Performance of parabolic greenhouse solar dryer equipped with rice husk burning system for banana drying

P. Pankaew[1], O. Aumporn[1], S. Janjai[1,*], T. Mundpookhiew[1], and B.K. Bala[2]

[1]Solar Energy Research Laboratory, Department of Physics, Faculty of Science, Silpakorn University, Nakhon Pathom 73000, Thailand
[2]Department of Agro Product Processing Technology, Jessore University of Science and Technology, Jessore 7408, Bangladesh
***Corresponding author's email**: serm.janjai@gmail.com
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Abstract

This paper presents performance of a parabolic greenhouse solar dryer equipped with a rice husk burning system for a production of high quality dried banana. The rice husk burning system was designed to provide flue gas free clean heated air to supplement heat to parabolic greenhouse dryer for the production of high quality dried bananas during cloudy and rainy days. Maximum effectiveness of the rice husk burning system was 87.7%. The parabolic greenhouse solar dryer equipped with the rice husk burning system was capable of maintaining sufficient drying temperature to produce high quality dried product. There was a considerable reduction in drying time for drying of banana in the greenhouse solar dryer equipped with the rice husk burning system as compared to natural sun drying and the dried banana was a high quality dried product. The drying efficiency of the parabolic greenhouse solar dryer equipped with a rice husk burning system was 12.6% and the payback period was about 2.2 years.

Keywords*:*

solar dryer, rice husk burning system, banana, energy efficiency

1. Introduction

Banana (*Musa x paradisiaca L.*) is one of the major fruits in Thailand. Among many varieties of banana, the variety commonly called "namwa" is the most grown banana in this country. Namwa banana is consumed both as fresh and dried products (Fig. 1). Although, dried banana is commercially produced throughout Thailand, the well-known area of dried banana production is located in Bangkratum district of Phisanulok province, upper part of the central region of Thailand. About 4,000 tons of dried banana are annually produced in this district. In the past, the natural sun drying method was used by dried banana producers. This method has been gradually replaced by solar drying using parabolic greenhouse solar dryers [1]. The use of the parabolic greenhouse solar dryer to dry banana for commercial purpose not only saves conventional fuels but also help reduce product losses mainly due to rain. In general, drying of banana in the parabolic greenhouse dryer requires approximately 4 days to reduce an initial moisture content from about 80% (w.b.) to a final moisture content of 15-20% (w.b.).

Drying of banana is sensitive to the drying air temperature. If the first day of banana drying in the parabolic greenhouse dryer is cloudy or rainy, banana will be spoiled. Therefore, auxiliary heater as a backup protection is needed for drying of the banana in the parabolic greenhouse solar dryer to provide heat during cloudy and rainy days to avoid this spoilage. Biomass burning system is one of efficient auxiliary units [2] among other traditional types of auxiliary heaters such as electric heating [3-14], LPG gas burner [15, 16] and diesel engine [7, 17]. Solar and biomass are two main renewable energy sources suitable for drying applications. The use of biomass burning system would be more appropriate from the costs and reliability points of view to provide clean air with uniform temperature for good quality dried product.

Over the past few decades, several researches on using biomass burner for auxiliary heating of solar dryers have been reported. Bena and Fuller [18] combined a direct-type natural convection solar dryer with a simple biomass burner to demonstrate solar drying technology for drying of small-quantity (20-22 kg) of fruits and vegetables in non-electrified area in Australia. Prasad and Vijay [19] developed and studied a small scale dryer (18 kg) for drying agricultural product using solar-biomass hybrid dryer in India. Madhlopa and Ngwalo [20] designed, constructed and evaluated a solar dryer with integrated collector-storage solar and biomass-backup heater for drying of 240 kg fresh of pineapple in Malawi. Yunus et al. [21] designed a biomass burner/gas-to-gas heat exchanger to back up a small scale (2.5 kg) solar dryer for drying food and fish in Malaysia. Sonthikun et al. [22] designed and constructed a solar-biomass hybrid dryer for drying of natural rubber sheet (320 kg) in Thailand. There is a research gap in auxiliary heater integrated greenhouse solar dryer. Therefore, the objectives of this study are to develop the parabolic greenhouse solar dryer equipped with rice husk burning system and to assess the performance of this dryer.

