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# Experimental Performance Analysis of a Solar Hybrid Recirculating Mixed-Flow Dryer With Different Drying Temperatures For Drying Paddy

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**Abstract**

This study is focussed on the performance of a solar hybrid recirculating mixed-flow dryer (SHRMFD) for drying paddy with different drying air temperatures. The drying experiments were carried out at average air temperatures of 50 °C, 60 °C and 70 °C. The SHRMFD reduced the mass of paddy from 420 kg (16.90% wb) to 406.07 kg (14.17% wb) in 360 min; from 420 kg (16.80 % wb) to 407.63 kg (14.17%) in 165.4 min; from 420 kg (16.75 % wb) to 407.35 kg (14.17% wb) in 143.3 min for average air temperatures of 50°C, 60°C and 70°C, respectively. The highest drying rate (3,324 kg/hour) was achieved at an average air temperature of 70°C. The specific moisture evaporation rate (0.171kg/kWh) and thermal efficiency of SHRMFD (25.04%) were achieved highest at an average air temperature of 50°C. The lowest specific energy consumption (11.804 kWh/kg) was achieved at an average air temperature of 50°C. The energy contributed by the biomass furnace and the solar collector for SHRMFD were 13.28 and 14.74%; 8.08 and 17.50%; and 6.10 and 20.35 for average air temperatures of 50°C, 60°C and 70°C, respectively. The SHRMFD performance is better at an average air temperature of 50°C because it has higher thermal efficiency and lower energy consumption.

**Keywords:** Paddy, drying, mixed-flow dryer, solar hybrid, performance

## INTRODUCTION

Indonesia is one of the largest grain producing countries in the world, suh as coffee, soybeans, green beans, corn and paddy. Paddy is a rice-producing crop that is the staple food of nearly 90% of Indonesia's population, and is also the economic resource of more than 30 million farmers [1]. National rice needs will continue to increase along with the rate of population growth. Paddy after harvest generally have high moisture content of about 20-27% wet basis. At this level of moisture content, the paddy is not safe to store because it is very susceptible to fungus or easily damaged [2]. Therefore, to secure long-term storage and milled paddy needs to be dried as soon as possible to achieve moisture content of about 14% wet basis [3].

So far, the most widely used paddy drying methods are the traditional method (open sun drying) and artificial dryer. The traditional method is drying the paddy directly under the sun, this method is very simple and inexpensive, but the drying time is long and the quality of the rice is low. The most widely used artificial dryer for paddy drying is the flat bed dryer. The flatbed dryers have disadvantages such as incapability of retaining uniform moisture content, some parts of product will be over dried and some other parts will not be dried adequately which will result in a lot of broken rice during milling process. In addition, most of the energy used to heat the drying air is fossil fuels such as LPG, while the fossil fuel sources are limited and their prices are high and steadily increasing. These sources can also cause air pollution.

Tahrir (2000) [4] conducted research on differences the quality of rice in the top layer and bottom layer of the rice pile, where the rice is dried using a flatbed dryer with drying thickness 50cm. From this research, the rice breaking rate was obtained in the upper layer as much as 7.35% while in the lower layer 13.80%. There is no level of rice breaking in the top and bottom layers meets SNI 6128:2008 [3] where the rice content is broken set at 5%. High levels of broken rice in the top layer and bottom because the rice in the top layer contains water high because it receives less heat, while in the layer the bottom of the rice is too dry (too little water content) because of the rice dries too quickly because it receives a lot of heat.

Low quality rice is sold at low prices, long drying times and large energy consumption requires high operating costs, and this has an impact on farmers' income. And also the use of fossil energy has an impact on national energy supplies and the environment, therefore an innovation in drying technology is needed that can produce high quality paddy, short drying time, and using alternative energy sources.

To overcome the limitations of open sun drying and flatbed dryer for drying paddy, a mixed-flow dryer using alternative energy such as solar energy and biomass energy can be used, which offers significant advantages, such as suitability for drying of paddy, short drying time, good quality of the dried products, and smaller losses in the quantity of paddy during the drying process. Therefore, the objective of this study was to evaluate the performance of a solar hybrid recirculating mixed-flow dryer with different air temperatures for drying paddy.

