using hot-wire anemometer. It was operated for ginger drying at the Faculty of Engineering, Mahasarakham University.

The fresh mature ginger (*Zingiber officinale*) from a Mahasarakham market was cleaned with water and sliced into 3 mm sizes. The 100 ± 0.01 g weight was used for determine initial moisture content by the oven method at 103˚C for 72 h. A sample of 1000 ± 0.02 g was weighed using digital weight measurement instrument (Explorer).

The 50 ±1 ˚C inlet air drying temperature at the drying chamber was investigated to observe the drying efficiency. Drying medium temperatures were measured using Chromel alumel type T and MX-100 in the range of -200 to 1100 ±0.2 ˚C of Data logger at the inlet and outlet of the drying chamber, evaporator, internal condenser and heater. Power and electric current of compressor and blower were measured using power meter and Clip-on meter. The sample was dried for 200 min. The inlet drying medium temperatures was varied for 60 and 70˚C. These same experiments were run for nitrogen. There were duplicate test.

Ginger drying was investigated for exergy analysis. The closed system heat pump dryer consists of a drying medium cycle and a refrigerant cycle. The input energy from the condenser to the drying medium was extracted from water in the evaporator. The total input energy, drying rate and specific moisture extraction rate are readily computed. A schematic diagram of the proposed dryer is shown in Fig. 1.
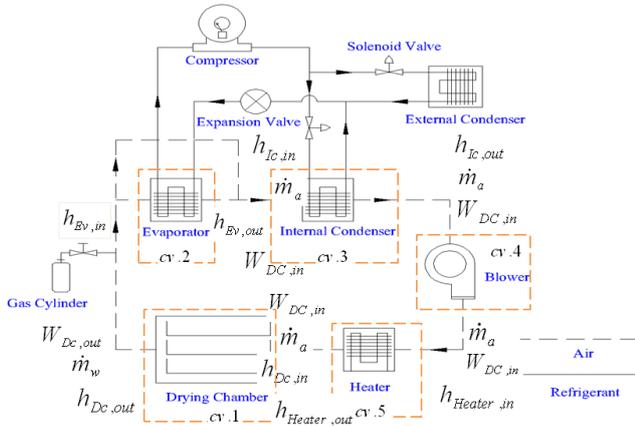

Fig. 1: Schematic diagram of the closed system heat pump dryer

3. Exergy analysis of heat pump dryer

Exergy analysis could be done base on seven parts; the exergy calculation of the drying medium cycle, vaporization at ginger and evaporator, refrigeration cycle and electricity. The reference temperature of 0 °C or 273.15 K was used. Then exergy loss of the whole system was determined. Finally, exergy efficiency was computed.

3.1 Exergy of drying medium cycle

Drying medium temperature play the important role in calculation of exergy, therefore the measured inlet and outlet temperatures at the apparatus exactly used for exergy calculation of the drying medium cycle. The drying medium passed heater through drying chamber, evaporator and internal condenser then cyclical flow. Exergy inflow and outflow were determined using Eq. (1) which the specific heat was found from the tables of properties of air and nitrogen at 1 atm pressure [10].

$$Ex = \dot{m} \cdot C_p \left[(T - T_0) - T_0 \ln \frac{T}{T_0} \right] \qquad (1)$$

3.2 Exergy of vaporization at ginger

Exergy of vaporization at ginger was found using Eq. (1). The evaporated mass flow rate was considered and assumed to use specific heat of the 78% water content of

potato which was 3.45 kJ/kg K. The average temperature of the drying chamber inlet and outlet were used for the ginger temperature. Moreover, there was assumed that only the exergy inflow of ginger.

3.3 Exergy of vaporization at evaporator

Exergy of vaporization at evaporator was found using Eq. (2), unlike the exergy of vaporization at ginger, which the average temperature between the inlet and outlet of evaporator. The table of properties of saturated water was used for the enthalpy and entropy values. Moreover, there was assumed that only the exergy outflow of exergy of vaporization at evaporator.

$$Ex = \dot{m} \left[(h - h_0) - T_0 \left(\frac{s}{s_0} \right) \right] \qquad (2)$$

3.4 Exergy of refrigerant cycle

The inlet and outlet refrigerant temperatures at the apparatus were used for exergy calculation of refrigeration cycle using Eq. (2) dealing with the R-22 P-h diagram. The refrigerant flowed from evaporator to compressor, condenser and expansion valve then cyclical flow.

However, in this dissertation the exergy of condenser were considered into two elements; external and internal condensers using Eq. (1) with assume half mass flow rate of refrigerant from evaporator each. Moreover, exergy at expansion valve was ignored since it already in a part of the exergy loss of the whole system.

