Energy and exergy analysis economic of continuous vibrating fluidized bed drying on celery drying

S U Handayani¹, I S Atmanto², F T Putri³, S Fujiwara⁴

¹,²,³Industrial Technology Department, Vocational School, Diponegoro University
⁴Mechanical Engineering Department, National Institute of Technology, Akashi, Japan

Abstract. This paper present the experimental work of celery drying using continuous vibrating fluidized bed drying. Fresh celery leaves dried at 50°C, 60°C and 70°C in continuous vibrating fluidized bed dryer with a dimension of 2350 mm x 300 mm. Energy and exergy analysis was conducted to determine the performance of the system, among others, energy utilization, energy efficiency, and efficiency of the exergy so it can be known potential energy savings can be obtained. From the calculation results can be concluded that the increase in drying temperature will increase energy utilization and energy utilization ratio and decrease the efficiency of the exergy. Average energy utilization ratio at 50°C is 0.0768, at 60°C is 0.1199 and at 70°C is 0.1682. Exergy efficiencies decrease with increasing temperature. Average exergy efficiencies are 0.19, 0.16 and 0.17 for 50°C, 60°C and 70°C drying temperature respectively. The main factor that causes thermodynamic inefficiency is the exergy that leaves the system, exergy destruction and loss of exergy to the surrounding air.

1. Introduction

Indonesia as a tropical country and large population has great potential to develop agriculture and food-based industries. One of the important processes in the agricultural and food industries is the drying process, therefore the development of drying technology is very important.

The vibrating fluidized bed (VFB) of solid particles is a modification of the conventional (bubbling) fluidized bed (BFB) where vibration energy is used to transfer the bed of particles from packed to fluidized state. VFB has reported has many advantages like shorter residence time, the intensity of mixing and heat and mass transfer properties are controllable in VFB by changing amplitude and/or frequency of vibration, and better processing for sticky and moist particle [1]. Research on vibrating fluidized dryer has been carried out on cassava starch [2], solid containing multicomponent moisture [3], barley grain [4], binary nanoparticle mixture [5], carrot cube [6], etc.

The drying process requires a large amount of energy. Planning an effective and efficient drying process will reduce overall production costs. Optimum energy consumption and energy consumption management method are very important because of the high prices of energy, environmental concerns, increasing world population and decreasing fossil fuel resources [7].

Thermodynamic analysis consisting of energy and exergy analysis is an important analysis in the design, evaluation, and optimization of thermal systems [8]. Exergy is defined as the maximum amount of work produced by heat and vapor in an equilibrium state. Energy is the maximum amount without calculating friction so it can be called the absolute amount of energy. Energy analysis aims to estimate the ratio of energy use and the amount of energy produced. Exergy is the maximum work obtained as a
system interaction with respect to heat transfer that occurs with the environment. Exergy analysis aims to determine energy loss during the drying process using the principle of mass and energy conservation and the second law of thermodynamics. The second law of thermodynamics assumes that energy cannot return with the formation of entropy. Exergy analysis is a useful tool, which has been widely used in the design and performance analysis of energy-related systems especially drying equipment [6].

There are several studies on exergy in the drying process that has been published. Using a simple exergy balance, obtained that only around 30% exergy is utilized for drying of paddy using industrial fluidized bed and the remaining large amount of exergy is wasted. Add sufficient insulation on the dryer body and recycling the exhaust air can increased exergy, which is needed to be studied further for investigating the economic feasibility [9]. Energy efficiency and exergy will increase if the drying air flow rate is lowered because less heat is required to heat smaller drying air. Decreasing the inlet air humidity ratio also increases the energy and exergy analysis, because the air is able to attract more moisture from the drying product [10]. Energy utilization and energy utilization ratio increased with an increase in drying air temperature and BD while decreased with an increase in cubes size [6].

2. Material and method

2.1. Material and equipment

The material used in this study is fresh celery which has been cut into pieces about 0.5 cm. The equipment used is a vibrating fluidized bed dryer with dimension 2350 x 300 mm as shown in figure 1 [11].

![Figure 1. Vibrating fluidized bed dryer [11]](image)

Vibrating fluidized bed dryer has an automatic control system to regulate temperature and an inverter to regulate the air flow rate. The unit is equipped with a thermometer and hygrometer that is mounted on the side of the entry, exit and along the bed.

2.2. Method

The schematic of the drying process with input and output term is shown in figure 2.

