

Energy and Exergy Analysis of Zedoary Slices Drying based on Experimental Data

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ABSTRACT: This paper concerned with energy and exergy analysis of the convective drying process of zedoary slices. The first and second laws of thermodynamics were used to calculate the energy and exergy. A laboratory scale dryer has been designed and used for drying experiments. The experiments were conducted on zedoary slices with thickness about 3 mm at four different air temperatures of 40, 50, 60 and 70 °C, and three different relative humidities (RH) of 20%, 30% and 40% at 0.9 m/s of drying air velocity. Drying mass flow rate varied between 0.050 kg/s and 0.060 kg/s. The energy utilization and energy utilization ratio were found to vary between 0.1 and 121.4 J/s and 0 and 16.25%, respectively. These values show that only a small proportion of the supplied energy by the heater was used for drying. The exergy loss and exergy efficiency were found to be in the range of 0.0 to 4.5 J/s and 0.69% to 1.00%, respectively, indicating that the drying process was thermodynamically inefficient and much energy was vented in the exhaust air. It was concluded that energy utilization ratio decreased with increasing drying air temperature and RH while the exergetic efficiency increased. Exergy efficiency varies between 0.69-1.00 for the temperature interval 40 to 70 °C at 40% RH and 0.73 - 1.00 for interval of 20% to 40% RH at 50 °C.

KEYWORDS: Convective drying, Energy utilization ratio, Exergy efficiency, Zedoary slices.

I. INTRODUCTION

Zedoary or *temuputih* (*Curcuma zedoaria* Rosc.) is one of the important medicinal plants in Indonesia. Its rhizome is used as a food supplement material and as traditional herbal medicine, called *jamu*. As one of the herbal producing countries in the world, Indonesia produced 518 million tones herbs, and 41.4 million tones out of it were exported, with a value of US\$ 211.4 million in 2011. Recently, there has been an increasing demand for organic and natural vegetables due to human health benefits [1]. Small traditional medicine companies need *temuputih* in dried-slices also called 'simplicia'. Simplicia (Latin word means simple) is a terminology used for minimally processed product to be used for further process of *jamu* production. Drying is the most important unit process in producing simplicia.

Drying is defined as reduction of moisture from the products and is the most important process for preserving agricultural products since it has a great effect on the quality of the dried products. Drying of vegetables and fruit is one of the oldest methods of food preservation. The major objective in drying of agricultural products is the reduction of the moisture content to a level which allows safe storage over an extended period [2]. During the drying process, the amount of heat supplied to the product should be more than the available one under ambient conditions for sufficiently increasing the vapor pressure of the moisture held within the product to enhance moisture migration from within the product, and for significantly decreasing the relative humidity of the drying air to increase its moisture carrying capability and to ensure a sufficiently low equilibrium moisture content [3,4,5]. Accordingly, drying is one of the most energy-intensive operations, and hence any effort to optimize its energy utilization is worth of great industrial significance.

During the past few decades, thermodynamic analysis, particularly exergy analysis, has appeared to be an essential tool for system design, analysis and optimization of thermal systems. From a thermodynamic point of view, exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to

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equilibrium with a reference environment. Exergy is not subject to a conservation law; rather exergy is consumed or destroyed, due to irreversibilities in any process. It is a measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment. For this reason, the state of the reference environment, or the reference state, must be specified completely. This is commonly done by specifying the temperature, pressure and chemical composition of the reference environment [6,7,8]. For practical uses, the reference environment can be represented by the system surrounding, and hence the exergy analysis based on experimental data and its specific condition is indispensable.

Exergy analysis evaluates the available energy at different parts of a system and provides the useful information to design appropriate component and operation parameters in a system. [3]. Several studies have been conducted on exergy analyses of drying processes. Topic presented a mathematical model for exergy analysis of drying plants [9]. Dincer and Sahin developed a new model for exergy analyses of a drying process [10]. Akpinar performed energy and exergy analyses of the drying of red pepper slices in a convective type dryer [11]. Colak and Hepbasli performed an exergy analysis of thin-layer drying of green olive in a tray dryer [12]. Corzo *et al.* performed energy and exergy analyses of thin-layer drying of coroba slices [8]. Nevertheless, exergy analysis based on experimental drying data of zedoary drying is not yet available.

The primary objective of this study is to present energy and exergy analyses of thin-layer drying of zedoary slices in a laboratory scale convective dryer at different drying conditions of air temperature and relative humidity.

