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Energy Efficiency of a Biomass Powered Dryer: An Analysis of Flue Gas Velocity Effects During Chili Drying

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ABSTRACT

The increasing emphasis on renewable energy sources has fostered interest in the use of biomass waste as a potential power source. Despite this, few studies have explored its application in powering drying machinery. This study presents the design, fabrication, and performance testing of a biomass-powered dryer, specifically developed for chili drying. The constructed dryer, featuring a drying box, biomass furnace, and flue gas passage, is distinguished by its simplicity, cost-effectiveness, and its capacity to operate during inclement weather due to its reliance on flue gas derived from biomass combustion. Given the rising culinary demand for chili powder, effective drying of chili prior to powdering is crucial. This research furthers this goal by conducting an energy and exergy analysis of the flue gas dryer, operating at varying flue gas velocities of 8, 13, 14, and 15.5 m/s, during the chili drying process. In addition, sustainability indicators such as the Waste to Energy Ratio (WER) and Sustainability Index (SI) were also investigated. Preliminary findings indicate that the biomass-powered dryer operates effectively under indirect-forced convection mode, with flue gas velocity significantly influencing the energy and exergy outcomes of the dryer. Peak efficiencies for both energy and exergy were found to be 22% and 23.99%, respectively, at a flue gas flow of 13 m/s.

1. INTRODUCTION

Sun-drying methods have been extensively employed worldwide by traditional farmers for the desiccation of agricultural products. This approach typically involves the exposure of the product to sunlight to facilitate moisture elimination. For example, around one week of adequate sunshine is necessary to reduce moisture content to an optimal 7.0-7.5% [1]. However, the drying time - defined as the period needed to reach the desired moisture content - is substantially extended during the rainy season and can negatively impact product characteristics [2]. To address these limitations, more effective drying methods are needed.

Hot air is commonly utilized as a heating medium in both direct and indirect contact drying methods, under either free or forced convection conditions. Direct contact drying refers to processes where the heating medium directly interacts with the product during drying. Conversely, indirect contact drying involves scenarios where the heating medium and the product remain separate throughout the drying process. Natural convection mode is characterized by the natural flow of the heating medium due to temperature differences, whereas forced convection drying involves heating medium movement driven by external forces.

Various energy sources can supply the heat for the air-heating medium, depending on the design and application objectives. These sources include solar energy [3-5], biomass energy [6, 7], hybrid solar-biomass energy [8, 9], or flue gas energy [10]. Dryers operating under forced convection mode are reported to have superior thermal efficiency compared to those operating under natural convection, with recorded energy efficiencies of 67.66% and 59.74% respectively [5]. Although solar dryers demonstrate relatively high thermal efficiency, their functionality is compromised during the rainy season.

In response to these challenges, hybrid solar-biomass powered dryers have been developed. Despite their potential, these hybrid dryers require additional costs for the combustion chamber and have demonstrated relatively low thermal efficiency. For instance, the thermal efficiency of a biomass-powered dryer used for drying sliced turmeric fingers was reported to be merely 4.35% and 4.62% for passive and active modes, respectively [6]. One potential solution to mitigate excessive heat loss from the drying chamber in biomass-powered dryers is the application of thermal insulation on the drying chamber's walls [11].

Biomass energy-powered dryers present a promising technology, particularly in regions such as Indonesia, which boasts considerable biomass energy resources, amounting to approximately 33 GW [12]. Furthermore, the use of alternative energy sources such as biomass can significantly reduce carbon dioxide emissions and prevent high carbon footprint processes [13, 14]. These factors have motivated the present research, in which an indirect biomass-powered dryer was developed and its thermodynamic performance analyzed.

The first law of thermodynamics, focusing on the quantity and type of energy, does not address the quality of that energy. To consider the effects of irreversibility and surrounding conditions on energy losses, the exergy concept of the second law of thermodynamics must be employed [15]. Exergy, or the maximum work that can be performed by a system, acknowledges that energy losses and entropy generation are inevitable [16]. Therefore, an evaluation of energy and exergy (EEA) provides a valuable tool for assessing the thermodynamic aspects of the dryer and for developing an efficient dryer that takes into account irreversibility and losses to the surroundings [17].

Several studies have reported on the Energy and Exergy Analysis (EEA) of various types of dryers used for different products. Darvishi et al. [18] conducted an EEA of a microwave dryer used for drying kiwi slices. Their findings indicated lower moisture diffusivity effectiveness as the thickness of the slices increased and power was stepped up. Energy efficiencies ranged from 15.15% to 32.27%, while exergy efficiencies were between 11.35% and 24.68%. Additionally, the Specific Energy Consumption (SEC) values ranged from 7.79 to 16.20 MJ/kg. Chowdhury et al. performed an EEA of a tunnel type solar drying machine used for drying jackfruit skin [19]. They reported that both the inflow and losses of exergy in the heating chamber increased as solar radiation intensified. The average energy and exergy efficiencies were found to be 48.21% and 41.42%, respectively. El-Mesery and El-Khawaga [20] examined the EEA of tomato drying using three different dryers: a hot air convection dryer (HAD), a combined hot air-microwave dryer (MW-HAD), and a hot air-infrared dryer (IR-HAD). They reported a peak SEC of 92.6 MJ/kg at an air velocity of 3 m/s and an air temperature of 60ºC. In contrast, the lowest SEC of 3.77 MJ/kg was observed at 900 W and 80ºC in MW-HAD, which was suggested as the optimal operating condition for the dryer.