## RESEARCH METHODS

### 2.1 Experimental set-up

A solar hybrid recirculating mixed-flow dryer (SHRMFD) for drying paddy, which comprised a solar collector, biomass furnace, drying column, vibratory feeder, bucket elevator, and blower, was designed and installed. Photographs and a schematic of the SHRMFD are presented in Figs. 1 and 2. The drying column was prepared to have a storage section, a drying section, and a discharge section. The dimensions of the drying column and the biomass furnace can be seen in the a biomass-assisted mixed flow dryer previously presented by Yahya et al. [5]. While, the dimension of solar collector can be seen in the a solar dryer previously presented by Yahya et al. [6]

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**Fig. 1. Photograph of the solar hybrid recirculating mixed-flow dryer (SHRMFD).**

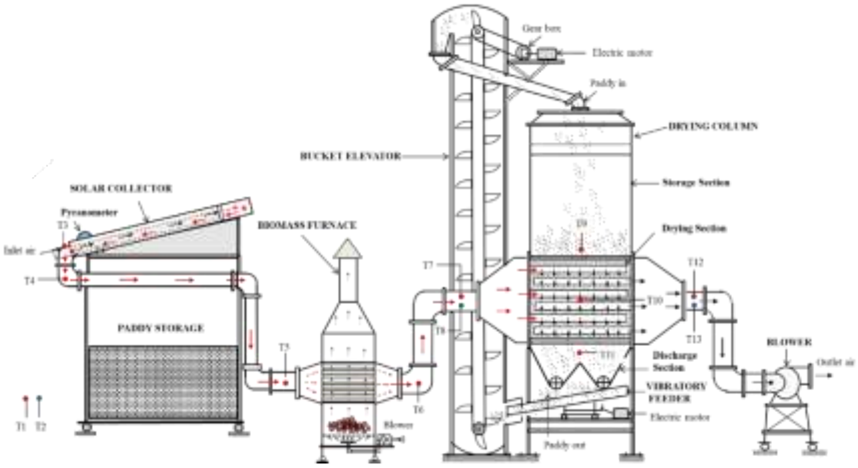


**Fig. 2. Schematic of the solar hybrid recirculating mixed-flow dryer (SHRMFD)**

### 2.2 Experimental procedure

A drying experiment was conducted to evaluate the performance of the SHRMFD, with a holding capacity of 420 kg. Fresh paddy was purchased from a farmer, and during the drying experiment the air temperatures at different points in the drying system were measured using thermocouples. The solar radiatian was measured using pyranometer. An anemometer was used to measure the air velocity at the inlet and outlet of the drying section. The air temperature and solar radiatian were recorded using a data logger. A grain moisture tester was used to measure the change in the moisture content of the paddy. The mass of biomass fuel and mass of the paddy were weighed using a weighing scale. The air temperatures, solar radiation, and moisture content of the paddy were recorded every 30 min.

### 2.3 Performance analysis

The performance of the solar hybrid recirculating mixed-flow dryer (SHRMFD), in terms of the drying rate $(\dot{m}_{water})$, specific energy consumption (SEC), specific moisture evaporation rate (SMER), thermal efficiency of the SHRMFD $(\eta_{th})$, efficiency of the biomass furnace $(\eta_{BF})$, and efficiency of the solar collector $(\eta_{SC})$. The perfomance of the SHRMFD were determined using the equations presented in Table 1.

**Table 1. Equations used to determine the performance of the SHRMFD.**

| Parameter | Formula | Eq.no. | Ref. |
|---|---|---|---|
| Paddy moisture content (wet basis) | $M_{wbpd} = \frac{m_{wetpd} - m_{dpd}}{m_{wetpd}}$ | (1) | [5] |
| Drying rate (DR) | $\dot{m}_{water} = \frac{M_{dbpd,t+dt} - M_{dbpd,t}}{dt}$ | (2) | [5] |
| Specific energy consumption | $SEC = \frac{Q_{Ise} + Q_{Ibmf} + W_C + W_{Bd} + W_{Bbf} + W_{Mt}}{\dot{m}_{water}}$ | (3) | [7,8,9] |
| Total electrical energy input of electrical motor | $W_{Mt} = W_{Mbe} + W_{Mvf} + W_{Mdr}$ | (4) | [8,10] |
| Energy contribution from biomass furnace | $EC_{BF} = \frac{Q_{Ebf}}{Q_{Ise} + Q_{Ibmf} + W_C + W_{Bd} + W_{Bbf} + W_{Mt}} \times 100\%$ | (5) | [6] |
| Energy contribution from solar collector | $EC_{SC} = \frac{Q_{Esc}}{Q_{Ise} + Q_{Ibmf} + W_C + W_{Bd} + W_{Bbf} + W_{Mt}} \times 100\%$ | (6) | [6] |
| Specific moisture extraction rate | $SMER = \frac{\dot{m}_{water}}{Q_{Ise} + Q_{Ibmf} + W_C + W_{Bd} + W_{Bbf} + W_{Mt}}$ | (7) | [9,11] |