II. MATERIAL AND METHODS

Sample preparation

Fresh zedoary rhizome obtained from test field of Centre for Medicinal and Aromatical Plant in Bogor, Indonesia. Samples of zedoaries were washed and sliced into chips of 3 mm thickness with a knife and then dipped into boiling water for 5 min.

Experimental dryer

The drying experiments were carried out using the laboratory dryer in the Department of Mechanical and Biosystem Engineering, Bogor Agricultural University of Indonesia, which could be regulated to any desired drying air temperature between 30 and 80 °C and relative humidity between 20 and 90%. The air temperature and the relative humidity are controlled by AVR Atmel microprocessor controller with temperature accuracy of ± 1 °C and relative humidity accuracy of $\pm 2\%$ (ASABE, 2006) [13]. The unit is equipped with a 2000 W steam injection humidifier, a 2000 W heating and heating control unit, an electrical fan, temperature and humidity measurement sensor by SHT15 Sensor and the drying chamber (Fig. 1). The desired drying air temperature and relative humidity (RH) are maintained by PID control system. The air from the heating unit at the desired temperature entered the drying chamber. The lever manual-controller regulate the velocity of the drying air flowing through the drying chamber and it was measured by a hot wire digital Kanomax anemometer with the accuracy of ± 0.1 m/s. Weighing of samples inside the drying chamber was done automatically at desired time interval using a digital balance (GF-3000 A and D with an accuracy of 0.01 g) and were interfaced to a PC via RS-232 port as data acquisition system.

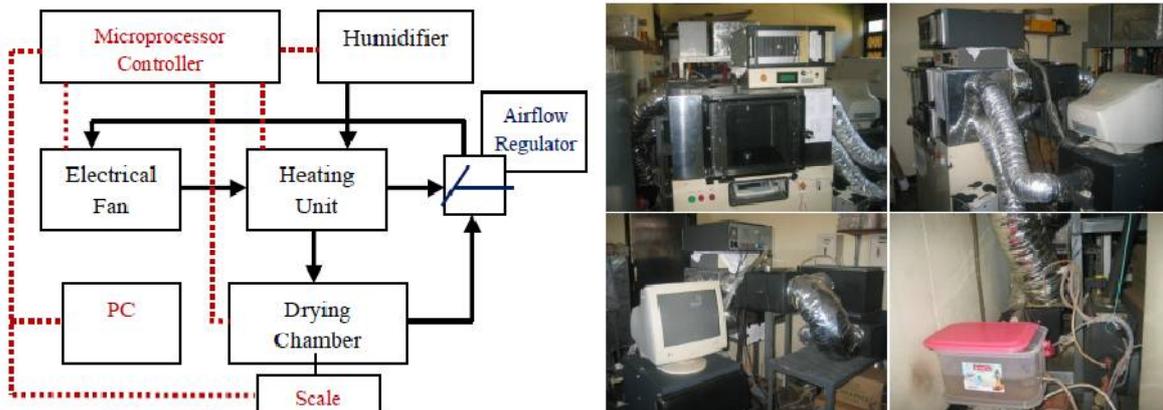


Fig. 1. Schematic (left) and photograph view (right) of the experimental dryer system

Drying experiments

Before each experiment, the dryer was run for one hour in order to achieve desirable steady-state conditions. The experiments were conducted in triplicate at four levels drying air temperatures of 40, 50, 60 and 70 °C at 40% RH and at three levels drying air relative humidity of 20%, 30% and 40% at 50 °C, while air velocity kept constant at 0.9 m/s. Drying experiments were continued until a constant mass was obtained. The temperature, relative humidity and velocity of air drying and sample weight were continuously monitored and recorded every 5 min during drying experiments. Drying was continued until the samples reach the fixed weight. After each drying experiment, the sample was oven-dried at 103 ± 2 °C to determine the moisture content.

Thermodynamics analysis

Thermodynamics system of the drying process of zedoary slices as moist solids was treated as a control volume system (Fig. 2). When applied to a control volume, the principle of mass and energy conservation states: the time rate of accumulation of mass and energy within the control volume equals the difference between the total rates of mass and energy flow in and out across the boundary. Energy can enter and exit a control volume by heat transfer and flowing streams of matter [14].