In another study, Lingayat et al. [21] conducted an EEA of a solar dryer of the indirect convective type under free convection (NCISD) while dehydrating bananas. The reported losses and exergy efficiencies ranged from 3.36 to 25.21 kJ/kg and 7.4% to 45.32%, respectively. The average exergy efficiency of the Solar Air Collector (SAC) was found to be 25.64%. Panwar utilized a NCISD drying machine for drying coriander leaves and performed an EEA [22]. The energy efficiency of the machine was observed to vary from 7.81% to 37.93%, while the exergy efficiency ranged from 55.35% to 79.39%. Karthikeyan and Murugavelh [23] conducted experiments and performed an EEA on a Forced Convection Indirect Solar Dryer (FCISD) for the dehydration of turmeric. They reported that the exergy efficiency of the FCISD ranged from 23.25% to 73.31% with an average of 49.12%. Akpinar [24] conducted a similar study using an FCISD on mint leaves. They reported an exergy efficiency that ranged from 34.76% to 87.717%, and identified the highest potential for improving performance (IP) as 0.017 kW. Mugi and Chandramohan [17] performed an EEA during the drying of okra in an Indirect Solar Dryer (ISD). The average SAC was 74.98% and the efficiency was 24.95% under forced convection conditions, while under free convection conditions, the average SAC was 61.49% and the efficiency was 20.13%. The EEA analysis revealed that the ISD operated more effectively under forced convection conditions.

In stark contrast to the extensive body of research on Energy and Exergy Analysis (EEA) pertaining to solar dryers, only a limited number of studies have been conducted on flue gas dryers. A notable contribution in this area is the work of Silva et al. [25] who conducted EEA on a flue gas-powered rotary dryer used for drying sawdust in a large-scale pellet facility. The rotary dryer exhibited an efficiency of 1.5% and 2.2% in terms of energy and exergy, respectively. Silva et al. further recommended the recovery of flue gas enthalpy for the pre-heating process.

A review of the literature reveals that while solar air dryers cannot operate during rainy seasons and have high initial costs, hybrid solar-biomass dryers suffer from low thermal efficiency. To optimize the design of biomass dryers, EEA can be used as a crucial tool for development. However, the majority of EEA studies focus on solar dryers, with very few examining flue gas dryers.

The current study addresses this gap in the literature by designing, fabricating, and testing a biomass-powered dryer. The primary objectives of this research are to create a biomass energy-powered dryer that operates efficiently in both dry and rainy seasons, and to analyze its performance using EEA under different flue gas velocities. Additionally, this work aims to investigate sustainability indicators in terms of Water-Energy Ratio (WER) and Sustainability Index (SI).

2. METHOD

The work is begun by designing and fabricating biomass energy powered dryer. The dryer is tested its performance while drying chili using rice husk as biomass energy source by performing energy and exergy analysis (EEA) at different flue gas velocities. The work also investigates sustainability indicators of the biomass energy powered dryer.

2.1 Material

Figure 1 present a photograph and technical drawing of a biomass energy powered dryer fabricated in the present work. The dryer has main component of a furnace, a drying cabinet, a blower, and an exhaust fan. The furnace and drying cabinet are made from Steel plate. The furnace has a size of 574×570×594 mm and the cabinet has an overall dimension of 1000×600×1200 mm. Flue gas from a furnace passes a drying cabinet through a passage between inner wall and outer wall of the cabinet (i.e. indirect contact dryer). Blower is used to blow a combustion air to a furnace. The dryer can be run in natural convection mode as well as in forced convection mode.

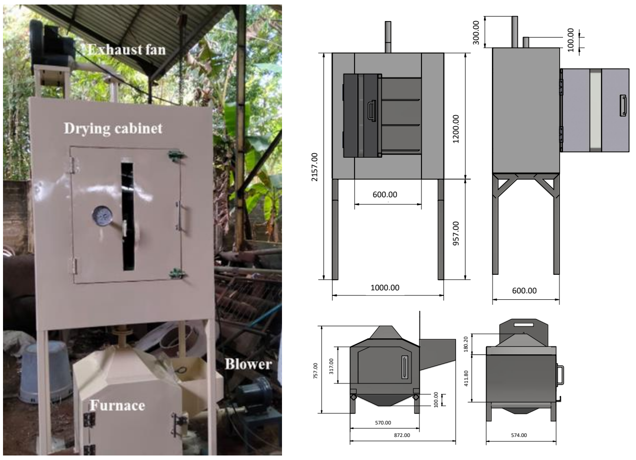

Figure 1. Photograph and its technical drawing of the dryer (unit: mm)

2.2 Experimental work

In the present work, the test is conducted using 6 kg rice husk as the energy source of a dryer while drying 3 kg chili for 2 hours. Every tray in the cabinet is loaded with 1 kg chili. The tests are performed in forced convection mode at different flue gas velocity, i.e., 8, 13, 14, and 15.5 m/s. The velocity of flue gas passing through the passage is controlled by mean controlling rotation speed of the exhaust fan. Figure 2 displays experimental setup of the work. During the test, temperature of a sample at each tray (T_1, T_2, and T_3), temperature of inlet flue gas (T_4) and outlet flue gas (T_5) are measured using K-type thermocouple and logged into data logger Graphtec240. Temperature of ambient air (T_0) is also measured using thermometer. For all tests, combustion air is supplied using blower with flow rate of 27 m^3/h. Mass of sample before and after drying are weighted using a digital balance. Meanwhile, energy, exergy, and efficiency of the furnace, the drying cabinet, and the entire system are calculated using data collection during the experimental work.