| | | | |
|---|---|---|---|
| Thermal dryer efficiency | $\eta_{th} = \frac{m_{water}H_{fg}}{Q_{Ise} + Q_{Ibmf} + W_C + W_{Bd} + W_{Bbf} + W_{Mt}}$ | (8) | [12] |
| Collector efficiency | $\eta_{SC} = \frac{Q_{EPsc}}{Q_{Ise}} \times 100\%$ | (9) | [12] |
| Biomass furnace efficiency | $\eta_{BF} = \frac{Q_{EPbf}}{Q_{Ibmf}} \times 100\%$ | (10) | [6] |
| Thermal energy input of solar collector | $Q_{Ise} = I_T A_{SC}$ | (11) | [13] |
| Power input of compressor | $W_C = VI\cos\varphi$ | (12) | [14] |
| Power input of dryer blower | $W_{Bfd} = \sqrt{3}VI\cos\varphi$ | (13) | [14] |
| Thermal energy input of biomass furnace | $Q_{Ibmf} = \dot{m}_{bf}C_{Pda}$ | (14) | [6] |
| Thermal energy produced by solar collector | $Q_{EPsc} = \dot{m}_a C_a (T_{o,sc} - T_{i,sc})$ | (15) | [6,15,16] |
| Thermal energy produced by biomass furnace | $Q_{EPbf} = \dot{m}_a C_a (T_{o,bf} - T_{i,bf})$ | (16) | [6] |

## RESULTS AND DISCUSSION.

### 3.1 Performance evaluation

The variation in the efficiency of solar collector and solar radiation versus drying time for different drying temperatures are presented in Fig.3. The efficiency of solar collector for an average air temperature of 50°C were in the range of 62.86-97.06% at an average value of 82.15% with solar radiation in the range of 365.94-796.51 W/m$^2$, with an average value of 592.47 W/m$^2$. For an average air temperature of 60°C in the range of 67.46-88.53% at an average value of 79.46% with solar radiation in the range of 469.09-766.55 W/m$^2$, with an average value of 643.28 W/m$^2$ . As well as, for an average air temperature of 70°C in the range of 55.60-80.70% at an average value of 70.67% with solar radiation in the range of 402.32-923.62 W/m$^2$, with an average value of 630.63 W/m$^2$.

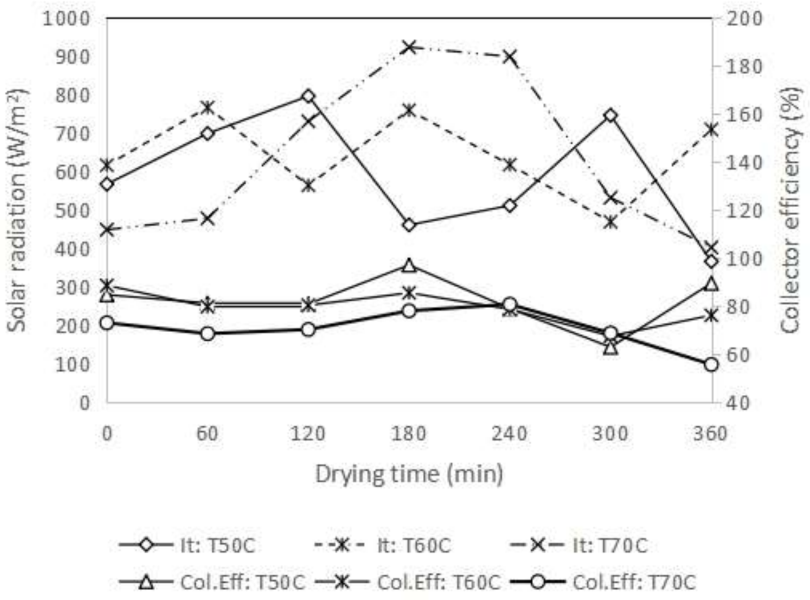


**Fig.3. Variation of efficiency of solar collector and solar radiation versus drying time with different air temperatures.**

The variation in the thermal efficiency of biomass furnace versus drying time for different air temperatures is presented in Fig.4. The efficiency of the biomass furnace were in the range of 20.26-38.20%, 21.45-27.21%, and 22.79-32.46%, for average air temperature of 50°C, 60°C, and 70°C, with average values of 29.14, 24.55, and 27.04%, respectively.