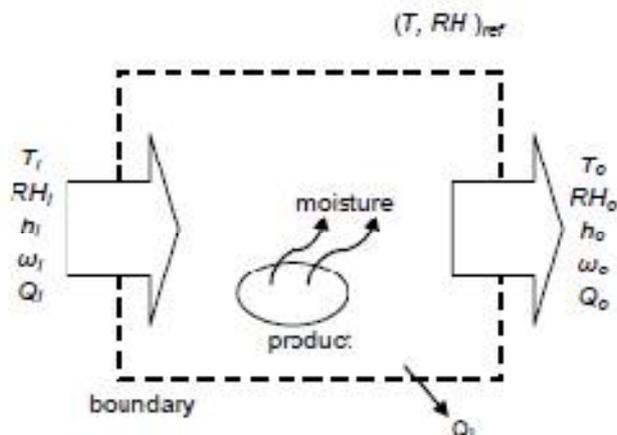


Fig. 2. Schematic of drying process with a control volume system

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The schematic presentation of the systems with input and output terms is shown in Fig. 3. As clearly seen in the figure, there are four major components to take into consideration as follows [10]:

- Point 1. Referring to the input of drying air to the drying chamber to dry the products.
- Point 2. Referring to the input of moist products to be dried in the chamber.
- Point 3. Referring to the output of the moist air after taking the evaporated moisture from the products.
- Point 4. Referring to the output of the dried products. In fact, their moisture contents are reduced to a certain level required for each commodity of the product.

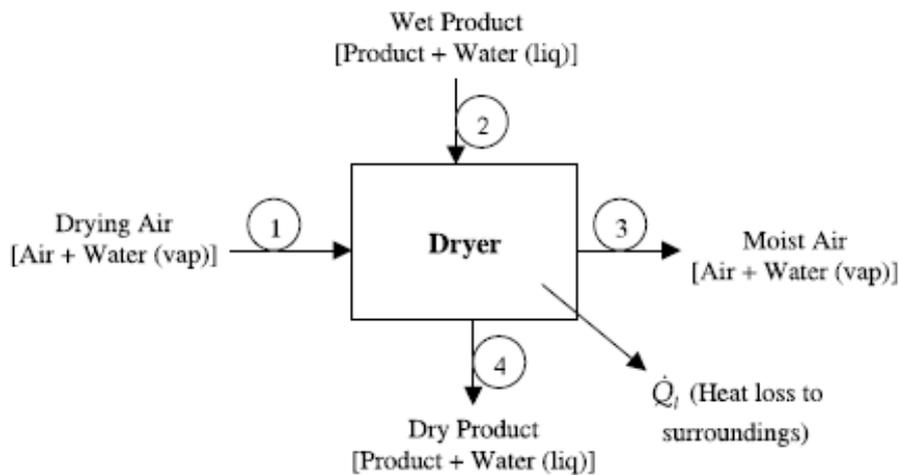


Fig.3. Schematic of drying process with input and output terms [10]

Mass balance

The air drying process throughout the drying of zedoary includes the processes of heating, vaporizing, and humidification. The air drying processes can be modeled as steady flow processes that are analyzed by applying the steady-flow conservation of mass (for product, dry air and water/moisture) and conservation of energy principles.

General equation of mass conservation of drying air [10]:

$$\text{Product: } (\dot{m}_p)_2 = (\dot{m}_p)_4 = \dot{m}_p \quad (1)$$

$$\text{Air : } (\dot{m}_a)_1 = (\dot{m}_a)_3 = \dot{m}_a \quad (2)$$

$$\text{Water : } \omega_1 \dot{m}_a + (\dot{m}_w)_2 = \omega_3 \dot{m}_a + (\dot{m}_w)_4 \quad (3)$$

Energy balance

The energy balance equation can be written for the entire system in the following manner, by taking input energy terms equal to output energy terms:

$$\dot{m}_a h_1 + \dot{m}_p (h_p)_2 + (\dot{m}_w)_2 (h_w)_2 = \dot{m}_a h_3 + \dot{m}_p (h_p)_4 + (\dot{m}_w)_4 (h_w)_4 + \dot{Q}_l \quad (4)$$

where

$$h_1 = (h_a)_1 + \omega_1 (h_v)_1 \approx (h_a)_1 + \omega_1 (h_g)_1 \quad (5)$$

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$$h_3 = (h_a)_3 + \omega_3(h_g)_3 \quad (6)$$