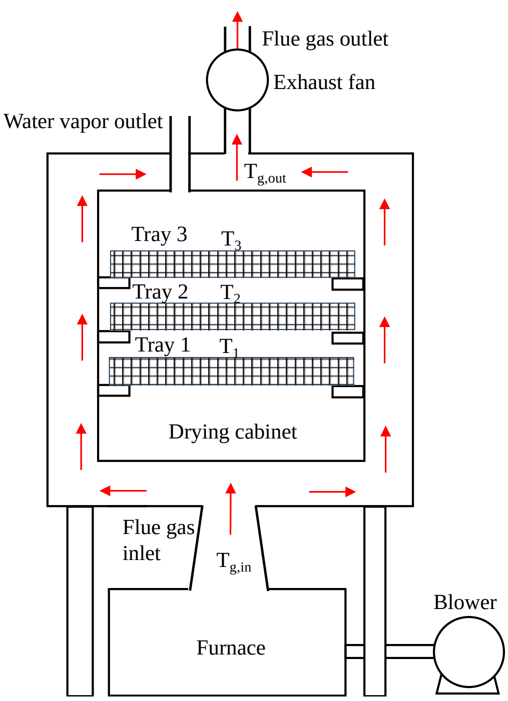

Figure 2. Experimental setup

2.3 Energy analysis

Once data are collected, EEA for the furnace, drying chamber and the overall system are conducted. In addition, sustainability indicators in terms WER and SI are also assessed in this work.

2.3.1 Energy analysis of the furnace

By assuming steady flow process, mass and energy conservation of the furnace are obtained using Eq. (1) and Eq. (2).

$$\sum m_{f,in} = \sum m_{f,out} \quad (1)$$

$$Q_{f,in} = Q_{f,out} + Q_{f,loss} \quad (2)$$

where, $m_{f,in}$ is the mass of total biomass and combustion air fed to the furnace, $m_{f,out}$ is the mass of flue gas produced by the furnace, $Q_{f,in}$ is the heat input to the furnace, $Q_{f,out}$ is the useful heat produced by the furnace, and $Q_{f,loss}$ is the heat loss from the furnace to the surrounding. $Q_{f,out}$ and $Q_{f,in}$ are calculated using Eq. (3) and Eq. (4).

$$Q_{f,out} = m_{f,out} c_{p,g} (T_g - T_0) \quad (3)$$

$$Q_{f,in} = m_b HHV_b \quad (4)$$

where, $c_{p,g}$ is the specific heat of flue gas (1.0 $kJkg^{-1}K^{-1}$) [25], T_g and T_0 are the flue gas temperatures and ambient temperature, m_b is the mass of biomass used, and HHV_b is the Higher Heating Value of the biomass.

The furnace energy efficiency ($\eta_{en,f}$) is defined as heat output to heat input ratio which is calculated using Eq. (5).

$$\eta_{en,f} = \frac{Q_{f,out}}{Q_{f,in}} = \frac{m_{f,out} c_{p,g} (T_g - T_0)}{m_b HHV_b} \quad (5)$$

2.3.2 Energy analysis of the drying cabinet

Similar with a furnace where process is assumed steady flow, the conservation of mass and energy of the cabinet are obtained using Eq. (6) and Eq. (7).

$$\sum m_{g,in} = \sum m_{g,out} \quad (6)$$

$$Q_{g,in} = Q_{g,used} + Q_{g,loss} \quad (7)$$

where, $m_{g,in}$ is the mass of flue gas at inlet of the drying cabinet, $m_{g,out}$ is the mass of flue gas at outlet of the dryer. By assuming 0.65 volumetric efficiency of the exhaust fan, the mass of a flue gas entering the drying cabinet is calculated using Eq. (8). Typically, the exhaust fan with forward curved blade has peak efficiency about 60-65%. Hence, it is acceptable to use fan's volumetric efficiency of 0.65 in Eq. (8).

$$\sum m_{g,in} = 0.65 \rho_g A v_g \quad (8)$$

where, ρ_g is the density of the flue gas, A is the passage area, and v_g is the flue gas velocity. Flue gas density at atmospheric pressure and flue gas temperature is obtained using a graph in www.pipeflowcalculations [26]. Meanwhile, energy input and used energy of the drying chamber are obtained using Eq. (9)

and Eq. (10).