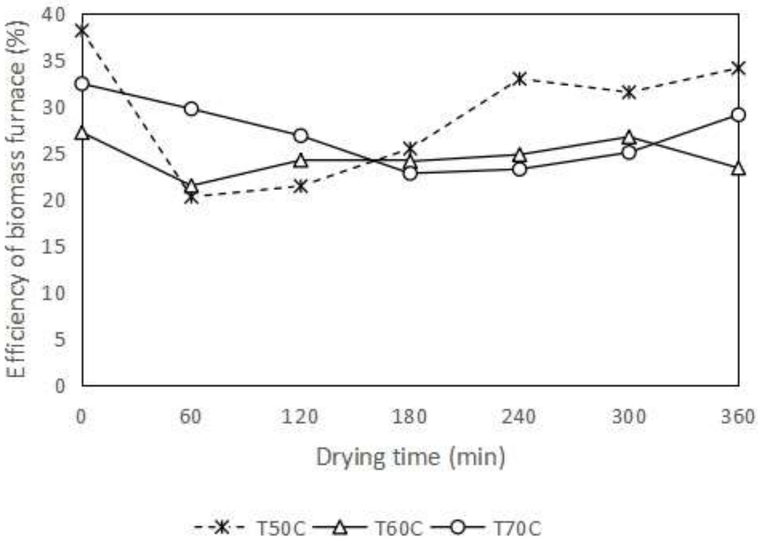


**Fig.4. Variation of efficiency of biomass furnace versus drying time with different air temperatures.**

The variation in the air temperatures at inlet and outlet of the drying section versus drying time for different air temperatures is presented in Fig.5. The air drying temperatures at inlet and outlet of the drying section for average air temperature of 50°C, 60°C, and 70°C were in the range of 49.30-50.80°C and 37.20-41.50°C; 58.20-61.40°C and 41.70-47.40°C, and 68.50-70.40°C and 42.10-50.60°C, respectively.

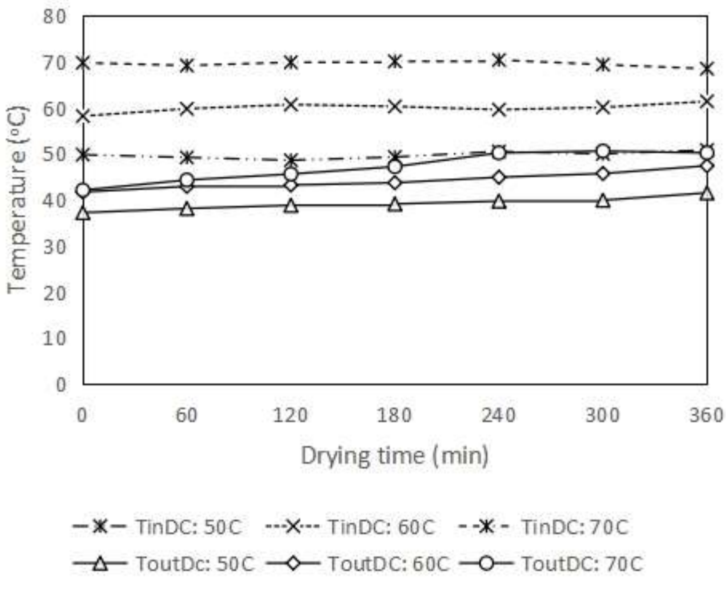


**Fig.5. Variation of temperatures at the inlet and outlet of the drying section versus drying time with different air temperatures.**

The variation in the paddy mass versus drying time for different air temperatures is presented in Fig.6. The drying paddy via SHRMFD at an average air temperature of 50°C reduced the mass of paddy from 420 kg to 406.07 kg in 360 min. For average air temperature of 60°C, this dryer reduced the mass of paddy from 420 kg to 407.63 kg in 165.4 min, as well as for average air temperature of 70°C, this dryer reduced the mass of paddy from 420 kg to 407.35 kg in 143.3 min.