(a)

(b)

Fig. 1 (a) A fresh namwa banana (b) Dried namwa banana.

2. Methodology

2.1. Parabolic greenhouse solar dryer equipped with rice husk burning system

The parabolic greenhouse solar dryer equipped with the rice husk burning system is shown in Fig. 2. The parabolic greenhouse solar dryer, previously called PV-ventilated solar greenhouse dryer, comprises mainly a parabolic roof structure covered by polycarbonate sheets, arrays of trays for placing products to be dried, ventilating fans and a concrete floor [23].

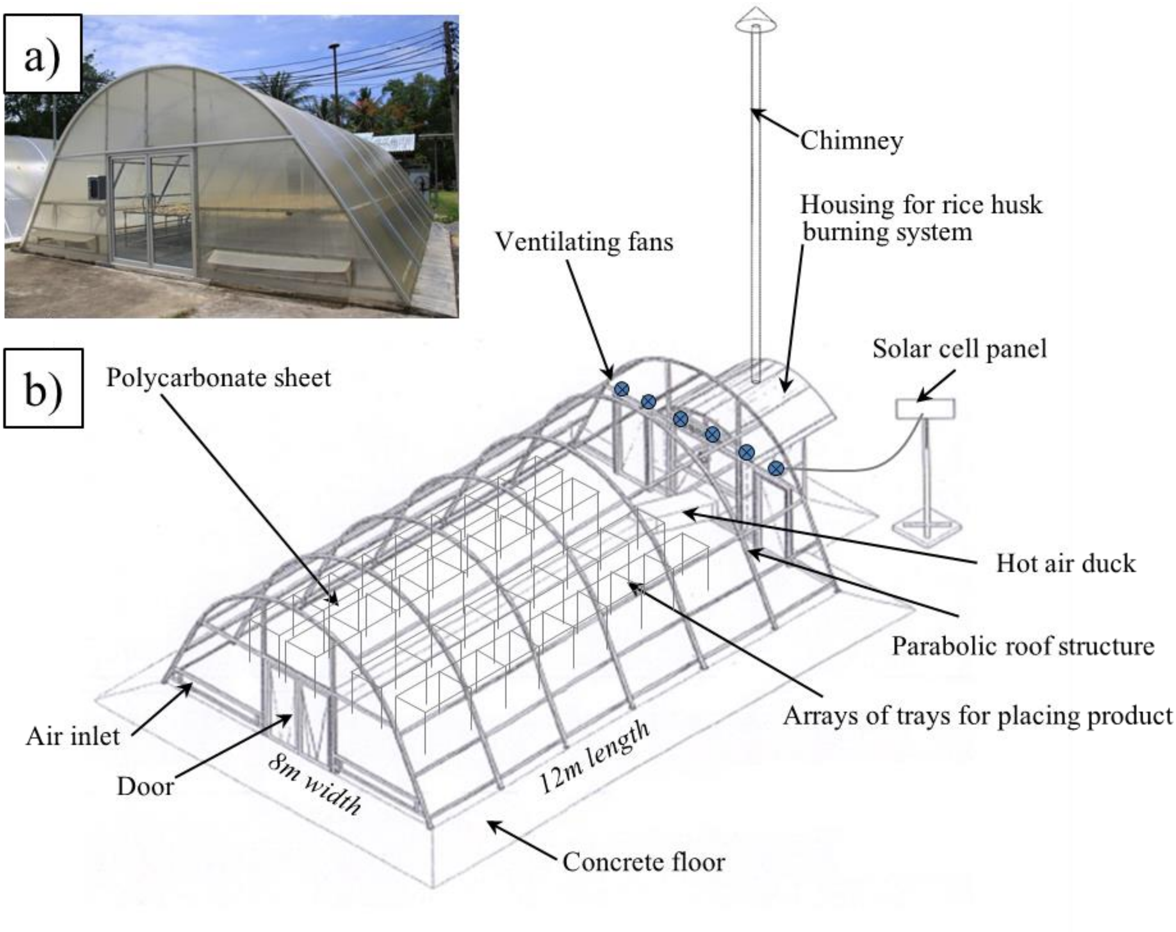
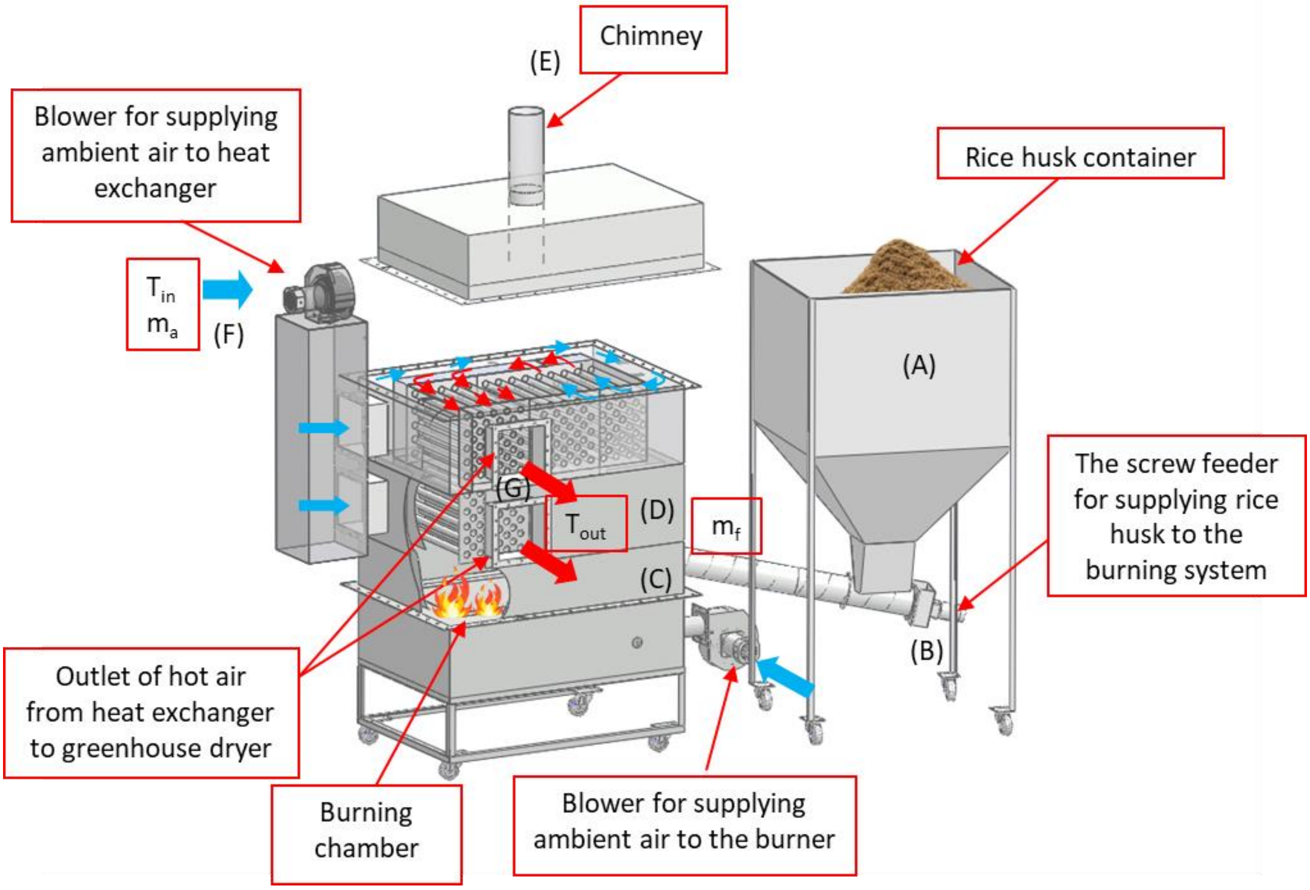


Fig. 2 Parabolic greenhouse solar dryer equipped with a rice husk burning system (a) pictorial view, (b) schematic diagram.

