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Study on the Energy and Exergy of a Biomass-Assisted Recirculating Mixed-Flow Dryer Utilized for Drying Paddy

M. Yahya[1] , **Dedi Wardianto**[2]

[1,2] Departemen of Mechanical Engineering, Institut Teknologi Padang
Jl. Gajah Mada Jl. Kandis Raya, Kp. Olo, Kec. Nanggalo, Kota Padang, Sumatera Barat 25173, INDONESIA

*Corresponding Dedi Wardianto, dediwardianto@itp.ac.id

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Abstract

The performance of a biomass-assisted recirculating mixed-flow dryer for drying paddy (Oryza sativa L.) was thoroughly assessed. The dryer system comprises a biomass furnace, drying column, vibratory feeder, bucket elevator, and blower. In the experimental setup, the drying time required to reduce the moisture content of paddy from 20.90% (wet basis) to 13.30% (wet basis) was measured at 4.5 hours. During this period, the average air temperature was recorded at 78.15 °C, accompanied by an average relative humidity of 8.55%. The observed drying rate ranged from 1.688 to 18.126 kg/h, with an average value of 7.792 kg/h. Further analysis revealed that the specific moisture evaporation rate (SMER) and specific energy consumption (SEC) varied between 0.122 and 1.308 kg/kWh, and 0.806 and 8.657 kWh/kg, respectively. The corresponding average values were 0.562 kg/kWh for SMER and 4.119 kWh/kg for SEC. The thermal efficiency of the dryer, along with exergy efficiency, demonstrated a range of 7.82% to 83.99% and 15.28% to 25.64%, respectively. The average values for thermal efficiency and exergy efficiency were calculated as 36.11% and 19.46%. Meanwhile, the efficiency of the biomass furnace ranged from 70.63% to 87.70%, with an overall average efficiency of 79.53%.

Keywords: Paddy, drying, recirculation, mixed flow, performance

INTRODUCTION

Indonesia stands as an agricultural economy, endowed with expansive and fertile agricultural land, coupled with a tropical climate conducive to plant growth due to abundant sunlight and rainfall. Notably, the country holds a prominent position as one of the world's leading rice producers. In 2022, rice production is anticipated to reach approximately 55.67 million tons of milled dry grain. When converted into rice, this would amount to around 32.08 million tons, with a harvested area covering approximately 10.61 million hectares.

Beyond its significant production capacity, Indonesia is also one of the largest consumers of rice globally, with an annual per capita consumption averaging around 111.58 kg [1]. This underscores the vital role that rice plays in the daily lives and dietary habits of the Indonesian population. The synergy of favorable agricultural conditions and a robust production-consumption cycle positions Indonesia as a key player in the global rice market.

Paddy (*Oryza sativa* L) produces rice as the primary staple food for nearly 90% of Indonesia's population. It, therefore, stands as a significant economic resource for over 30 million farmers in Indonesia. Following the harvest, it typically carries a relatively high water content, ranging from approximately 20-23% on a wet basis during the dry season and around 24-27% on a wet basis in the rainy season. This elevated water content renders rice susceptible to fungal attacks and damage, making it unsafe for extended storage. To ensure the long-term safety and suitability for milling, it is imperative to promptly dry paddy until it reaches a moisture content of around 14% on a wet basis [2].

Traditionally, paddy is dried through the straightforward method of sun drying. This approach presents several advantages, including its simplicity, low initial and maintenance costs, and the utilization of readily available solar energy. However, traditional drying also comes with certain drawbacks. These include the need for a substantial drying area, dependence on weather conditions, extended drying times, and potential compromises in rice quality. Additionally, there is a risk of significant rice yield losses due to issues such as scattering and being susceptible to consumption by birds and chickens.

To address the drawbacks associated with traditional grain drying methods, the use of recirculating mixed-flow dryers can be a viable solution. These dryers present notable advantages, including their appropriateness for grain drying, efficient and shortened drying times, high-quality drying outcomes, and minimal loss of rice during the drying process [3].

Recirculating mixed-flow dryers have been successfully employed in the drying of high-moisture grain products, including rice [4], corn [5], wheat [6], and soybeans [7]. However, it is worth noting that despite the efficacy of these dryers, fossil fuels are commonly utilized as an energy source to heat the drying air during the drying process. This reliance on fossil fuels poses environmental concerns, given their non-renewable nature, high costs, perpetual price increases, and limited supply [8,9].

The utilization of biomass energy serves as a promising alternative to address the limitations associated with fossil fuel energy sources. Biomass energy offers several advantages, including low emissions, sustainability as a renewable energy source, and availability in large quantities at a relatively affordable cost.

Numerous researchers have successfully developed various types of dryers incorporating biomass energy sources for drying a range of products. These dryers are integrated with biomass furnaces, and examples include a fluidization dryer designed for drying rice [9,10], a rack-type dryer used for drying corn [11], red chilies [12], cashew seeds [13], and pineapples [14], as well as tunnel dryers for drying fish [15] and red pepper [16]. Notably, the drying process for paddy demands a substantial amount of heat energy to facilitate the evaporation of water present in the rice grains [17].