The enthalpy of drying air can be determined [15] as follows:

$$h_a = c_{pa}(T - T_{ref}) + \omega h_{fg} \quad (7)$$

$$h_a = (1.004 + 1.88\omega)(T - T_{ref}) + \omega h_{fg}$$

The heat transfer rate due to evaporation of the dryer is determined [8] as follows,

$$\dot{Q}_{ev} = \dot{m}_v h_{fg} \quad (8)$$

For steady flow process and heat loss to surrounding was neglected, the energy utilization (EU) was:

$$EU = \dot{Q}_{ev} \quad (9)$$

The energy utilization ratio of drying process (EUR) was calculated using the following equation :

$$EUR = \frac{\dot{Q}_{ev}}{\dot{m}_a(h_{a1} - h_{a0})} \quad (10)$$

Exergy balance

Exergy inflow, outflow and losses of the drying chamber were estimated in the scope of the second law analysis of thermodynamics. The basic procedure for exergy analysis of drying chamber is to determine the exergy values at steady-state points and the reason of exergy variation for the process [8,16]. For this purpose, the general form of exergy equation applicable for steady flow systems [10] was employed:

$$\dot{m}_a e_1 + \dot{m}_p(e_p)_2 + (\dot{m}_w)_2(e_w)_2 = \dot{m}_a e_3 + \dot{m}_p(e_p)_4 + (\dot{m}_w)_4(e_w)_4 + \dot{E}_q + \dot{E}_d \quad (11)$$

The classical way of describing the thermodynamic properties of humid air is to view it as a perfect gas mixture of dry air (a) and water vapor (v) [17]. Therefore, the specific exergy (e_1) of air drying -as a humid air mixture- for point 1 is

$$e_1 = (C_{pa} + \omega_1 C_{pv}) \left(T_1 - T_0 - T_0 \ln \frac{T_1}{T_0} \right) + R_a T_0 \left\{ (1 + 1.608\omega_1) \ln \left(\frac{1 + 1.608\omega_0}{1 + 1.608\omega_1} \right) + 1.608\omega_1 \ln \left(\frac{\omega_1}{\omega_0} \right) \right\} \quad (12)$$

And the specific exergy (e_3) of air drying for point 3 is

$$e_3 = (C_{pa} + \omega_3 C_{pv}) \left(T_3 - T_0 - T_0 \ln \frac{T_3}{T_0} \right) + R_a T_0 \left\{ (1 + 1.608\omega_3) \ln \left(\frac{1 + 1.608\omega_0}{1 + 1.608\omega_3} \right) + 1.608\omega_3 \ln \left(\frac{\omega_3}{\omega_0} \right) \right\} \quad (13)$$

The specific exergy for the moist products is

$$e_p = C_p \left(1 - \frac{T_0}{T_p} \right) T_p \quad (14)$$

The specific exergy for the evaporation is

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$$e_{ev} = \dot{Q}_{ev} \left(1 - \frac{T_0}{T_{ev}}\right) \tag{15}$$

Exergetic efficiency of drying process

The exergy loss can be determined as follows [11,16]:

$$\text{Exergy loss} = \text{Exergy inflow} - \text{Exergy outflow} \tag{16}$$

The exergy efficiency can be defined as the ratio of exergy use (investment) in the drying of the product to exergy of the drying air supplied to the system [8].

$$\eta_{ex} = \frac{\text{Exergy inflow} - \text{Exergy loss}}{\text{Exergy inflow}} \tag{17}$$

In this study the reference dead state were taken as the environment: $T_0 = 30^\circ\text{C}$ (303.15 K), $RH_0 = 70\%$ and $P_0 = 1$ atm.

III. RESULTS AND DISCUSSION

Mass changes

Drying kinetics of zedoary slices are shown in Fig. 4 where weight is represented along drying time for air temperatures between 40°C and 70°C and air relative humidities between 20-40%. The initial weight of zedoary slices was 0.150 kg and the final weight ranged from 0.020 kg to 0.010 kg. It can be seen that mass decreased with increasing drying time, temperature and decreasing RH. The decreases were faster in the initial period of drying and then the rate decreased.