In this study, we designed a rice-husk burning system to use it as an auxiliary heater for drying banana in the parabolic greenhouse dryer. The burning system consists of a burning chamber, air-to-air heat exchanger, screw feeder of rice husk and controller (Fig. 3).

(a)



(b)

Fig. 3 Rice husk burning system a) pictorial view b) schematic diagram.

The function of the rice husk burning system can be described as follows. Rice husk from the container (A) is supplied to the burning chamber (C) by a screw feeder (B). Ambient air is brown to the chamber to supply air for rice husk burning and to blow flue gas through air-to-air heat exchanger (D) situated above the burning chamber. Then flue gas leaves the heat exchanger to ambient environment through a chimney (E). For the transfer of thermal energy, a blower (F) sucks ambient air and blows it to the heat exchanger. Hot air from the outlet of the heat exchanger (G) is supplied to the dryer. The controller regulates the rice husk feeder and the ignition of rice husk in the burning chamber according to the setup temperature of the outlet air of the heat exchanger.

2.2. Performance of the burning system

The performance of the burning system was measured in terms of the effectiveness (ε) which is defined as:

$$\varepsilon = \frac{\text{actual heat transfer rate}}{\text{maximum heat transfer rate}}$$

$$= \frac{m_a C_{pa}(T_{out} - T_{in})}{m_f h_f} \tag{1}$$

where m_a is mass flow rate of ambient air to the heat exchanger ($kg{\cdot}s^{-1}$), m_f is flow rate of rice husk to the burning system ($kg{\cdot}s^{-1}$), h_f is heating value of rice husk ($J{\cdot}kg^{-1}$), C_{pa} is specific heat of air ($J{\cdot}kg^{-1}{\cdot}°C^{-1}$), T_{out} is outlet temperature of hot air from the heat exchanger (ºC) and T_{in} is ambient air temperature (ºC).

2.3. Experimental procedure

Four drying experiments were conducted during 12-30 July 2017. For each experiment, 300 kg of ripe banana collected from a local market was dried in the parabolic greenhouse solar dryer equipped with the rice husk burning system installed at Silpakorn U

niversity, Nakhon Pathom, Thailand. The solar energy was employed for direct heating of inside air during sunny days while the rice husk burning system was used to supply hot air to the dryer during cloudy and rainy days. The drying was started at 8 am and continued till 6 pm. To compare the performance of the parabolic greenhouse solar dryer equipped with the rice husk burning system with that of natural sun drying, three control samples were placed on trays and dried at the same weather condition outside the dryer. Weights of the representative samples at various positions inside dryer and control samples outside the dryer were periodically recorded at 3-hour interval using a digital balance (Kern, model 474-42, accuracy ± 0.1 g). There was some rainfall in many days of the experiment. The rice husk burning system was operated when rain started and the temperature inside the dryer was maintained above 50°C by controlling supply of rice husk.

Important parameters affecting the dryer performance including solar radiation, air temperature, relative humidity and air velocity were measured. Solar radiation was measured by a pyranometer (Kipp & Zonen model CM 11, accuracy ± 0.5%) and it was placed on the roof of the dryer. Temperature was measured by K-type thermocouples. Hot wire anemometer (Airflow, model TA5, accuracy ± 2%) was used to measure the air velocity at the air inlet, air outlet of the dryer. The relative humidity of ambient air and drying air was periodically measured by hygrometers (Electronik, model EE23, accuracy ± 2%). Voltage signals from the pyranometer, hygrometers and thermocouples were recorded every 10 minutes by a multi-channel data logger (Yokogawa, model DC100). The moisture content of the samples was determined by the oven method (103°C for 24 hours).

2.4. Uncertainty analysis

Uncertainty analysis refers to the uncertainty or error in experimental data. In general, there are two types of error, namely systematic error and random error. The systematic error in the experimental data is a repeated error of systematic value and the random error is due to imprecision. The systematic error can be removed by calibration but the random error cannot be removed. The imprecision due to random error can be defined statistically from a number of measurements.