Several researchers have conducted performance analyses, particularly in terms of energy consumption, for various types of drying equipment used in rice drying processes. These drying equipment include fixed bed dryers [18], inclined bed dryers [19], fluidized bed dryers [9,10,20,21], spouted bed dryers [20,22], mixed-flow dryers [23], and rotary dryers [24]. The findings of these studies collectively underscored that the drying process demands a significant amount of heat energy to facilitate the evaporation of water within the material being dried.

Exergy is defined as the maximum amount of network obtainable when a flow of material, heat, or current work attains equilibrium with a reference environment. Exergy analysis is a valuable method employed to devise strategies for designing and operating optimal systems in industrial processes. This analytical approach proves effective in various aspects such as design, determination of operating costs, energy conservation, assessment of fuel versatility, and evaluation of pollutants. In recent years, exergy analysis has gained widespread use for evaluating the performance of thermal systems.

In the context of the drying process, the primary objective is to utilize the minimum amount of energy required to extract the maximum amount of water from the material, achieving the desired final product state. Employing exergy analysis in the evaluation of drying processes contributes to the efficient use of energy resources and aids in the development of systems that are both economically and environmentally sustainable [25].

Based on a literature review, there is currently no reported study on the performance, specifically in terms of energy and exergy, of a biomass-assisted recirculation mixed-flow dryer for drying paddy. Furthermore, considering Indonesia's substantial annual production of biomass energy, estimated at around 236 million tons, there exists a significant potential to utilize this biomass energy as a source of heat energy in the drying process [26]. Therefore, the objective of this research is to design, manufacture, and assess the performance of a mixed flow type recirculation dryer assisted by biomass energy specifically tailored for drying paddy. available in Indonesia for more sustainable and efficient rice drying processes.

MATERIALS AND METHOD

2.1 Experiment Set-up

A mixed-flow recirculation dryer using biomass energy to dry rice has been designed and manufactured, as shown in **Fig. 1**. This dryer has several components, namely: biomass furnace, drying column, vibratory feeder, bucket elevator, blower, and duct. air. The drying tower or column consists of three parts: a storage section, a drying section, and a discharge section. A biomass furnace consists of several main parts, namely: biomass fuel combustion chamber, heat transfer pipe, chimney, and blower.

The working principle of a mixed flow type recirculation dryer using biomass energy, as shown in **Fig. 1**, is as follows: First, the dryer is filled with rice using a bucket elevator into the hopper above the dryer and flows vertically downwards with gravity, while the rice discharge section is closed or the paddy dispensing roller at the bottom of the dryer is turned off. The material discharge roller is operated on the rotary valve principle to allow a constant product mass flow rate. When the rice in the dryer has reached the desired height, Then air from the environment is flowed into the biomass furnace using a blower. In a biomass stove, the air is heated in a heat exchanger by utilizing heat energy from the combustion of biomass in the combustion chamber. The air is heated in the biomass furnace according to the desired drying temperature. Then the hot air coming out of the biomass furnace is channeled to the drying room (drying section) using a blower for the drying process. In this drying room, hot air is forced through the gaps between the rice grains and comes out, carrying moisture from the dried material. Then the moist air is discharged into the environment. In the drying section, the moist rice crosses the drying section almost vertically while the hot air (drying air) flows horizontally. After that, the draining section is opened, and the dried material falls into the vibratory feeder. Then the vibration feeder flows or moves the rice to the bottom of the elevator bucket, and the rice at the bottom of the elevator bucket is moved or circulated to the top of the dryer for the next drying process. This process is carried out continuously until the water content of the rice has reached the desired limit.