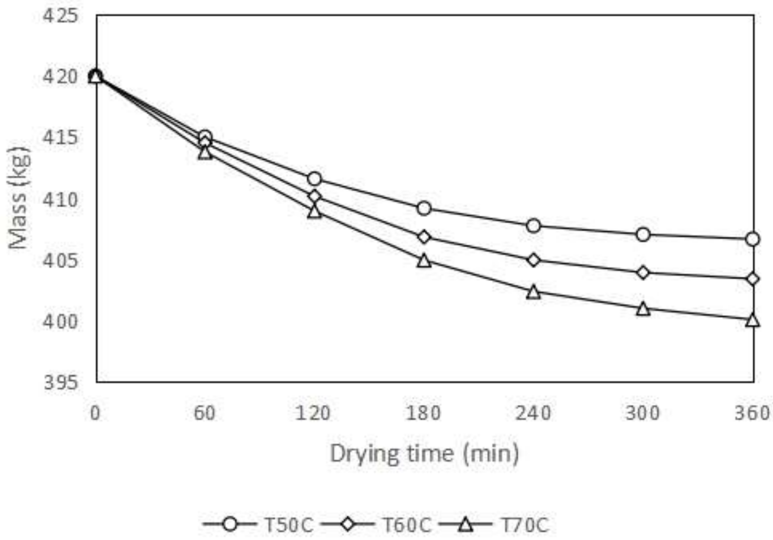


**Fig.6. Variation of paddy mass versus drying time with different air temperatures.**

The variation in the moisture content of paddy versus drying time for air drying temperatures is presented in Fig.7. In the SHRMFD, at an average air temperature of 50°C the moisture content of paddy was reduced from 16.90% wb to 14.17% wb in 360 min. For average air temperature of 60°C, this SHRMFD reduced the moisture content from 16.80 % wb to 14.17% wb in 165.43 min, as well as for average air temperature of 70°C, this SHRMFD reduced the moisture content from 16.75 % wb to 14.17% wb in 143.29 min.

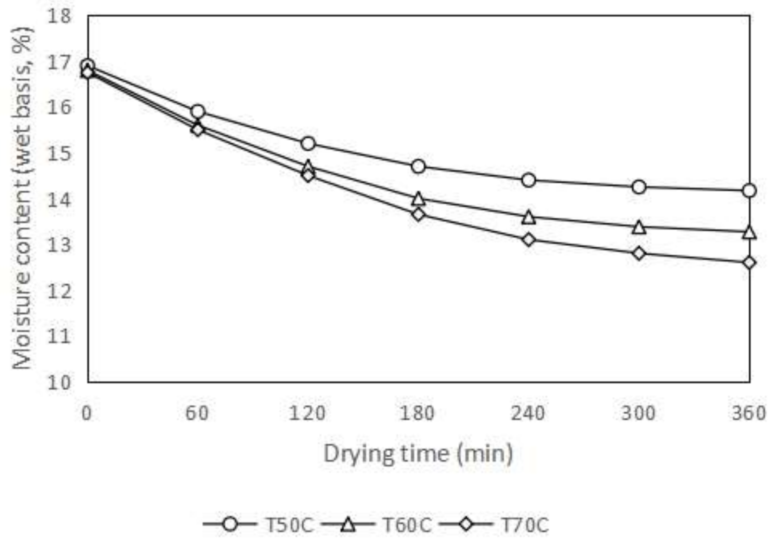


**Fig.7. Variation of paddy moisture content (wb) versus drying time with different air temperatures.**

The variation in the drying rate versus drying time for different air temperatures is presented in Fig.8. The highest average drying rate was achieved by SHRMFD at an average air temperature of 70°C (3.324 kg/h), followed by an average air temperature of 60°C (2.849 kg/h), and an average air temperature of 50°C. The range of drying rate is displayed as follows: 0.379 to 4.994 kg/h, 0.512 to 5.972 kg/h, and 0.918 to 6.213 kg/h for average air temperature of 50°C, 60°C, and 70°C, respectively.