$$Q_{g,in} = m_{g,in}\, c_{p,g}\left(T_{g,in} - T_0\right) \quad (9)$$

$$Q_{g,used} = \left(m_{s,in} c_{p,s} \Delta T_s\right) + \left(m_v h_{fg}\right) \quad (10)$$

where, $m_{g,in}$ is the mass of a flue gas, $c_{p,g}$ is the specific heat of a sample, $T_{g,in}$ is the flue gas temperature, T_0 is the ambient temperature, $m_{s,in}$ is the sample initial mass, $c_{p,s}$ is the sample specific heat (1.87 kJ/kg.K), ΔT_s is the temperature difference of the sample before and after drying, m_v is the mass of water vapor, and h_{fg} is the latent heat of vaporization of water (2260 kJ/kg). The m_v is calculated using Eq. (11).

$$m_v = m_{cb,in} - m_{cb,out} \quad (11)$$

where, $m_{s,in}$ and $m_{s,out}$ are the mass of sample before and after drying, respectively.

Energy efficiency of drying cabinet ($\eta_{en,d}$) is the ratio of useful energy for drying to the drying cabinet which is calculated using Eq. (12).

$$\eta_{en,d} = \frac{Q_{g,used}}{Q_{g,in}} = \frac{\left(m_{s,in} c_{p,s} \Delta T_s\right) + \left(m_v h_{fg}\right)}{m_{g,in}\, c_{p,g}\left(T_{g,in} - T_0\right)} \quad (12)$$

Once energy analysis results of the furnace and drying cabinet are obtained, the overall efficiency, SEC, and drying rate are calculated. SEC of the dryer is defined as 1 kg of water evaporate per 1 kg. Meanwhile, drying rate is a mass of water vapor evaporated divided by drying time [7, 27].

$$SEC = \frac{Q_{f,in}}{m_v} = \frac{m_b HHV_b}{m_v} \quad (13)$$

$$\dot{m}_p = \frac{m_v}{t} \quad (14)$$

$$\eta_{en,o} = \eta_{en,f}\eta_{en,d} \quad (15)$$

2.4 Exergy analysis

Exergy analysis of the thermal system is based on the second law of thermodynamics. Exergy is a measure of the quality of energy. It is the available energy that can be used in a system. It gives information about available energy that can be used to optimize the drying process in the dryer [21]. Assuming steady flow drying process, exergy per unit mass of any system is proposed by Mugi and Chandramohan [17] as:

$$Ex = mc_p\left[(T - T_0) - T_0 ln\left(\frac{T}{T_0}\right)\right] \quad (16)$$

2.4.1 Exergy analysis of furnace

Exergy balance for the furnace is calculated using Eq. (14) where $Ex_{f,in}$, $Ex_{f,out}$, and $Ex_{f,loss}$ are the exergy inflow, the exergy outflow, and the energy loss for the furnace, respectively.

$$\sum Ex_{f,in} = \sum Ex_{f,out} + \sum Ex_{f,loss} \quad (17)$$

Exergy inflow to furnace denotes biomas chemical exergy fed into a furnace which can be computed using a simple equation [28].

$$Ex_{f,in} = Ex_{b,in} = 1.047 m_b HHV_b \quad (18)$$

Exergy outflow from the furnace is expressed in Eq. (19).

$$Ex_{f,out} = m_g c_{p,g}\left[\left(T_g - T_0\right) - T_0 ln\left(\frac{T_g}{T_0}\right)\right] \quad (19)$$

Exergy loss or irreversibility of the furnace (I_f) is expressed as:

$$Ex_{f,loss} = I_f = 1.047 m_b HHV_b - m_g c_{p,g} \left[\left(T_g - T_0\right) - T_0 ln\left(\frac{T_g}{T_0}\right)\right] \quad (20)$$

The furnace exergy efficiency is obtained from Eq. (21).

$$\eta_{ex.f} = \frac{Ex_{f,out}}{Ex_{f,in}} = 1 - \frac{Ex_{f,loss}}{Ex_{f,in}} \quad (21)$$

2.4.2 Exergy analysis of drying cabinet

The exergy balance of the drying cabinet is formulated in Eq. (22) where, $Ex_{d,in}$, $Ex_{g,used}$, and $Ex_{g,loss}$ are the exergy inflow, exergy outflow, and exergy loss of the drying chamber, respectively.

$$\sum Ex_{d,in} = \sum Ex_{g,used} + \sum Ex_{g,loss} \quad (22)$$

Following Kuzgunkaya and Hepbasli [29], the $Ex_{d,in}$ and $Ex_{d,out}$ of the heating chamber:

$$Ex_{g,in} = m_g c_{p,g}\left[\left(T_{g,in} - T_0\right) - T_0 ln\left(\frac{T_{g,in}}{T_0}\right)\right] \quad (23)$$

$$Ex_{g,used} = m_s c_{p,s}\left[\left(T_{s,out} - T_0\right) - T_0 ln\left(\frac{T_{s,in}}{T_0}\right)\right] \quad (24)$$

where, m_g is flue gas mass entering a drying passage, $c_{p,g}$ is the flue gas specific heat (1 kJ/kg.k), $T_{g,in}$ and $T_{g,out}$ are the flue gas temperatures entering and leaving the drying cabinet, ms is the mass of dried sample, $c_{p,s}$ is the specific heat of sample (1.87 kJ/kg.K), Ts,in and Ts,out are the sample temperature, and T_0 is the temperature of ambient air.