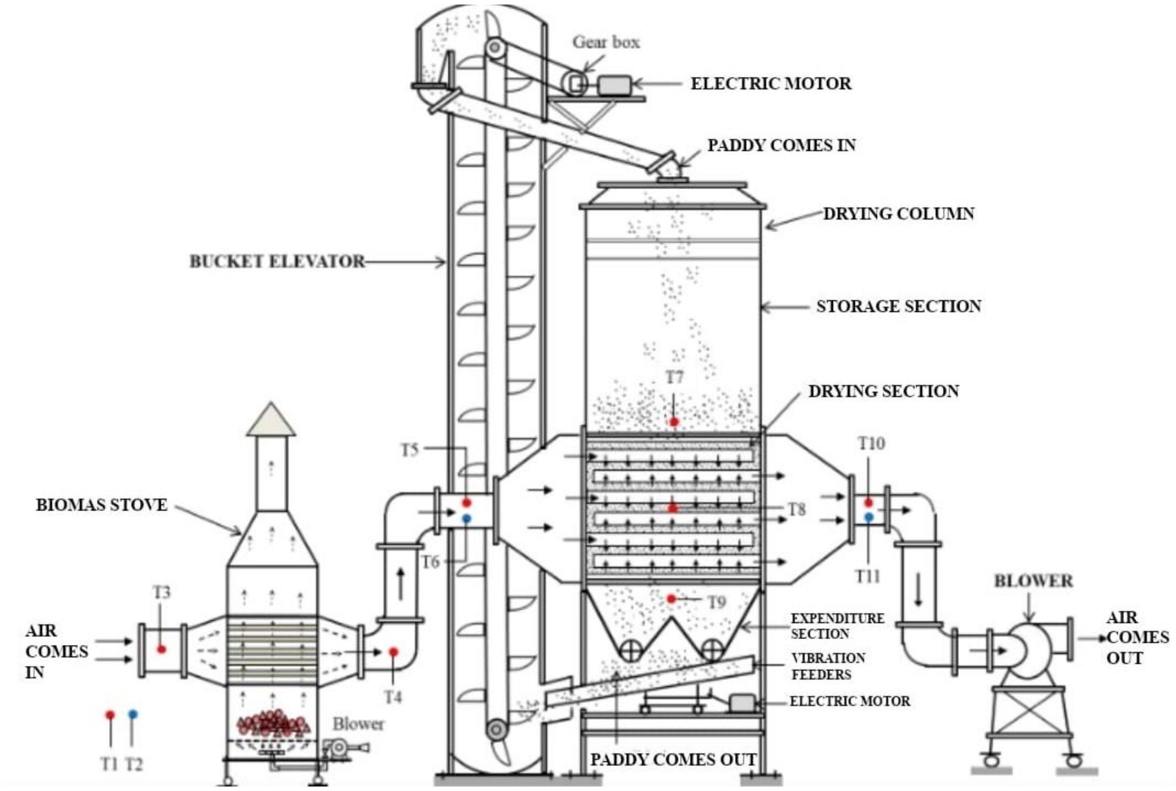

Fig. 1. Schematic of a biomass-assisted recirculating mixed-flow dryer

2 .2. Testing Procedure

The testing of the dryer took place at Institut Teknologi Padang in Sumatra Barat, Indonesia. As much as 400 kg of fresh paddy (*Oryza sativa* L.) sourced from local farmers in Padang was introduced into the drying column, as illustrated in Figure 1. Temperature measurements, including the temperature of air at the biomass furnace inlet and outlet and at the drying chamber inlet and outlet, the temperature of paddy within the drying chamber, and ambient temperature, were conducted using a type T thermocouple with an accuracy of ± 0.1°C and an operating temperature range of (-200°C to 400°C). Air speed was measured using an HT-383 anemometer with an accuracy of ± 0.2 ms^{-1}, operating in the range of 0-30 ms^{-1}, and within an operating temperature range of (-10°C to 45°C). An AH4000 data logger with an accuracy of ± 0.1°C recorded air and paddy temperatures. Changes in the moisture content of paddy (*Oryza sativa* L.) were monitored using a moisture tester model OEM MC-7828G, featuring an accuracy of ±0.5% and a measurement range of ±0%–50%. Regular measurements of paddy moisture content, air temperature, and rice temperature were taken at 30-minute intervals throughout the testing process, providing a comprehensive understanding of the drying dynamics.

2.3 Performance (Energy and Exergy) Analysis

The evaluation of a biomass-assisted recirculating mixed-flow dryer involves several performance metrics, including the drying rate ($\dot{m}_{water}$), specific energy consumption (SEC), specific moisture evaporation rate (SMER), thermal efficiency of the dryer (η_{th}), drying chamber exergy efficiency (η_{Ex}), and biomass furnace efficiency (η_{BF}). The respective equations used to quantify these performance indicators are detailed in **Table 1**.

Table 1. The equations used to determine the performance of the dryer

Performance Indicator	Equation	Eq. No.	Ref.
Specific energy consumption	$\mathrm{SEC} = \frac{E_{bmf} + E_{Bbf} + E_{Mdr} + E_{Mbe} + E_{Mvf} + E_{Bmfd}}{\dot{m}_{water}}$	(1)	[21]
Specific moisture evaporation rate	$\mathrm{SMER} = \frac{\dot{m}_{water}}{E_{bmf} + E_{Bbf} + E_{Mdr} + E_{Mbe} + E_{Mvf} + E_{Bmfd}}$	(2)	[28]
Drying rate	$\dot{m}_{water} = \frac{M_{Cdb\,t+\Delta t} - M_{Cdb\,t}}{\Delta t}$	(3)	[27]
Paddy moisture content (wet basis)	$M_{Cwb} = \frac{m_{wetpd} - m_{bonedrypd}}{m_{wetpd}}$	(4)	[27]
Paddy water content (dry basis)	$M_{Cdb} = \frac{m_{wetpd} - m_{bonedrypd}}{m_{bonedrypd}}$	(5)	[27]
The electrical energy required by the biomass furnace blower, bucket elevator motor, and vibration feeder motor	$E_{Bbf}, E_{Mbe}, \text{ and } E_{Mvf} = VI\cos\varphi$	(6)	[12]
Electrical energy required by the discharge roller motor and dryer blower	$E_{Mdr} \text{ and } E_{Bmfd} = \sqrt{3}VI\cos\varphi$	(7)	[9]
Thermal efficiency of the dryer	$\eta_{th} = \frac{\dot{m}_{water} H_{fg}}{E_{bmf} + E_{Bbf} + E_{Mbe} + E_{Mvf} + E_{Bmfd}}$	(8)	[23]
Exergy inflow	$EX_{i,ds} = \dot{m}_a C_{Pa}\left[\left(T_{ai,ds} - T_{amb}\right) - T_{amb}\ln\frac{T_{ai,ds}}{T_{amb}}\right]$	(9)	[9,25]
Exergy outflow	$EX_{o,ds} = \dot{m}_a C_{Pa}\left[\left(T_{ao,ds} - T_{amb}\right) - T_{amb}\ln\frac{T_{ao,ds}}{T_{amb}}\right]$	(10)	[9,25]
Exergy loss	$EX_{loss} = EX_{i,ds} - EX_{o,ds}$	(11)	[9,25]
Exergy efficiency of the drying section	$\eta_{Ex} = \frac{EX_{o,ds}}{EX_{i,ds}} = 1 - \frac{EX_{loss}}{EX_{i,ds}}$	(12)	[9,25]
Biomass furnace efficiency	$\eta_{BF} = \frac{E_{Ubf}}{E_{bmf}} x100\%$	(13)	[12]
Heat energy produced from biomass fuel combustion	$E_{bmf} = \dot{m}_{bmf} CV_{bmf}$	(14)	[12]
Useful energy in biomass furnace	$E_{Ubf} = \dot{m}_a C_{Pa}\left(T_{ao,bf} - T_{ai,bf}\right)$	(15)	[12]