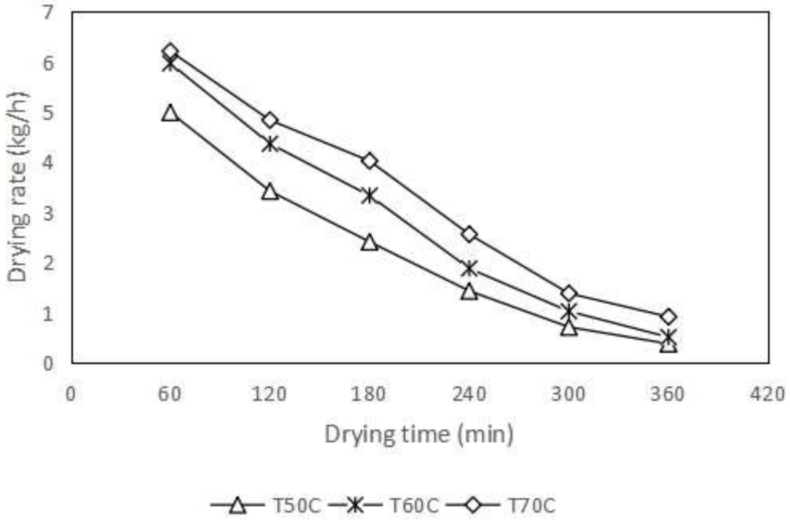


**Fig.8. Variation of drying rate versus drying time with different air temperatures.**

The variation in the SMER versus drying time for different air temperatures is presented in Fig.9. The SMER were in the range of 0.032-0.378 kg/kWh, 0.022-0.259 kg/kWh, and 0.034-0.227 kg/kWh, for air temperature 50°C, 60°C, and 70°C, with average values of 0.171, 0.125, and 0.118 kg/kWh, respectively.

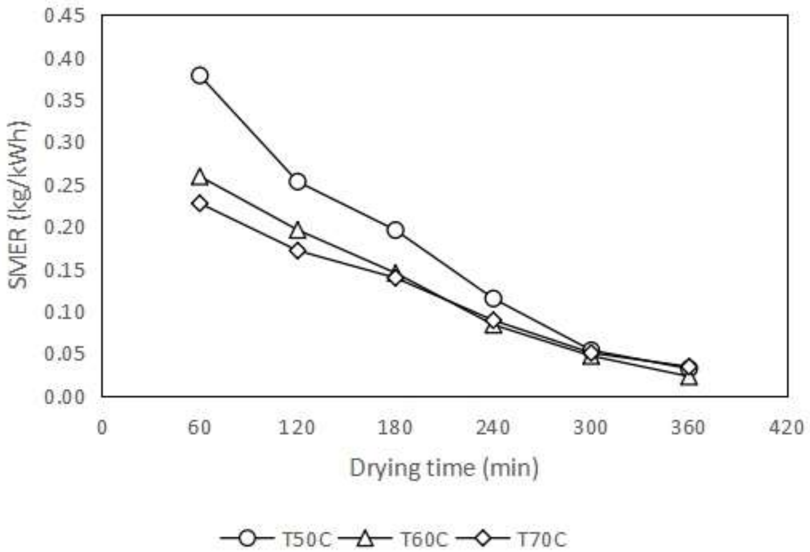


**Fig.9. Variation of SMER versus drying time with different air temperatures.**

The variation in the SEC versus drying time for different air temperatures is presented in Fig.10. The SEC were in the range of 2.643-31.631 kWh/kg, 3.860-44.652 kWh/kg, and 4.402- 29.512 kWh/kg, for air temperature 50°C, 60°C, and 70°C, with average values of 11.804, 15.649, and 13.018 kWh/kg, respectively.

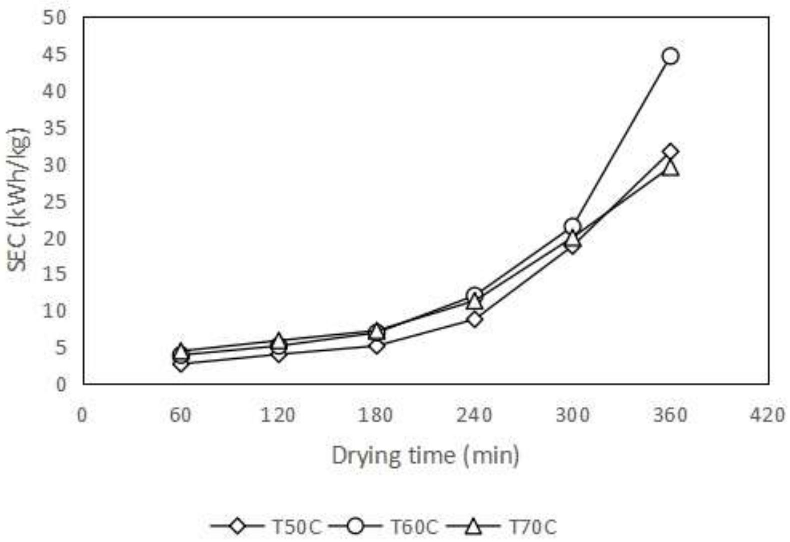


**Fig.10. Variation of SEC versus drying time with different air temperatures.**

The variation in the thermal efficiency of the SHRMFD versus drying time for different air temperatures is presented in Fig.11. The highest average thermal efficiency was achieved by SHRMFD at an average air temperature of 50°C (11.32%), followed by an average air temperature of 60°C (8.30%), and an average air temperature of 70°C (7.83). The range of thermal efficiency of the SHRMFD is displayed as follows: 2.09 to 25.04% for an average air temperature of 50°C, 1.48 to17.14% for an average air temperature of 60°C, and 2.24 to 15.03% for an average air temperature of 70°C,