In this study, the pyranometer, thermocouples and hygrometers were calibrated prior to the use in the experiments. From the experiments, the mean value of the measurements and standard deviation of the data on solar radiation, ambient air temperature, drying air temperature and relative humidity were determined. The variable x_i that has an uncertainty δx_i is expressed as [24-26]:

$$x_i = x_{mean(measured)} \pm \delta x_i \quad (2)$$

where x_i is actual value, x_{mean} is measured value (mean value of the measurements) and δx_i is uncertainty in the measurement. There is an uncertainty in x_i that may be as large as δx_i. The value of δx_i is the precision index that is usually taken as 2 times the standard deviation and it encloses approximately 95% of the population for a single sample analysis.

2.5. Drying efficiency

The drying efficiency is defined as the ratio of energy output of the drying system to energy input to the drying system [27]. Solar radiation input (E_{solar}) on the parabolic greenhouse dryer is computed as:

$$E_{solar} = A_{dryer} \int S_r(t)dt \qquad (3)$$

where A_{dryer} is the base area of the parabolic greenhouse dryer (m^2) and $S_r(t)$ is solar radiation at time t (W·m^{-2})

The output of the dryer in terms of energy (E_{dryer}) is

$$E_{dryer} = m_r L_g \qquad (4)$$

where m_r is moisture removed (kg) and L_g is latent heat of vaporization of moisture (J·kg^{-1})

Thus, the efficiency of the dryer equipped with the burning system (ε_{eff}) is

$$\varepsilon_{eff} = \frac{E_{dryer}}{E_{solar} + E_{PV} + E_{rice\ husk}} \times 100\,\% \qquad (5)$$

where E_{PV} is energy output from solar cell panel (J) and $E_{rice\ husk}$ is energy output from rice husk burning system (J). Note that this dryer uses a solar cell panel to power the ventilation system.

3. Results and Discussion

Typical results were presented as follows.

3.1. Performance of the rice husk burning system

The average consumption rate of dry rice husk was 12 kg/hour and the heating value of the rice husk sample used in this study is 14.51 MJ/kg. Maximum power input from the rice husk burning system was 132.49 kW and the average power needed from the husk burning system was 39.75 kW for drying of banana during cloudy and rainy days. The overall effectiveness of the rice husk burning system was 87.7%. The burning system has the capacity to support the greenhouse dryer properly in rainy and cloudy days to maintain the set temperature of the drying air as a backup protection for the production of high quality dried banana.

3.2. Performance of the greenhouse solar dryer equipped with the rice husk burning system

The variations of the solar radiation during the drying period are shown in Fig. 4. The fluctuations of the solar radiation during the period of drying were very high especially during the first, second and third days of the drying. For all of the days of drying, the sky was cloudy. The solar radiation increased sharply in the second day up to 1200 kW·m^{-2} and fourth day up to 1000 kW·m^{-2}. There was little rainfall in the morning and afternoon of first day and in the afternoon of the third day. The second day and the fourth day were cloudy.