The cabinet exergy efficiency is valued using Eq. (25) given by Akpinar [24].

$$\eta_{ex.d} = \frac{Ex_{d,out}}{Ex_{d,in}} \quad (25)$$

Meanwhile, overall exergy efficiency of the system is obtained using

$$\eta_{ex,o} = \eta_{ex,f}\eta_{ex,d} \quad (26)$$

2.5 Sustainability indicator analysis

Thermodynamics performance of the dryer can be better evaluated using exergy sustainability indicators in terms of a WER and SI. The indicators address the irreversibility and exergy waste during a process [17]. The WER and SI are calculated using equations proposed by Ndukwu et al. [30].

$$WER = \frac{Ex_{loss}}{Ex_{in}} \quad (27)$$

$$SI = \frac{1}{1 - \eta_{ex}} \quad (28)$$

3. RESULT AND DISCUSSION

Figure 3(a) to 3(d) display temperature profile of a sample in tray 1, tray 2, and tray 3 during the test for flue gas velocity of 8, 13, 14, and 15.5 m/s. Temperature of sample in tray 1, 2, and 3 increase gradually after 20 minutes drying at flue gas velocity of 8 and 13 m/s and the temperature step up significantly after 10 minutes at flue gas velocity of 14 and 15.5 m/s. At this stage, combustion rate of the biomass in the furnace reaches maximum which releases maximum heat and more heat is transferred to the drying cabinet. After reaching 60 to 70°C, the drying temperature relatively stable and declined gradually at the end of the drying at all flue gas velocity investigated. The amount of heat from the furnace to the drying cabinet reduces due to combustion rate get slower at the end of the drying. Mostly, the biomass in the furnace has already bunt out at this time.

From Figure 3, similar temperature trend of the sample at tray 1, tray 2, and tray 3 at flue gas velocity of 8, 13, 14, and 15.5 m/s are reveled. The temperature of a sample can be ranked as tray 1>tray 2>tray 3. More amount of heat is obtained by tray 1 which causes higher temperature of tray 1. The more uniform the temperature in the drying cabinet, the better the performance of the dryer. The most uniform temperature in the drying cabinet is observed at velocity of 13 m/s. As indicated in Figure 3, the temperature difference between the trays at 13 m/s is the smallest when compared with the same at other flue gas velocities. Almost equal amount of heat is transferred to the tray 1, tray 2, and tray 3 when flue gas velocity is maintained 13 m/s. Compared with Alit et al. [7], temperature distribution on the tray is better in the present work, since the temperature difference between the tray is smaller in the present work.

Figure 4(a) and 4(b) present energy analysis in terms of energy input and energy output of a furnace and a drying chamber. Although same amount of rice husk is fed for 2 hours drying time, but heat input is different for different flue gas velocity. This difference in heat input due to completeness level of feedstock combustion. The less unburnt rice husk at the end of drying, the more complete the combustion. More amount of rice husk burnt leads to higher heat input. As can be seen from Figure 4(a), the highest heat input occurs at 13 m/s. The amount of unburnt rice husk is the lowest at velocity of 13 m/s. It indicates the highest level of combustion which impacts the highest of heat input. This heat input directly affects heat output of the furnace. Increasing energy input causes enhancing heat output of the furnace. Thus, the trend of heat output is similar to trend of energy input.

The trend of energy input to the drying cabinet follows the trend of energy generated by the furnace. Flue gas velocity gives significant effect on energy used for drying the sample in the furnace. As shown in Figure 4(b), increasing velocity from 8 m/s to 13 m/s enhances energy utilization in the furnace. Increasing flue gas velocity causes heat transfers enhancement from the passage to the drying cabinet due to enhancing convection coefficient of the flue gas. However, energy utilization in the drying cabinet reduces even though flue gas velocity further increases. The convection coefficient increases with increasing flue gas velocity, but contact time between flue gas and the cabinet also reduces which causes heat transfer to the cabinet steps down. It can be stated that heat transfer from a flue gas to the sample is affected not only by convection coefficient but also by contact time. Convection heat transfer improves as increasing flue gas velocity, but in other hand contact time reduces as increasing heating medium velocity. The shorter gas residence time, resulting in the heat transfer rate reduces [10]. At velocity of 13 m/s, the net effect of these two are the highest, causes optimum heat transfer from the flue gas to the drying cabinet.