RESULTS AND DISCUSSION

In **Fig. 2**. Illustrates the temperature of the air at the drying chamber inlet and outlet as a function of the drying time, while Figure 3 depicts the changes in the relative humidity of the air during the same period. The recorded temperatures for the air entering and leaving the drying chamber fall within the ranges of 75.40–81.40 °C and 46.30–54.70 °C, with average values of 78.15 °C and 50.14 °C, respectively. Concurrently, the relative humidity levels of the air at the drying chamber inlet and outlet are observed in the range of 6.77%-9.57% and 39.75%-57.45%, with average values of 8.55% and 50.35%. Analysis of **Fig. 2** and 3 indicates an increase in the air temperature at the drying chamber outlet with prolonged drying time, while its relative humidity at the same diminishes. This is attributed to the decreasing rates of both heat transfer and mass transfer as the drying process progresses.

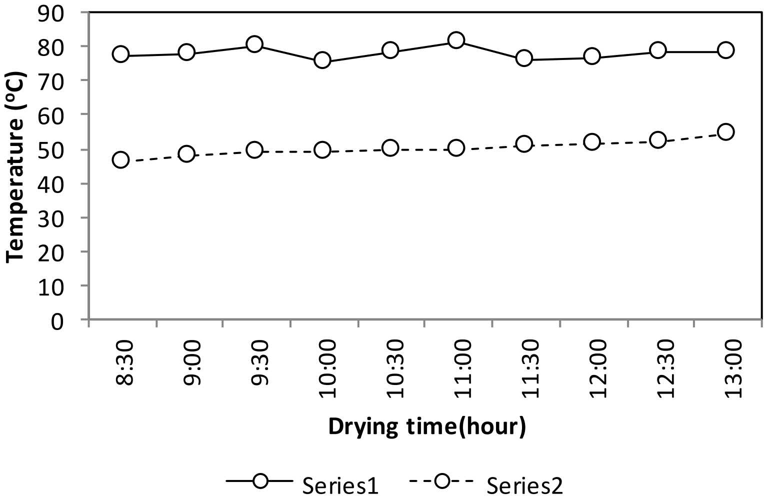

Fig. 2. Temperature of the air at the drying chamber inlet and outlet as a function of drying time

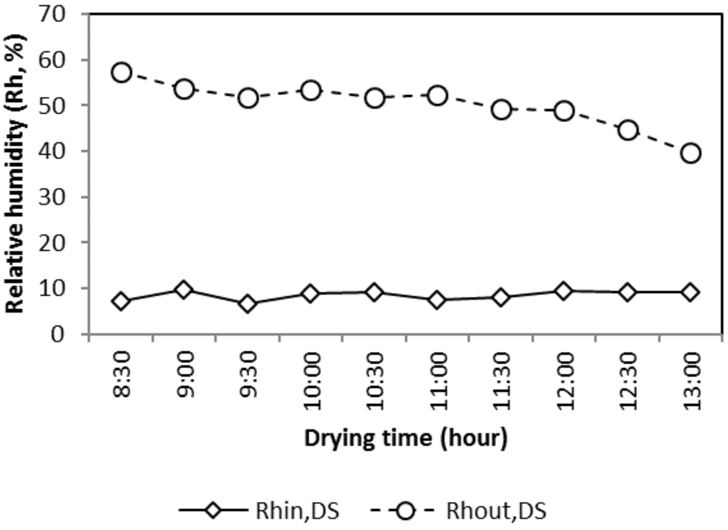

Fig. 3. Variation of relative humidity of air entering and leaving the drying room with respect to drying time.