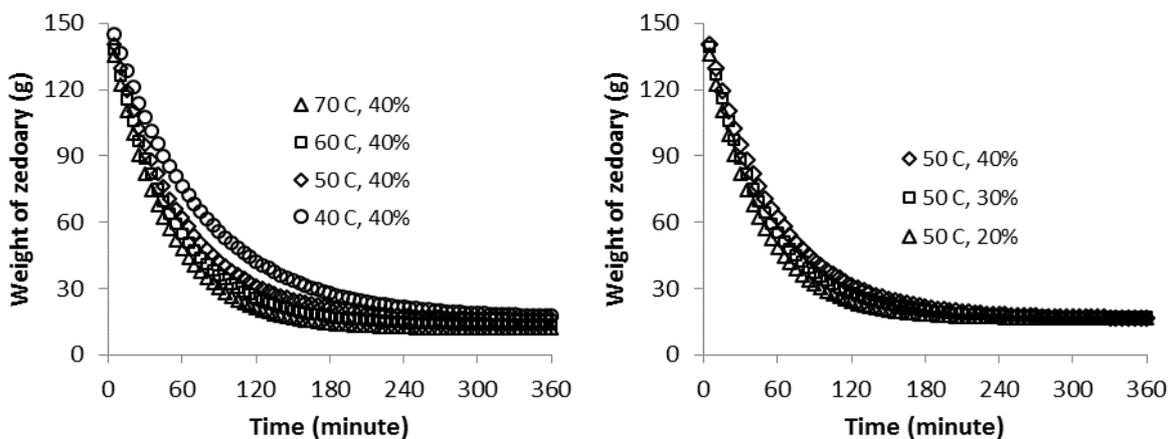


Fig. 4. Variation of weight of zedoary as a function of drying time at different air temperatures (left) and RHs(right)

Energy analysis

The energy analysis of a thin-layer drying process of zedoary slice was performed by using data obtained from the experiments. Fig. 5 shows the variation of energy inflow to drying chamber for various drying process condition. The energy inflow increased with increasing air drying temperature (left) and relative humidity (right).

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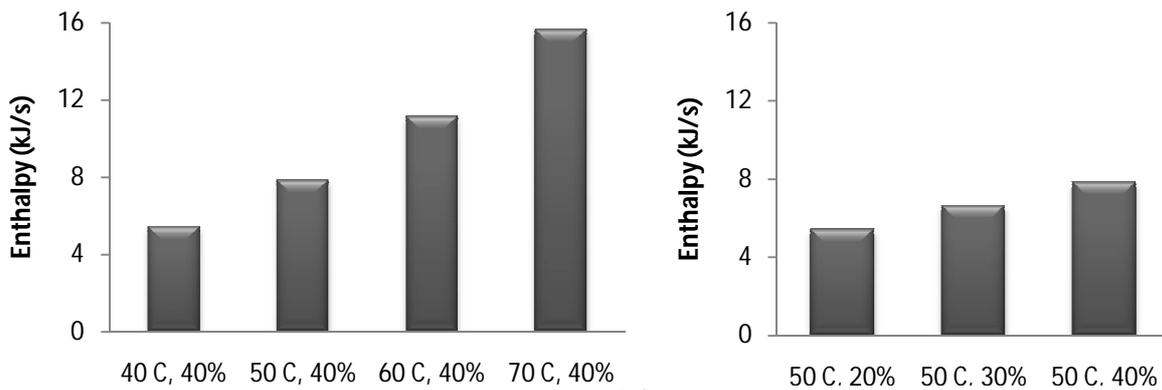


Fig. 5. Effect of drying air temperature(left) & RH(right) on energy inflow

Fig. 6 shows the variation of energy utilization for evaporation as a function of drying time for different air temperatures and RHs. The energy utilization decreased with increasing drying time. The energy utilization was high at the beginning of drying process due to the high moisture of the samples while it quickly decreased because of the low moisture content of the samples towards the end of the process