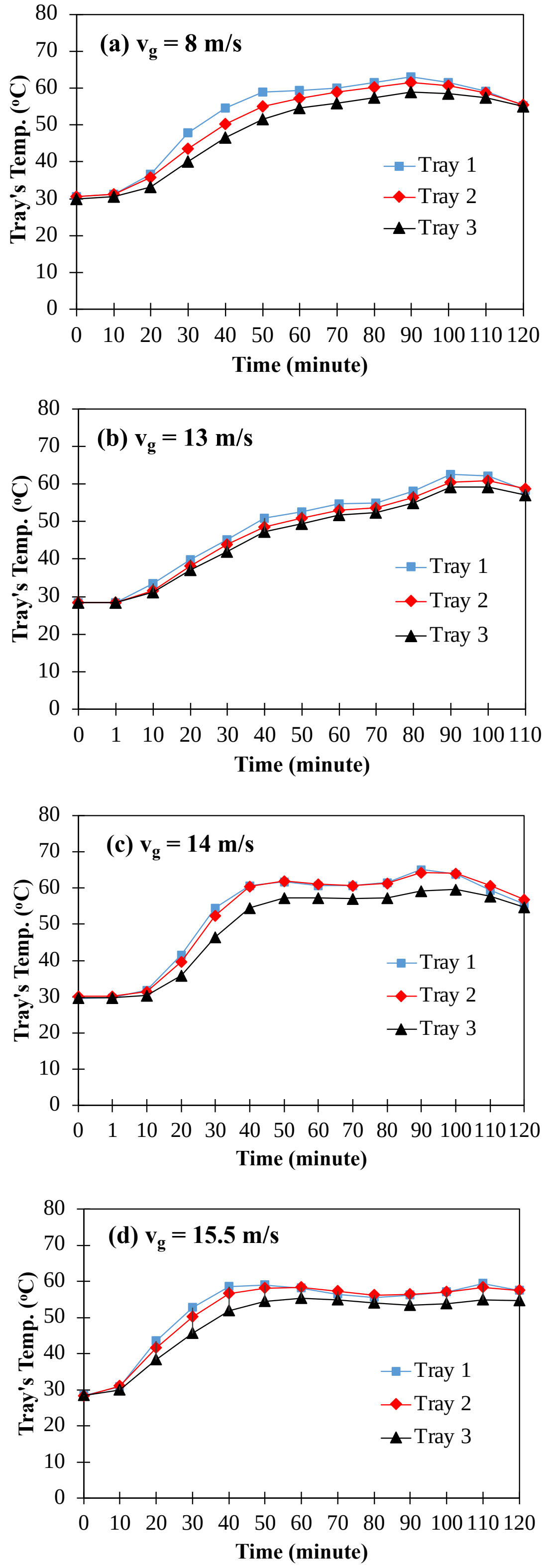

Figure 3. Temperature profile of a sample

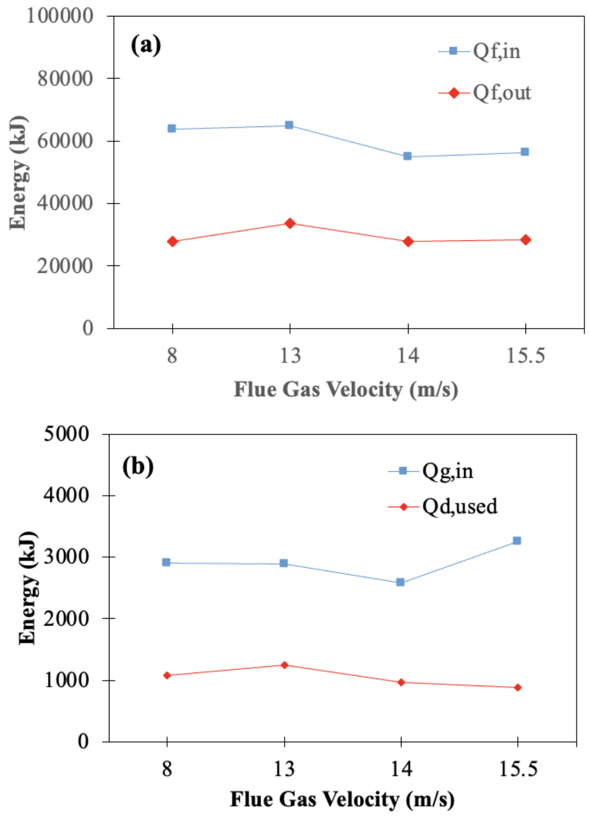

Figure 4. Energy analysis

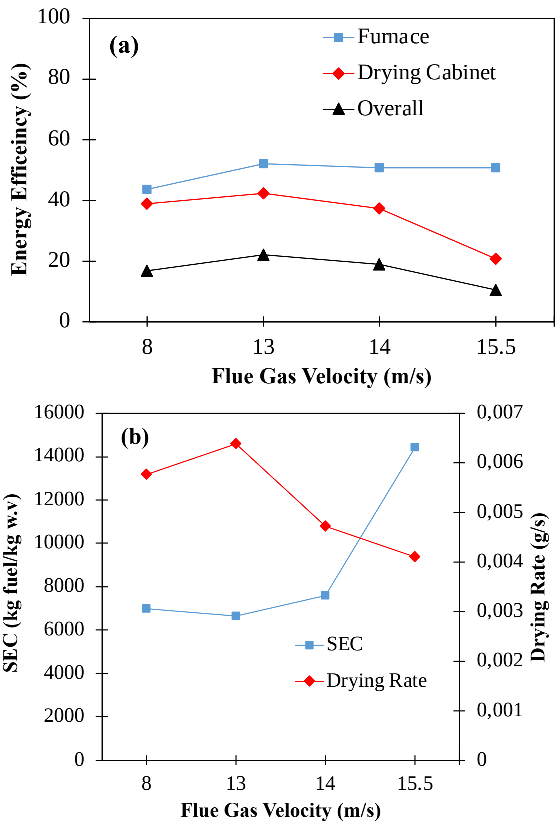

Figure 5. Energy efficiency, SEC, and drying rate

Energy efficiency of the furnace, drying cabinet, and overall efficiency of the system is given in Figure 5(a). Energy efficiency of the furnace steps up when flue gas velocity increases from 8 m/s to 13 m/s. Maximum energy efficiency of the furnace is found to be 52.05% at flue gas velocity of 13 m/s. The values are slightly decreases for flue gas velocity higher than 13 m/s. Meanwhile, energy efficiency of the drying cabinet decreases after reaching maximum value of 42.28% at flue gas velocity of 13 m/s. At velocity of 13 m/s, optimum heat of flue gas is transferred to the drying cabinet. Since the overall energy efficiency of the dryer is affected by energy efficiency of the furnace and the drying box, the overall energy efficiency of the dryer is obtained at velocity of 13 m/s. The maximum energy efficiency of the dryer is 22.01%. This value is higher than thermal efficiency of biomass-fired heater (4.62%) obtained by Rabha [6], but lower than that reported by Asnaz and Dolcek [5].

Figure 5(b) presents an effect of velocity on specific energy consumption (SEC) and drying rate. It is obtained inversely proportional relation between SEC and drying rate. The SEC decreases as velocity increases from 8 m/s to 13 m/s and it inclines at velocity higher than 13 m/s. The lower the SEC, the lesser energy needed for evaporating 1 kg water vapor of the sample. The lowest SEC of 6651.96 kJ rice husk per kg water vapor is obtained at flue gas velocity of 13 m/s. In contrast, drying rate steps up at velocity moves from 8 m/s to 13 m/s and it declines as velocity higher than 13 m/s. The highest drying rate of 0.0063 g/s occurs at the lowest SEC, i.e., at velocity of 13 m/s.