In **Fig. 4.** paddy's temperature at the inlet, inside, and outlet of the drying chamber are presented as a function of drying time. The recorded temperatures for these three points range from 34.90 to 41.70 °C, 40.40 to 48.40 °C, and 34.10 to 40.30 °C, with average values of approximately 38.22, 44.41, and 38.58 °C, respectively.

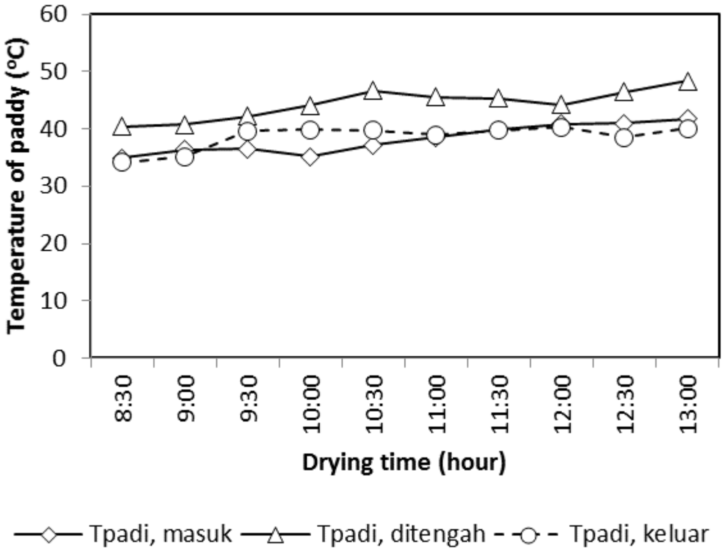

Fig. 4. Temperature of paddy at the inlet, inside, and outlet of the drying chamber as a function of drying time

Fig. 5, Fig. 6 depict the moisture content and drying rate of paddy as a function of drying time. In Figure 5, the moisture content of paddy in the drying chamber decreases from the initial 20.90% on a wet basis, with an initial weight of 400 kg, to the final 13.30% on a wet basis, with a final weight of 364 kg, over a duration of 4.5 hours. The mass flow rate during this process is recorded at 0.1084 kg/s, with an average air temperature of approximately 78.15 °C and an average relative humidity of around 8.55%. Figure 6 illustrates the drying rate, ranging between 1,688 and 18,126 kg/hour, with an average of 7,792 kg/hour. Notably, the drying rate diminishes with prolonged drying time, indicative of a decrease in the amount of water evaporated from the paddy as the drying process advances.

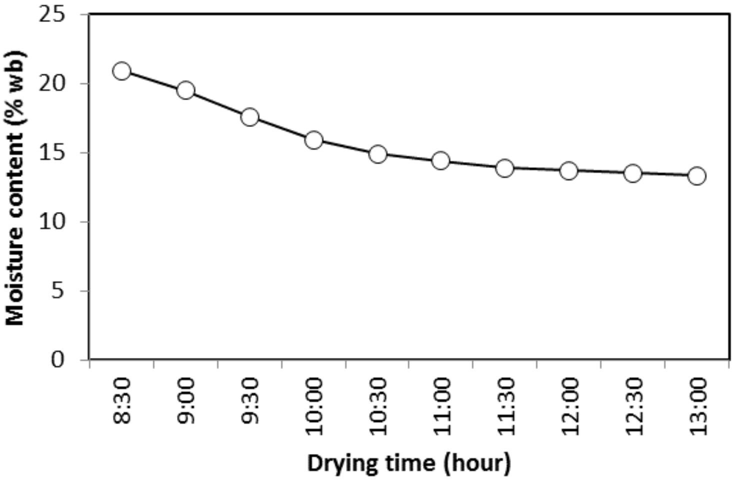

Fig. 5. Moisture content as a function of drying time

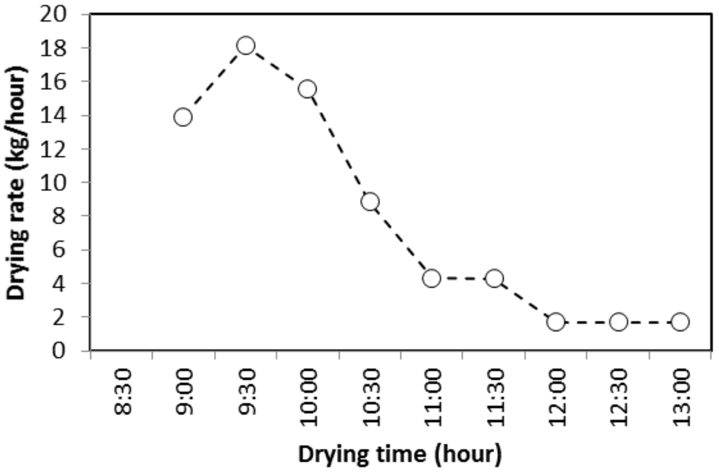

Fig. 6. Drying rate as a function of drying time

Fig. 7. Illustrates Specific Moisture Evaporation Rate (SMER) and Specific Energy Consumption (SEC) as a function of drying time. The SMER values range between 0.122 and 1.308 kg/kWh, with an average of 0.562 kg/kWh. On the other hand, the SEC values vary between 0.806 and 8 .657 kWh/kg, with an average of 4.119 kWh/kg. The trends in Figure 7 reveal that SMER decreases with prolonged drying time, while SEC exhibits an increasing trend over time. This behavior is attributed to the diminishing drying rate as time progresses, coupled with the nearly constant energy input into the drying system.