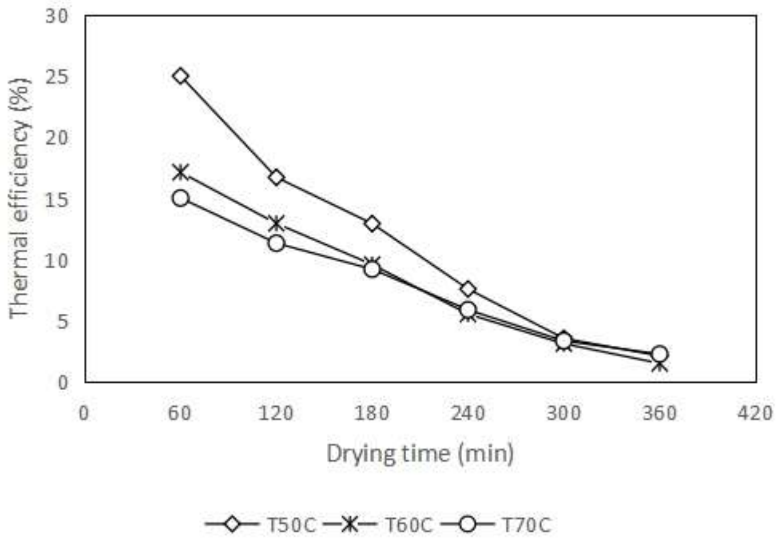


**Fig.11. Variation of efficiency versus drying time with different air temperatures.**

The variation in the energy contributed by the biomass furnace and the solar collector versus the drying time for different air temperatures are presented in Fig.12. The energy contributed by the biomass furnace and the solar collector for SHRMFD at an average air temperature of 50°C were in the range of 9.82-17.11% and 10.43-19.33%, with average values of 13.28 and 14.74%, respectively. For average air temperature of 60°C were in the range of 5.18-10.15% and 15.27-19.95%, with average values of 8.08 and 17.50, respectively. As well as, for average air temperature of 70°C were in the range of 2.97-9.05% and 17.11- 23.65%, with average values of 6.10 and 20.35, respectively.

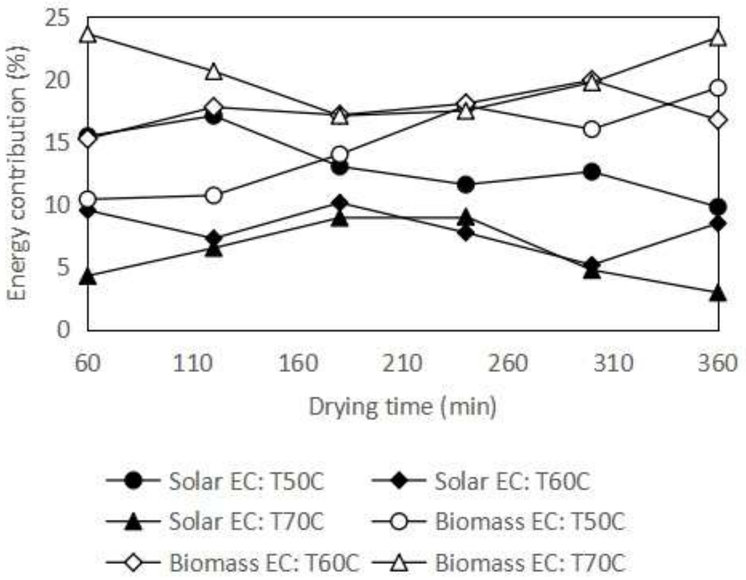


**Fig.12. Variation of energy contribution versus drying time with different air temperatures.**

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**CONCLUSIONS.**

A solar hybrid recirculating mixed-flow dryer (SHRMFD) designed for drying paddy was tested and evaluated. The drying experiments were carried out at average air temperatures of 50 °C, 60.0 °C and 70 °C. The drying experiment results showed that:

1. During the drying experiment, in general, the thermal energy used to heat the drying air were contributed by biomass fuel and solar energy.
2. The average efficiency of solar collector were 82.15%, 79.46% and 70.67% for average air temperatures of 50°C, 60°C, and 70°C, respectively.
3. The average efficiency of the biomass furnace were 29.14%, 24.55% and 27.04% for average air temperatures of 50°C, 60°C, and 70°C, respectively.
4. The SHRMFD reduced the mass of paddy from 420 kg (16.90% wb) to 406.07 kg (14.17% wb) in 360 min; from 420 kg (16.80 % wb) to 407.63 kg (14.17%) in 165.4 min; from 420 kg (16.75 % wb) to 407.35 kg (14.17% wb) in 143.3 min, for average air temperatures of 50°C, 60°C, and 70°C, respectively.
5. The average drying rate (DR) were 2.226 kg/h, 2.849 kg/h and 3.324 kg/h for average air temperatures of 50°C, 60°C, and 70°C, respectively.
6. The average SMER were 0.171; 0.125 and 0.118 kg/kWh for average air temperatures of 50°C, 60°C, and 70°C, respectively.
7. The average SEC were 11.804; 15.649 and 13.018 kWh/kg for average air temperatures of 50°C, 60°C, and 70°C, respectively.
8. The thermal efficiency of the SHRMFD were 25.04%, 17.14% and 15.03% for average air temperatures of 50°C, 60°C, and 70°C, respectively.
9. The average energy contributed by the biomass furnace and the solar collector for SHRMFD were 13.28 and 14.74%; 8.08 and 17.50%; and 6.10 and 20.35 for average air temperatures of 50°C, 60°C, and 70°C, respectively.
10. The SHRMFD performance is better at an average air temperature of 50°C because it has higher thermal efficiency and lower energy consumption.

**NOMENCLATURE**

| | |
|---|---|
| $C_{Pa}$ | air specific heat ($Jkg^{-1}C^{-1}$) |
| $CV_{bmf}$ | biomass fuel caloric value (kcal/kg) |
| $\cos\varphi$ | power factor |
| $E_{Bbf}$ | electrical energy required by the biomass furnace blower (W) |
| $E_{bmf}$ | heat energy produced from burning of the biomass fuel (W) |
| $E_{Bmfd}$ | electrical energy required by the mixed flow dryer blower (W) |
| $E_{Mbe}$ | electrical energy required by the bucket elevator motor (W) |
| $E_{Mdr}$ | electrical energy required by the discharge roller motor (W) |
| $E_{Mvf}$ | electrical energy required by the vibratory feeder motor (W) |
| $H_{fg}$ | latent heat of vaporization of water (kJ/kg) |
| I | current (A) |
| $\dot{m}_a$ | mass flow rate of air (kg/s) |
| $\dot{m}_{bmf}$ | consumption rate of biomass fuel (kg/h) |
| $m_{bonedrypd}$ | mass of bone dry of paddy (kg) |
| $M_{Cdb,t}$ | paddy moisture content (dry basis) at the time "*t*" |
| $M_{Cdb,t+\Delta t}$ | paddy moisture content (dry basis) at the time "$t+\Delta t$" |
| $\dot{m}_{water}$ | drying rate (kg/h) |
| $m_{wetpd}$ | mass of wet of paddy (kg) |
| T1($T_{amb\,(db)}$) | dry bulk ambient temperature (°C) |
| T2($T_{amb\,(wb)}$) | wet bulk ambient temperature (°C) |
| T3($T_{i,sc}$) | air temperature at the inlet of the solar collector (dry bulk) (°C) |
| T4($T_{o,sc}$) | air temperature at the outlet of the solar collector (dry bulk) (°C) |
| T5($T_{i,bf}$) | air temperature at the inlet of the biomass furnace (dry bulk) (°C) |
| T6($T_{o,bf}$) | air temperature at the outlet of the biomass furnace (dry bulk) (°C) |
| T7($T_{i,ds\,(db)}$) | temperature of dry bulk air entering the drying section (°C) |
| T8($T_{i,ds\,(wb)}$) | temperature of wet bulk air entering the drying section (°C) |
| T12($T_{o,ds\,(db)}$) | dry bulk air temperature at the outlet of the drying section (°C) |
| T13($T_{ao,ds\,(wb)}$) | wet bulk air temperature at the outlet of the drying section (°C) |
| V | voltage (V) |

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