Figure 6(a) and 6(b) present exergy analysis results of the furnace and the drying cabinet. The graph in Figure 6(a) indicates similar trend between inflow exergy and outflow exergy in the furnace. The outflow energy increases as increasing inflow energy in the furnace and vice versa the outflow energy reduces as reducing inflow energy. From Figure 6(b), the similar trend of inflow exergy and used exergy is also observed.

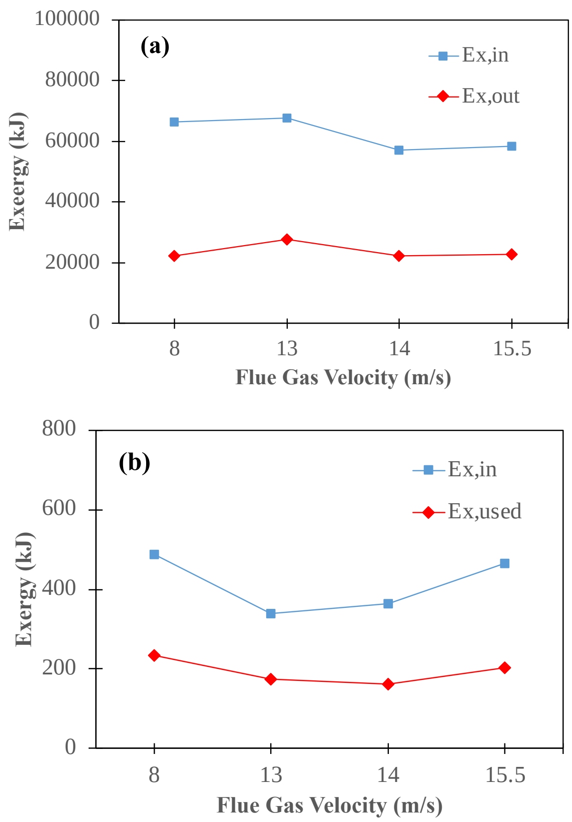

Figure 6. Exergy analysis

Ratio between inflow exergy and outflow exergy is defined as exergy efficiency. The exergy efficiency of the furnace and the drying cabinet, and also overall exergy efficiency of the dryer are given in Figure 7(a). Exergy efficiency of the furnace, the drying box, and the overall dryer are incline as flue gas velocity steps up from 8 m/s to 13 m/s. After reaching maximum values at flue gas velocity of 13 m/s, those exergy efficiencies decrease as increasing flue gas velocity from 13 m/s to 15.5 m/s. Maximum exergy efficiency for the furnace, the drying cabinet and the overall system are 40.97%, 58.56%, and 23.99%, respectively.

Sustainability indicator of the biomass energy powered dryer is analyzed in terms of waste to energy ratio (WER) and sustainability index (SI). The WER is defined as a ratio of exergy loss to exergy input. The smaller the WER, the better the performance of the system. On the other hand, the SI indicates the potential of the dryer as a sustainable energy system. The higher the SI, the better the sustainability of the dryer. Figure 7(b) shows an effect of flue gas velocity on WER and SI of the biomass energy powered dryer. From the graph in Figure 7(b), the WER of the dryer ranges from 0.41 to 0.56 and the SI is in the range of 1.78-2.41. The SI in the present work is lower than SI obtained by Ndukwu et al. [30]. The best performance on the dryer in terms of sustainability is obtained at flue gas velocity of 13 m/s. At this flue gas velocity, the WER is minimum (0.41) and SI is maximum (2.41). In can be stated that the rice husk powered dryer fabricated in the present work has to be operated at flue gas velocity of 13 m/s.