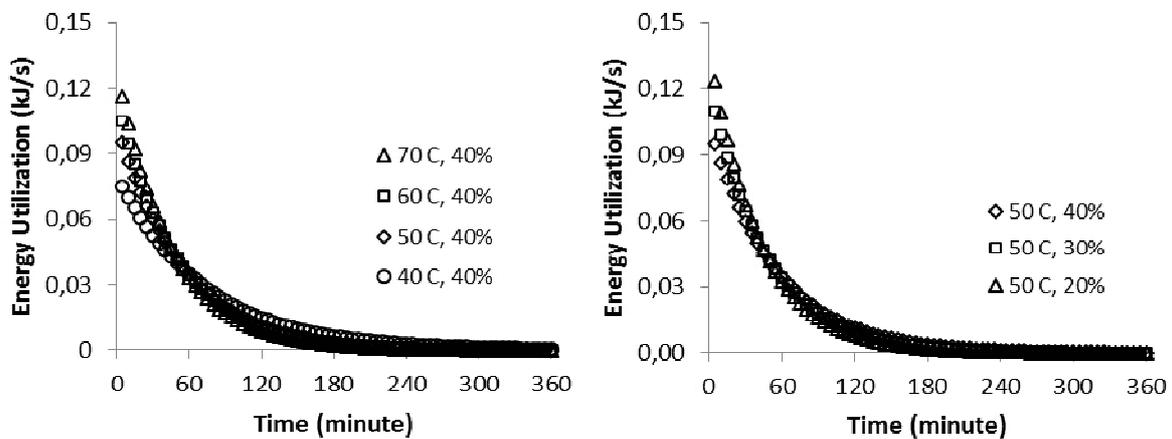


Fig.6. The variation of energy utilization at different temperature (left) and RH (right)

Heat loss from the dryer frame increased when the drying air temperature increased, possibly due to an increase in the overall heat transfer coefficient. However, the effect of heat loss from this source on energy utilization was very small compared to the effect of the inlet enthalpy on heat and mass transfer, which resulted in a high degree of energy utilization. Therefore, the majority of energy supplied to the drying chamber was used for the evaporation of moisture from the product being dried.

Fig.7 shows the variation in the energy utilization ratio (EUR) as a function of drying time for each drying temperature (left) and RH. The values of EUR decreased with increasing drying time. The EUR increased with decreasing air temperature (from 70 °C to 40 °C) and also air drying RH (from 40% to 20%). A similar finding has been reported by several other researchers studying the effect of air temperature on energy utilization ratio [11,18].

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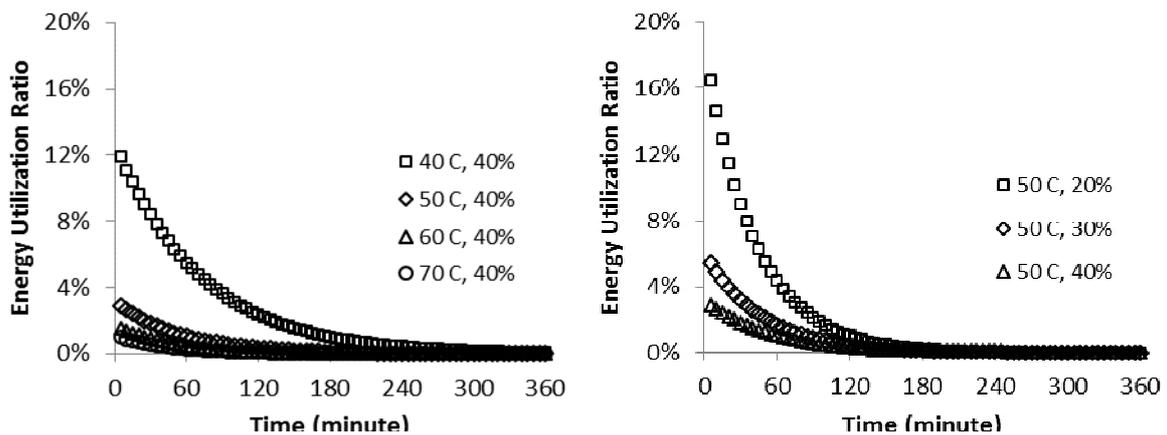


Fig. 7. The variation of energy utilization ratio at different temperature (left) and RH(right)

The EUR varied between 0 and 11.93% at various air temperature at constant RH and 0 to 16.25% at various RH at constant temperature. The values of EUR were low for different conditions of drying. This means that the energy is still available at the outlet. In order to use the energy more effectively we can reuse the energy leaving the dryer by feeding it back. It would be advantageous if enthalpy could be further exploited through recycling of the exhaust air.

Exergy analysis

The exergy analysis of drying process of zedoary slice was performed by using data obtained from the experiments. The exergy inflow during drying experiment with an air mass flow rate 0.06 kg/s is presented in Table 1. The exergy inflow varied between 10.12 J/s and 581.13 J/s at drying air temperature increased from 40 °C to 70°C. The exergy inflow varied between 40.74 and 68.08 J/s at drying air relative humidity increased from 20% to 40%. Maximum value of exergy inflow of 581.13 J/s was obtained at a drying air of 70°C with an air RH of 40%. Minimum value of exergy inflow was 10.12 J/s while drying air temperature was 40° C and air RH was 40%.