![Figure 2. The schematic of drying process](image)
2.3. Energy analysis
The dryer is considered a volume control, and the mass equilibrium equation applies as follows:

Product:
\[
(m_p)_2 = (m_p)_4 = \dot{m}_p
\]

Air:
\[
(m_a)_1 = (m_a)_3 = \dot{m}_a
\]

Water:
\[
\omega_1 \dot{m}_a + (m_w)_2 = \omega_2 \dot{m}_a (m_w)_4
\]

The energy balance equation, considering the energy input is equal with energy output, can be written as follow:
\[
\dot{m}_a h_1 + \dot{m}_p (h_p)_2 + (m_w)_2 (h_w)_2 = \dot{m}_a h_3 + \dot{m}_p (h_p)_4 + (m_w)_4 (h_w)_4 + \dot{Q}_l
\]
\[
h_1 = (h_a)_1 + \omega_1 (h_v)_1 \approx (h_a)_1 + \omega_1 (h_g)_1
\]
\[
h_3 = (h_a)_3 + \omega_3 (h_g)_3
\]

The enthalpy of drying air:
\[
h_a = c_{pa}(T - T_{ref}) + \omega h_f g
\]
\[
h_a = (1.004 + 1.88\omega)(T - T_{ref}) + \omega h_f g
\]

The heat transfer rate due to evaporation of the dryer:
\[
\dot{Q}_{ev} = \dot{m}_v h_f g
\]

For steady flow process and heat loss to surrounding was neglected, the energy utilization (EU):
\[
EU = \dot{Q}_{ev}
\]

2.4. Exergy analysis
Energy analysis cannot provide information about the irreversibility aspects of the thermodynamic process so that it needs exergy analysis based on the second law of thermodynamics [12].
Mathematical calculations on exergy equilibrium can be calculated using equation [13].
\[
EX = Cp \left[ (T - T_\infty) - T_\infty ln \frac{T}{T_\infty} \right]
\]

The equation is used to calculate exergy in and out at the temperature in and out. The exergy at the inlet and outlet point then can be defined as follow:
\[
EX_i = Cp \left[ (T_{ai} - T_\infty) - T_\infty ln \frac{T_{ai}}{T_\infty} \right]
\]
\[
EX_i = 1.0029 + 5.4 \times 10^{-5} T_{ai} \times \left[ (T_{ai} - T_\infty) - T_\infty ln \frac{T_{ai}}{T_\infty} \right]
\]
\[ \mathcal{E}_x = C_p \left[ (T_{ao} - T_\infty) - T_\infty \ln \frac{T_{ao}}{T_\infty} \right] \] (14)

\[ \mathcal{E}_x = 1.0029 + 5.4 \times 10^{-5} T_{ai} \times \left[ (T_{ao} - T_\infty) - T_\infty \ln \frac{T_{ao}}{T_\infty} \right] \] (15)

The exergy loss in the process is calculated using this equation:

\[ \eta_{EX} = \frac{EX_i - EX_l}{EX_i} \] (16)

Exergy efficiency can be defined as the exergy ratio used in the drying process to the drying air supplied to the system\(^{14}\).\n
\[ h_1 = (h_a)_1 + \omega_1 (h_v)_1 \approx (h_a)_1 + \omega_1 (h_g)_1 \] (17)

3. Result and discussion

3.1. Exergy utilization

Energy utilization is calculated using equation 10. Energy utilization in the Vibro continuous fluidized bed dryer is shown in figure 3. Energy utilization varied from 0.25 kJ/s to 0.02 kJ/s for 50°C, 0.58 kJ/s to 0.02 kJ/s for 60°C, and 0.67 kJ/s to 0.01 kJ/s for 70°C drying temperature. Energy utilization will decrease with increasing drying time. High energy utilization at the beginning of drying due to the high water content of celery, but will quickly drop due to a decrease in water content during the drying process. This result is similar to the research using a fluidized bed dryer on carrot cube\(^{6}\), pistachio\(^{15}\), eggplant\(^{8}\) and moist particle\(^{16}\).

Average energy utilization in 50°C, 60°C and 70°C is 0.1184 kJ/s, 0.1716 kJ/s, and 0.21 kJ/s. From the figure 4, it also can be seen that energy utilization will increase with increasing temperature because drying in celery is dominated by surface drying, so the higher the temperature, the higher the heat and mass transfer occurs, thus increasing energy use in reducing the water content of the product. The same results have been obtained in research about cassava starch\(^{12,13}\).
3.2. Energy utilization ratio

The energy utilization ratio varies with temperature and drying time. The maximum energy utilization ratio is 0.5 which is reached at 50°C drying temperature and the minimum is 0.0044 at 70°C. Figure 5 shows the effect of drying time on the energy utilization ratio. The longer the drying time, the ratio of energy utilization will be smaller. This happens because of high energy utilization at the beginning of drying because of the high water content in celery, but it will quickly drop due to a decrease in water content during the drying process. This result is in accordance with the research that has been done previously on carrot 6, eggplant 8, coroba slices 14, corn and unshelled pistachios 15, moist particle 17, zedoary slices [18].
The energy utilization ratio will increase with increasing temperature. Average energy utilization ratio at 50°C is 0.0768, at 60°C is 0.1199 and at 70°C is 0.1682. Energy utilization and energy utilization ratio increase by increasing the drying air temperature due to the fact that the high drying air temperature causes a higher decrease in moisture content.