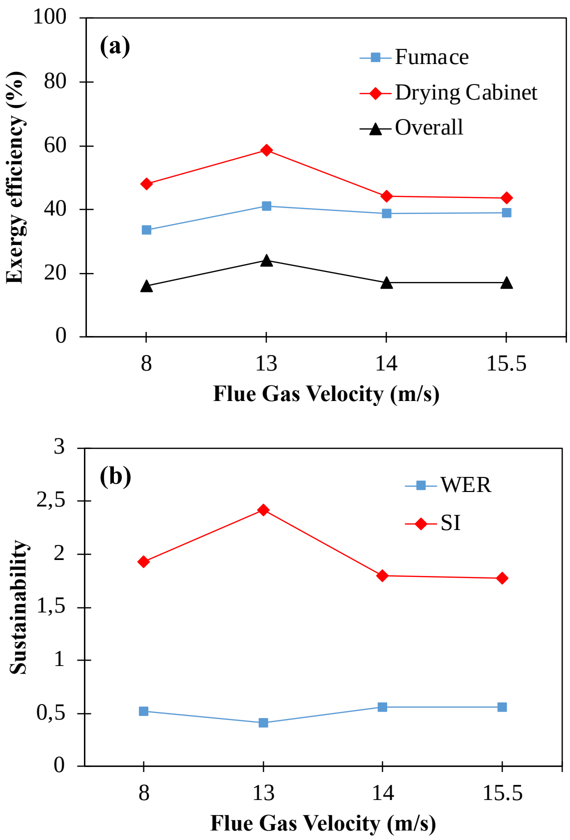

Figure 7. Exergy efficiency and sustainability

Figure 8(a) and 8(b) show the photograph of the chili as a sample of dried product before and after drying in the rice husk powered dryer for 2 hours. The color of dried chili turns dark after drying which indicates the sample has experience water vapor loss after 2 hours drying. The rice husk powered dryer work properly while drying 3 kg of chili. However, it requires longer drying time to fulfil the minimum water content of the chili for making chili powder.

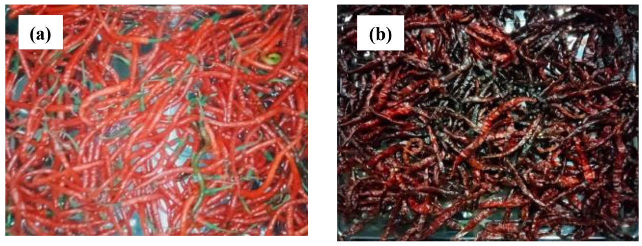

Figure 8. Photograph of a sample

It can be summarized that flue gas velocity affects performance (i.e., energy, exergy, efficiency, and sustainability) of the biomass powered dryer. Increasing flue gas velocity means that its mass flow rate inclines and its convection coefficient improves, leads to enhance heat transfer to the drying cabinet, in turns improve performance of the dryer. If the flue gas velocity is too high, the performance of the dryer reduces due to contact time between the flue gas and the cabinet wall is shorten which impacts on reduction in heat transfer to the cabinet that leads performance of the dryer decreases. The best performance of the dryer is obtained under forced convection mode with flue gas velocity of 13 m/s. At flue gas velocity of 13 m/s, the net effect between convection coefficient and contact time are the highest which causes optimum heat transfer from the flue gas to the drying cabinet, and results the best performance of the dryer.

4. CONCLUSION

The biomass energy powered dryer has been fabricated and tested in this work. EEA is conducted while drying chili using rice husk as biomass energy source at different flue gas velocity. The sustainability indicator of the dryer has also been investigated. It can be concluded that:

1. The biomass energy powered dryer works properly for drying the agriculture product under indirect-forced convection mode.
2. Velocity of flue gas effect energy and exergy of the dryer significantly. Velocity impacts convection coefficient and contact time. Increasing flue gas velocity gives positive effect on convection coefficient but give negative effect on contact time between flue gas and drying cabinet's wall. The highest overall energy efficiency (22%) and the highest exergy efficiency (23.99) of the dryer are obtained at flue gas velocity of 13 m/s.
3. The biomass waste, such as rice husk waste, has a good potential for drying an agriculture product. The rice husk powered dryer while drying chili has lower waste to energy ratio (0.41) and high sustainability index (2.41) at velocity of 13 m/s.
4. The biomass powered dryer is interesting technology for farmer in rural area since simplicity of the design and low-cost fabrication. The most important is that the dryer will help the farmer in drying their agriculture product during rainy season. In addition, the use of waste of biomass as a feedstock of the dryer can contribute diversification of biomass utilization.

5. In the next work, the performance of the dryer should be investigated under various biomass feedstocks. It is recommended that the moisture content of the feedstocks has to be maintained under 30% to obtain better combustion in the furnace. It is suggested to investigate dryer performance under free convection in the future work to get more comprehensive understanding of the dryer.

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