Table 1. Exergy and energy inflow at different drying condition

T (°C)	RH (%)	Exergy (J/s)	Energy (J/s)
40	40	10.12	5436
50	40	68.08	7832
60	40	235.90	11119
70	40	581.13	15633
50	20	40.74	5428
50	30	43.03	6630
50	40	68.08	7832

Fig.8 shows the exergy outflow as a function of drying time for different air temperature and RH. The value of exergy outflow increased with decreasing drying time. We can note that the exergy outflow is still comparable to the exergy inflow. This indicates that a small amount of exergy is used. This also means that the energy is still available at the outlet.

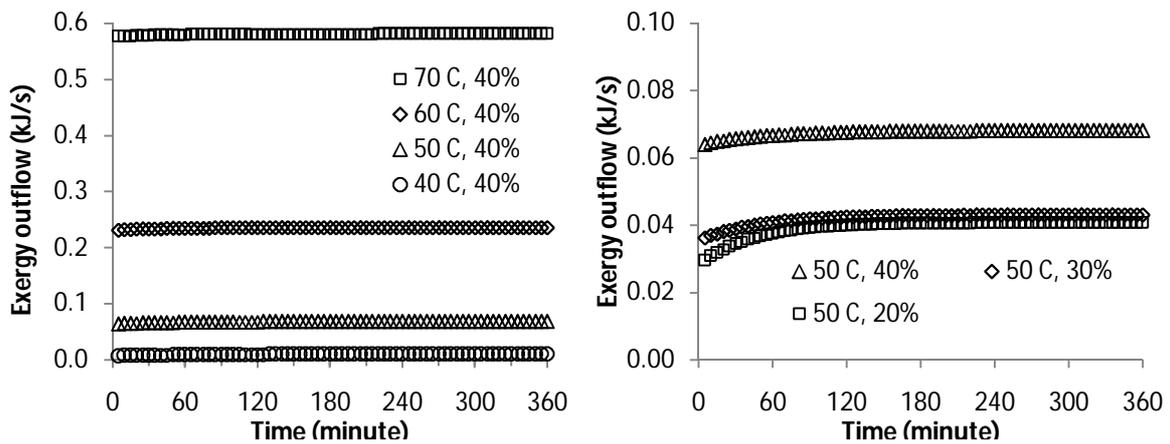


Fig. 8. Exergy outflow changes with drying time at different air temperature (left) and RH(right)

The exergy loss curves are shown in Fig. 9 for convective drying of zedoary slice as influenced by air temperature and RH, respectively. The maximum value of exergy loss was 0.0045 kJ/s at air temperature of 70 °C, RH 40%. The exergy loss decreased continually with drying time. This can be explained by the fact that the moisture content of zedoary samples decreased with drying time and capability of product to absorb and use the exergy for evaporation decreased continually, therefore, the exhaust air had more proportion of incoming exergy. Similar findings have been reported by several researchers studying the effect of air temperature on exergy loss [16,18,19].

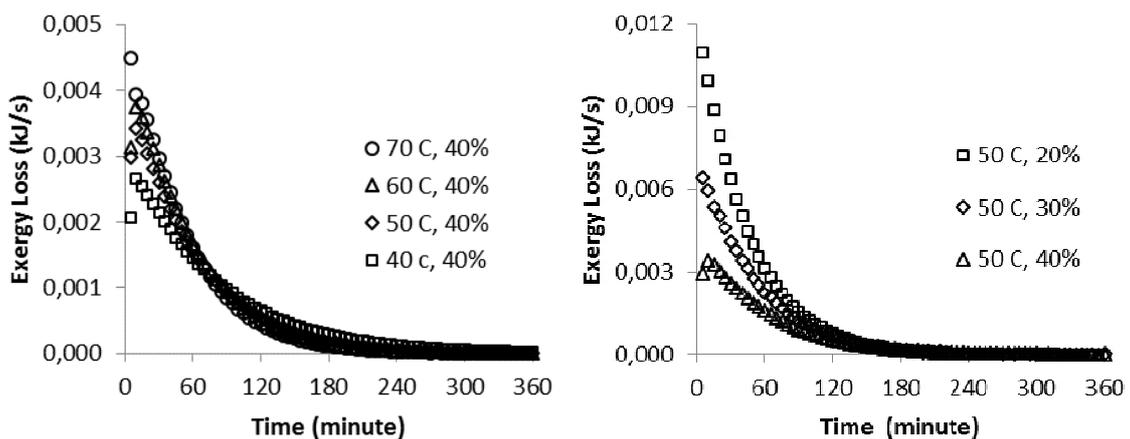


Fig. 9. Exergy loss changes with drying time at different air temperature(left) and RH(right)