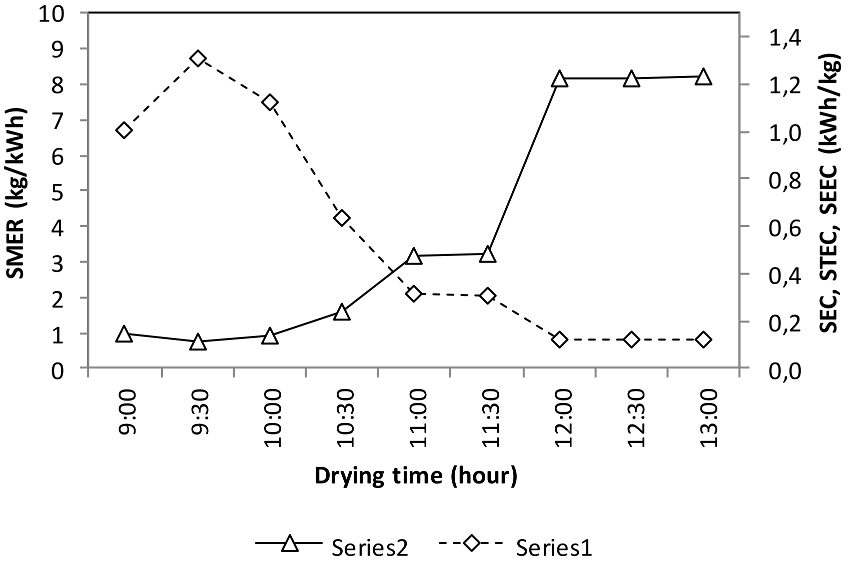

Fig. 7. SMER and SEC as a function of drying time

Fig 8. presents exergy inflow, exergy outflow, and exergy loss within the drying chamber as a function of drying time. The values for these three parameters fluctuate within ranges of 1439.42 to 1959.34 W, 249.24 to 398.17 W, and 1154.94 to 1630.24 W, respectively. The average values for exergy inflow, exergy outflow, and exergy loss were recorded as 1708.32 W, 330.08 W, and 1378.24 W, respectively.

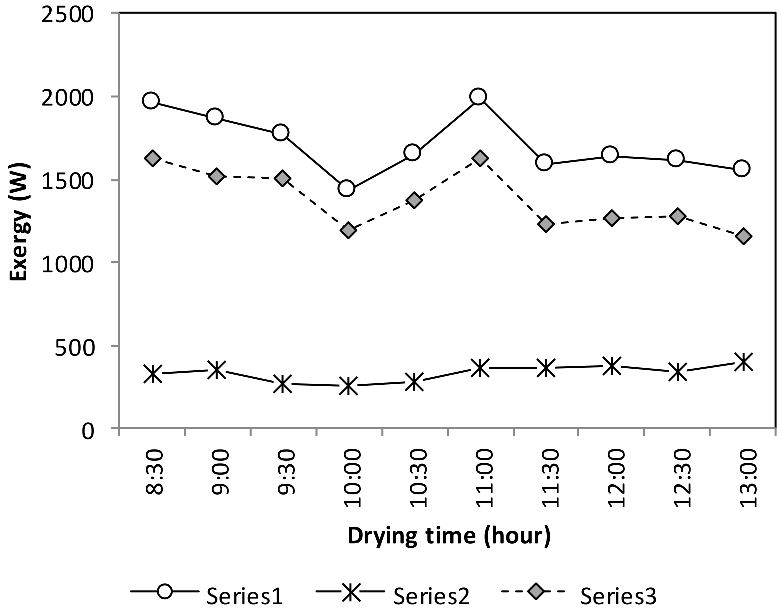

Fig 8. Exergy as a function of drying time

Fig. 9 and **Fig. 10** depict the thermal efficiency and exergy efficiency of the dryer as a function of drying time. In Figure 9, the thermal efficiency of the dryer fluctuates between 7.82% and 83.99%, with an average of 36.105%. Meanwhile, Figure 10 illustrates that the exergy efficiency ranges from 15.28% to 25.64%, with an average value of 19.46%