3.3. Exergy loss
The maximum exergy loss is 0.91 kJ/kg at 50°C and the minimum exergy loss is 0.741 at 50°C. Fig. 7 shows the relation between exergy loss and drying time, exergy loss increased with drying time. The longer the drying time, the water content in celery leaves decreases and more energy is wasted along with drying air. As the drying temperature increase, exergy loss will also increase, exergy loss at 50°C, 60°C and 70°C are 0.82, 0.84 and 0.87 respectively (fig. 8). This fact shows that the energy wasted in the outlet is still large. Reducing the energy loss along with the drying air out of the system can be done by recirculating the drying air into the drying system.

![Figure 7. Exergy loss with drying time at different temperature](image)

![Figure 8. Average exergy loss at different temperature](image)

3.4. Exergy efficiency
Exergy efficiency was calculated by comparing between exergy loss and exergy input. Maximum exergy efficiency is 0.29 for 50°C and minimum exergy efficiency is 0.09 for 50°C drying temperature. The figure shows that exergy efficiency decrease with increasing drying time. The low water content in celery leaves causes the less amount of energy used and the amount of energy wasted along with the drying air coming out. This causes more energy loss and smaller exergy efficiency. The main factor that causes thermodynamic inefficiency is the exergy that leaves the system, exergy destruction and loss of exergy to the surrounding air. This can be reduced by recycling the outlet air, reducing exergy destruction in the drying chamber and reducing heat transfer across the system boundary [16].
From figure 10, it can be seen that exergetic efficiencies decrease with increasing temperature. Average exergy efficiencies are 0.19, 0.16 and 0.17 for 50°C, 60°C and 70°C drying temperature respectively. This result is in line with research at the olive mill wastewater using an indirect type of natural convection solar dryer[19].

**Figure 9.** Exergy efficiency with drying time at different temperature

**Figure 10.** Exergy efficiency at different temperature

4. Conclusion
The energy utilization ratio will increase with increasing temperature. Average energy utilization ratio at 50°C is 0.0768, at 60°C is 0.1199 and at 70°C is 0.1682. Maximum exergy efficiency is 0.29 for 50°C and minimum exergy efficiency is 0.09 for 50°C drying temperature. Exergy efficiencies decrease with increasing temperature. Average exergy efficiencies are 0.19, 0.16 and 0.17 for 50°C, 60°C and 70°C drying temperature respectively. The main factor that causes thermodynamic inefficiency is the exergy that leaves the system, exergy destruction and loss of exergy to the surrounding air.

Acknowledgment
This work was supported by the Grant-in-Aid for Scientific Research from Vocational School, Diponegoro University, Indonesia.

References
[1] Stakic M, Urosevic T 2011 *Chem Eng Process Process Intensif* 428-437
[2] Suherman, Trisnaningtyas R 2015 *AIP Conf Proc*. 1699 (2015)
[3] Picado A 2006 *Simulation Of A Vibrated Fluidised Bed Dryer For Solids Containing A*
Multicomponent Moisture.

[4] Keppler S, Bakalis S, Leadley C E, Fryer P J 2015 J Food Eng. 1-10
[5] Liang X, Duan H, Wang J, Zhou T 2015 Procedia Eng. 102 887-892
[6] Nazghelichi T, Kianmehr M H, Aghbashlo M 2010 Energy (12) 4679-4684
[7] Alta ZD, Ertekln C, Machinery F, Agricultural F A 2014 review on exergy analysis of food production processes. 22 6-10
[8] Azadbakht M, Torshizi MV, Ziaratban A, Aghili H 2017 Int Agric Eng J. 19(3) 177-182
[9] Sarker M S H, Ibrahim M N, Abdul Aziz N, Punan M S 2015 Energy 84 131-138.
[10] Terehovics E, Veidenbergs I, Blumberga D 2017 Energy Procedia 128 551-557
[11] Handayani S U, Atmanto I S, Putri F T, Yulianto M E, Handayani D, Siswanto A P 2018 Adv Sci Lett. 24 (12) 9803-9805
[12] Suherman, Trisnantingtyas R 2016 Reaktor 16(1) 24-31
[13] Aviara N a, Onuoha L N, Falola O E, Igbeka J C 2014 Energy 73 809-817
[14] Corzo O, Bracho N, Vásquez A, Pereira A 2008 J Food Eng. 86(2) 151-161
[15] Özahi E, Demir H 2014 Measurement 60 85-96
[16] Syahrul S, Hamdullahpur F, Dincer I 2002 Exergy An Int J. 2(2) 87-98
[17] Syahrul S, Dincer I, Hamdullahpur F 2003 Int J Therm Sci. 42(7) 691-701
[18] Manalu L P, Tambunan A H, Subandrio, Wibowo T Y 2016 Int J Innov Res Sci Eng Technol. 5(7) 13607
[19] Celma a. R, Cuadros F 2009 Renew Energy 34(3) 660-666