3.5 Exergy of the electricity

Exergy of the electricity consists of exergy at heater, compressor and blower. Absolutely, it was considered as there was only the exergy inflow of these input apparatus. Exergy of the electricity at heater, compressor and blower could be found from Eq. (3)-(5).

$$Ex_h = \sqrt{3} \cdot I \cdot V \cos \theta \qquad (3)$$

$$Ex_{bl} = \sqrt{3} \cdot I \cdot V \cos \phi \cdot \eta_{bl} \cdot \eta_m \qquad (4)$$

$$Ex_{Comp} = I \cdot V \cos \phi \qquad (5)$$

3.6 Exergy loss

When exergy inflow and outflow were found using Eq. (6)-(7), exergy loss was determined using Eq. (8).

$$Ex_{El,in} = \sum Ex_{in} \tag{6}$$

$$Ex_{El,out} = \sum Ex_{out} \tag{7}$$

$$Ex_l = Ex_{El,in} - Ex_{El,out} \tag{8}$$

3.7 Exergy efficiency of the whole system

Exergy inflow of the whole system were found using Eq. (9). Since exergy loss was already found, exergy efficiency was determined using Eq. (10).

$$Ex_{WS,in} = Ex_H + Ex_{Comp} + Ex_{Bl} \tag{9}$$

$$\varepsilon = \frac{Ex_{WS,in} - Ex_l}{Ex_{WS,in}} \times 100 \tag{10}$$

4. Results and Discussion

Exergy inflow and outflow were calculated. However, exergy of vaporization at ginger was added to exergy inflow of drying chamber. Moreover, exergy outflow of internal condenser was added to exergy inflow of blower. Then exergy loss was computed.

4.1 Exergy inflow

From Table 1, It was found that the major component with highest exergy inflow was electrical heater. The exergy inflow of air in heater increased from 2.842 to 3.027 kW for 50 to 70°C of ginger drying because of the increase of air drying temperature. Total Exergy inflow increased from 5.706 to 6.848 kW for 50 to 70°C of ginger drying in air.

It was showed that exergy inflow increased with the increase of drying medium temperature due to the increase of exergy of electricity in heater which was the main value of exergy inflow. This result was similar to the sliced of potato for tray dryer and pumpkin for convective cyclone type dryer at 60, 70 and 80 °C drying air temperature in 1 m/s drying air velocity [11].

4.2 Exergy outflow

Total exergy outflow of ginger drying in a closed system heat pump dryer is shown in Table 2. Total exergy outflow increased from 2.781 to 3.391 kW for 50 to 70°C of ginger drying in air It was showed that exergy outflow increased with the increase of drying medium temperature, like exergy inflow. Compressor was the main component which resulted in highest exergy outflow.

Table 1: Exergy inflow of ginger drying in a closed system heat pump dryer

Apparatus	Exergy inflow (kW)		
Drying temperature (°C)	50	60	70
Heater	2.842	2.943	3.027
Drying chamber	0.492	0.648	0.822
Evaporator	-0.352	-0.078	0.082
Compressor	1.635	1.691	1.672
External condenser	0.045	0.058	0.054
Internal condenser	0.328	0.232	0.334
Blower	0.716	0.752	0.857
Total	5.706	6.246	6.848

Table 2: Exergy outflow of ginger drying in a closed system heat pump dryer

Apparatus	Exergy outflow (kW)		
Drying temperature (°C)	50	60	70
Heater	0.509	0.675	0.868
Drying chamber	0.439	0.574	0.716
Evaporator	0.298	0.400	0.330
Compressor	0.774	0.688	0.584
External condenser	0.019	0.016	0.013
Internal condenser	0.481	0.517	0.619
Blower	0.261	0.261	0.261
Total	2.781	3.131	3.391

4.3 Exergy loss

From Table 3, Exergy loss was 2.925, 3.115 and 3.457 kW for 50, 60 and 70°C, respectively,. It was found that exergy loss increased with only the increase of air drying temperature because exergy loss depended both on the amount of exergy inflow and outflow at any drying medium temperature. This result was similar to the sliced of potato for tray dryer and pumpkin for convective cyclone type dryer at 60, 70 and 80 °C drying air temperature in 1 m/s drying air velocity [12] and the stream injected gas turbine (STIG) with turbine inlet temperature (TIT) of 900-1400°C which found that the total exergy destruction (or exergy loss) in the cycle increased with TIT [13].
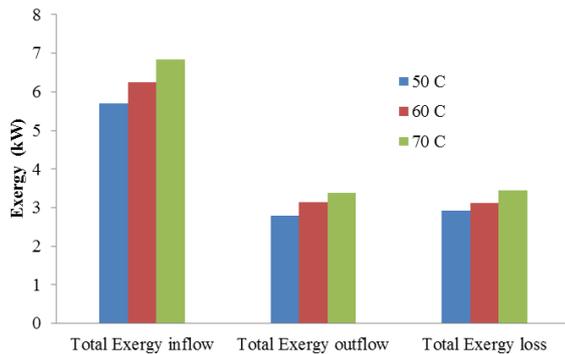
Table 3: Exergy loss of ginger drying in a closed system heat pump dryer