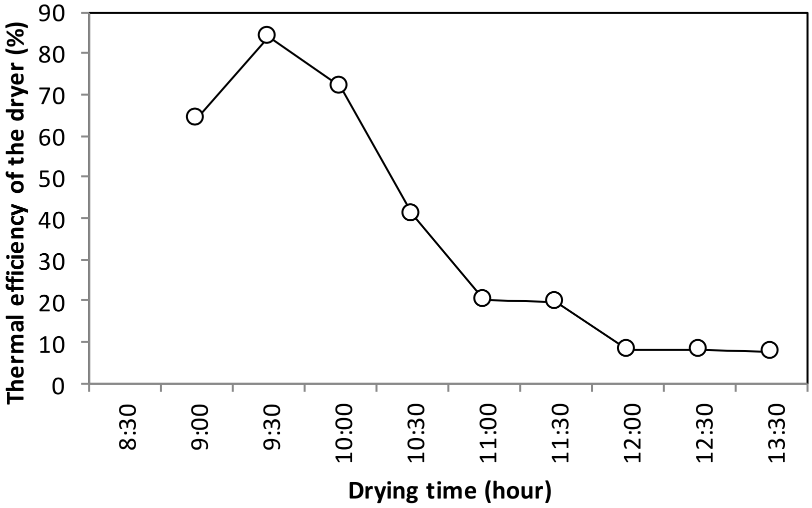

Fig. 9. The thermal efficiency of the dryer as a function of drying time

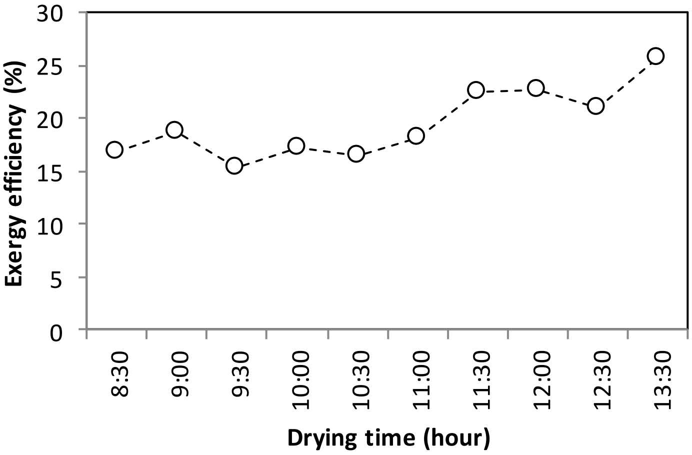

Fig. 10. Exergy efficiency as a function of drying time

Fig. 11 and **Fig. 12** illustrate the temperature of the air entering and leaving through the biomass furnace inlet and outlet and the efficiency of the biomass furnace as a function of drying time. In **Fig. 11**, the temperature of the air entering and leaving the biomass furnace ranges from 30.60 to 35.50°C and from 78.20 to 88.90°C, with average values of 32.73°C and 83.51°C, respectively. Meanwhile, **Fig. 12** shows that the biomass furnace efficiency fluctuates between 70.63% and 87.70%, with an average value of 79.53%.

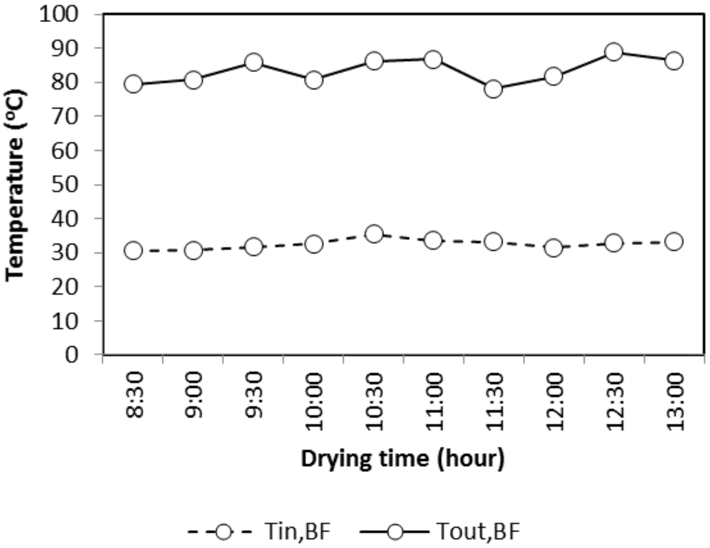

Fig. 11. Temperature of air at the biomass furnace inlet and outlet as a function of drying time.