Exergy efficiency

The exergy efficiency curves are shown in Fig. 10. As can be seen, exergy efficiency increased continually with drying time. This is because during the drying process the available energy in the drying chamber increases with drying time, since the amount of moisture decreases with time. In addition, increasing the drying temperature and RH caused an increase in exergy entered. Therefore, the exergy efficiency increased with increasing in drying air temperature and RH. At the end of drying, the value of exergy efficiency closes to one. This happens because there is no more water is evaporated from the product due to the achievement of equilibrium moisture content. Akpınar *et al.*[16] reported that the exergetic efficiency increased with the increase of drying air temperature. It was realized that the exergy losses were

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equal to zero at the point where the exergetic efficiency was estimated as 100% due to discontinuity of drying process in the system.

Exergy efficiency varies between 0.69-1.00 for the temperature interval 40 to 70 °C at 40% RH and 0.73 - 1.00 for interval of 20% to 40% RH at 50 °C.

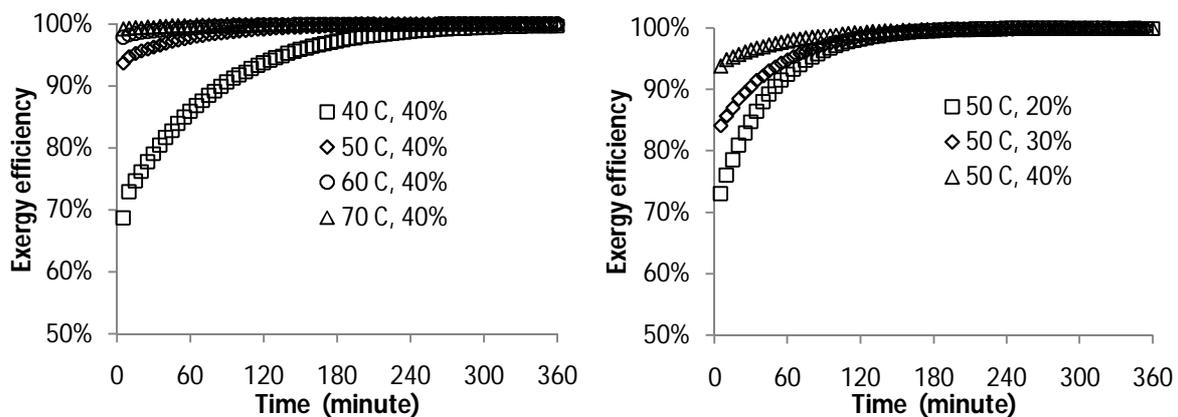


Fig. 10. Exergy efficiency changes with drying time at different air temperature(left) and RH(right)

IV. CONCLUSION

Energy and exergy analysis of zedoary slices drying were accomplished in this study. Energy utilization ratio increased with decreasing drying air temperature and RH, while the exergy efficiency decreased. In order to use the energy and exergy more effectively, the energy leaving the dryer can be reused by feeding it back. Exergy efficiency varies between 0.69-1.00 for the temperature interval 40 to 70 °C at 40% RH and 0.73 - 1.00 for interval of 20% to 40% RH at 50 °C. In addition, the results showed that the temperature and RH of the drying air had an important effect on energy and exergy use. This knowledge will provide insights into the optimization of a convective dryer and the operating parameters that causes reduction of energy consumption and losses.

NOMENCLATURE

C_p	specific heat
EU	Energy Utilization
EUR	Energy Utilization Ratio
e	specific exergy
h	specific enthalpy
\dot{m}	Mass flow rate
\dot{Q}	Rate of heat transfer
R	gas constant
RH	relative humidity
T	temperature
t	time
η	efficiency
ω	humidity ratio of air

Subscript

0	reference (dead state)
$1,2,3,4$	related to point 1, 2, 3, 4 (Figure 3)

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<i>a</i>	air
<i>d</i>	destruction
<i>ev</i>	evaporation
<i>ex</i>	exergy
<i>fg</i>	vaporization
<i>g</i>	saturated vapor state
<i>i</i>	in
<i>l</i>	loss
<i>o</i>	out
<i>p</i>	product
<i>q</i>	heat transfer related
<i>ref</i>	reference
<i>v</i>	vapor
<i>w</i>	water

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