| Apparatus	Exergy lossflow (kW)		
Drying temperature (°C)	50	60	70
Heater	2.333	2.268	2.159
Drying chamber	0.053	0.074	0.106
Evaporator	-0.650	-0.478	-0.248
Compressor	0.861	1.003	1.088
External condenser	0.026	0.042	0.041
Internal condenser	-0.153	-0.285	-0.285
Blower	0.455	0.491	0.596
Total	2.925	3.115	3.457

4.4 Exergy efficiency of the whole system

Exergy efficiency could be found from exergy loss calculated earlier and exergy flow of the whole system.

Exergy flow of the whole system was the summation of exergy of electricity in heater, compressor and blower. Therefore, it was constant at 4.076 kW. Exergy inflow of the whole system of ginger drying in a closed system heat pump dryer is shown in Fig. 2.

Fig. 2: Total exergy flow and loss of the whole system of ginger drying in a closed system heat pump dryer at different drying temperature

Exergy efficiency was 28.24, 23.58 and 15.19 % for 50, 60 and 70°C, respectively, of ginger drying in air as shown in Fig 3.
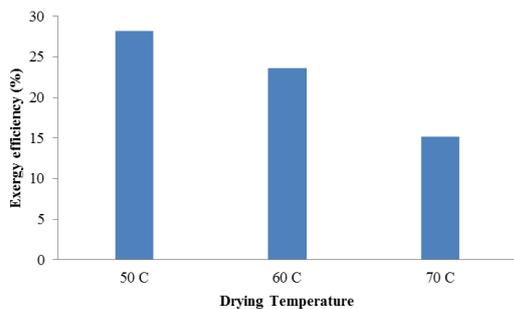
Fig. 3: Exergy efficiency of ginger drying in a closed system

The result showed that exergy efficiency of ginger drying decreased with only the increase of air drying temperature due to the increase of exergy loss. This was the same result to the study of a new model for thermodynamic analysis, in terms of exergy, of a drying process [14]. Unlike the study of pumpkin sliced for convective cyclone type dryer at 60, 70 and 80 °C drying air temperature in 1 m/s drying air velocity [11]-[12].

Since exergy inflow of the whole system was constant, exergy efficiency depended on only exergy loss. Like a heat pump drying of Kiwi, avocado and banana at the drying air temperature changed between 40-40.2°C which was found that exergy loss increased at the onset of the drying process and exergy efficiency decreased due to the exergy loss. After that the exergy efficiency increased as the drying process continued [15].

Although exergy efficiency showed in this article was low, exergy efficiency for pumpkin sliced in convective cyclone type dryer at 60, 70 and 80 °C drying air temperature in 1 m/s drying air velocity was in the range of 3.17 – 33.85 % [11] and it was 31.18-37.01 % for drying of paddy which meant that the remaining large amount of exergy were wasted [16].

5. Conclusion

Exergy inflow and outflow of drying medium cycle, vaporization at ginger and evaporator, refrigeration cycle and electricity were calculated to determine exergy loss of the whole system and, finally, compute exergy efficiency for drying temperature between 50 to 70°C.

- Exergy inflow increased with the increase of drying medium temperature from 5.7 to 6.8 kW
- Exergy outflow increased with the increase of drying medium temperature from 2.8 to 3.4 kW
- Exergy loss increased with only the increase of air drying temperature from 2.9 to 3.5 kW for 50 to 70°C.
- Ginger drying at the lowest drying temperature, 50˚C, provided the highest exergy efficiency of 28%

Acknowledgements

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Biography

Nattapol Poomsa-ad has been working as a lecturer in biological and mechanical engineering in Mahasarakham University, Thailand since year 2002. He graduated B.Eng, M.Eng and Ph.D from King Mongkut's University of Technology Thonburi, Bangkok, His Ph.D. degree was energy technology. His research interest includes thermal processing for food and agricultural product drying technology and energy conservation and management

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