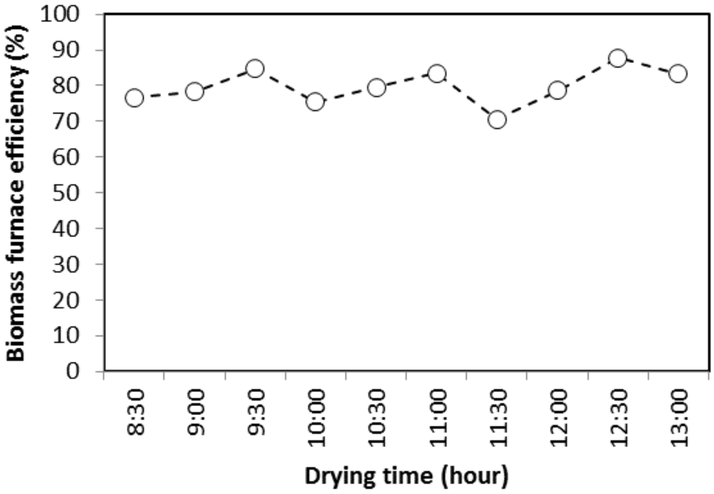

Fig. 12. **Biomass furnace efficiency as a function of drying time**

This research fills a gap in the existing literature by providing empirical data on the energy and exergy performance of a biomass energy-assisted mixed-flow type recirculating dryer for drying rice. Tests show that this dryer is capable of drying 400 kg of rice from a moisture content of 20.90% (wet basis) to 13.30% (wet basis) in 4.5 hours with an average thermal efficiency of 36.11% and an average exercise efficiency of 19.46%. These results show increased efficiency compared to several previous studies. For example, Purohit et al. [29], who used a biomass-assisted hybrid solar dryer, reported longer drying times and lower thermal efficiency. Research by Kumar et al. [30], who used a biomass-based single-flow type dryer, also reported lower thermal efficiency and slower drying rates.

In addition, research by Mahmoud et al.[31], who used a biomass-based rotary dryer for rice drying, found similar thermal and exergy efficiencies to the results of this study, but the efficiency of their biomass furnace was lower compared to the biomass-assisted mixed-flow type dryer discussed in this study. This research emphasizes the importance of further economic analysis to provide valuable information for other researchers and farmers, given the higher energy and exercise efficiency and the potential for significant cost savings. These results show that the use of biomass-based dryers can not only increase rice drying efficiency but also offer a more environmentally friendly and sustainable solution for the agricultural industry.

CONCLUSION

Testing of a biomass-assisted circulation mixed-flow dryer for drying rice (Oryza sativa L.) at the Padang Institute of Technology produced several main findings. This dryer takes 4.5 hours to dry 400 kg of rice from a moisture content of 20.90% (wet basis) to 13.30% (wet basis) with an average air temperature of 78.15 °C and average relative humidity 8.55%, and the air mass flow rate is around 0.1084 kg/s. The average drying rate achieved was 7.792 kg/hour. The average specific humidity evaporation rate (SMER) was measured to be approximately 0.562 kg/kWh. Average specific energy consumption (SEC) is around 4,119 kWh/kg. The average thermal efficiency of the dryer was determined to be approximately 36.11%. The average exergy efficiency was found to be around 19.46%. The efficiency of the biomass stove is calculated to be around 79.53%. It is recommended that further research be carried out on the economic analysis of these dryers to provide valuable information for other researchers and farmers.

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NOMENCLATURE

C_{Pa}	specific heat of air ($Jkg^{-1}C^{-1}$)
CV_{bmf}	calorific value of fuel (kcal/kg)
$\cos\varphi$	power factor
E_{Bbf}	electrical energy required by the biomass furnace blower (W)
E_{bmf}	heat energy produced from biomass fuel combustion (W)
E_{Bmfd}	electrical energy required by the dryer blower (W)
E_{Mbe}	electrical energy required by the bucket elevator motor (W)
E_{Mdr}	electrical energy required by the output section roller motor (W)
E_{Mvf}	electrical energy required by the vibration feed motor (W)
H_{fg}	latent heat of vaporization of water (kJ/kg)
I	current (A)
$\dot{m}_a$	air mass flow rate (kg/s)
$\dot{m}_{bmf}$	biomass fuel consumption rate (kg/h)
$m_{bonedrypd}$	mass of paddy solids (kg)
$M_{Cdb,t}$	paddy moisture content (dry basis) at time "*t*"
$M_{Cdb,t+\Delta t}$	paddy moisture content (dry basis) at time "$t+\Delta t$"
$\dot{m}_{water}$	drying rate (kg/h)
m_{wetpd}	mass of wet paddy (kg)
Rh_{amb}	ambient relative humidity (%)
$Rh_{i,ds}$ and $Rh_{o,ds}$	air relative humidity levels at drying chamber inlet and outlet (%)
$T1=T_{amb\ (db)}$	ambient temperature (dry bulb) (°C)
$T2=T_{amb\ (wb)}$	ambient temperature (wet bulb) (°C)
$T3=T_{ai,bf}$	air temperature at biomass furnace inlet (dry bulb) (°C)
$T4=T_{ao,bf}$	air temperature at biomass furnace inlet (dry bulb) (°C)
$T5=T_{ai,ds\ (db)}$	air temperature at drying chamber inlet (dry bulb) (°C)
$T6=T_{ai,ds\ (wb)}$	air temperature at drying chamber inlet (wet bulb) (°C)
$T7=T_{pdi,ds}$	paddy temperature at drying chamber inlet (dry bulb) (°C)
$T8=T_{pdc,ds}$	paddy temperature within drying chamber (dry bulb) (°C)
$T9=T_{pdo,ds}$	paddy temperature at drying chamber outlet (dry bulb) (°C)
$T10=T_{ao,ds\ (db)}$	air temperature at drying chamber outlet (dry bulb) (°C)
$T11=T_{ao,ds\ (wb)}$	air temperature at drying chamber outlet (wet bulb) (°C)
V	voltage (V)
Δt	drying time interval (hour)