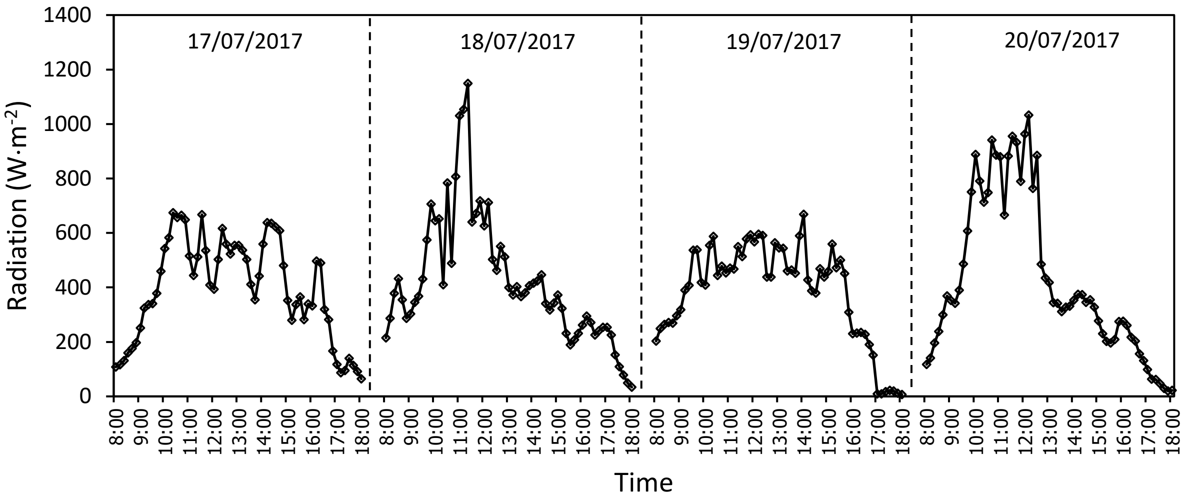


Fig. 4 Variations of solar radiation during drying period.

Fig. 5 shows energy inputs from solar radiation and biomass burning system to the greenhouse solar dryer. Energy input to the greenhouse solar dryer from solar radiation follows the pattern of the solar radiation, but the energy input from the biomass burning system provides heat to raise the desired drying air temperature during cloudy and rainy days. Fig. 5 shows that most of the energy input from biomass burning system was needed in the first and third day and the least in the second and fourth day.

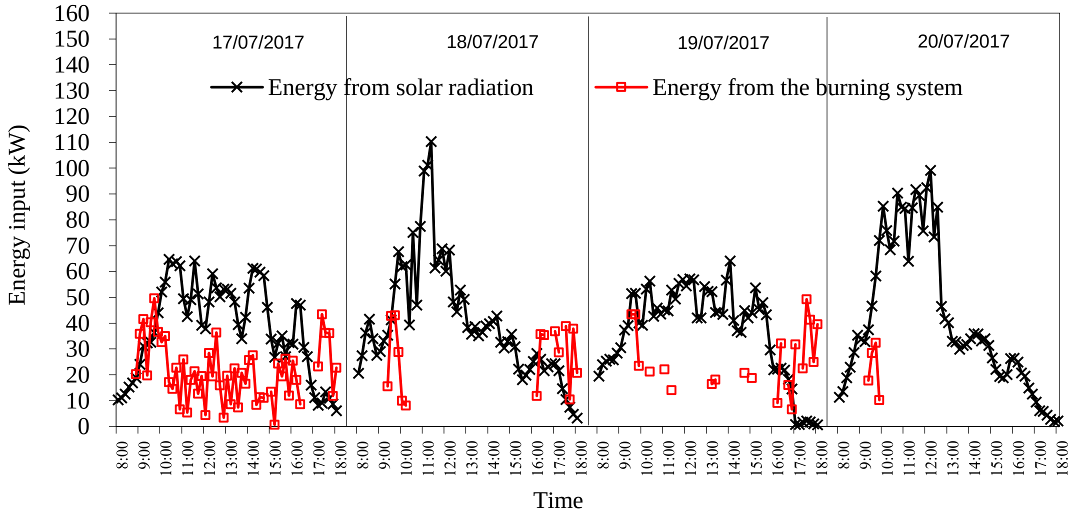


Fig. 5 Variation of energy input with time inside the greenhouse solar dryer.

The temperatures at different points inside the greenhouse dryer are shown in Fig. 6 and these temperatures are significantly different from the ambient temperature outside the dryer. The temperature inside the dryer was maintained fairly constant to the set temperature of 50˚C, but the fluctuations of the temperatures of the air supplied from the burning system during auxiliary heating from biomass are produced in such fashion that the set temperature for drying of banana is maintained. Fig. 6 shows that the air temperature inside the dryer supported by the burning system was approximately 20°C higher than the ambient air temperature and it was maintained at 50°C for most of the drying time.

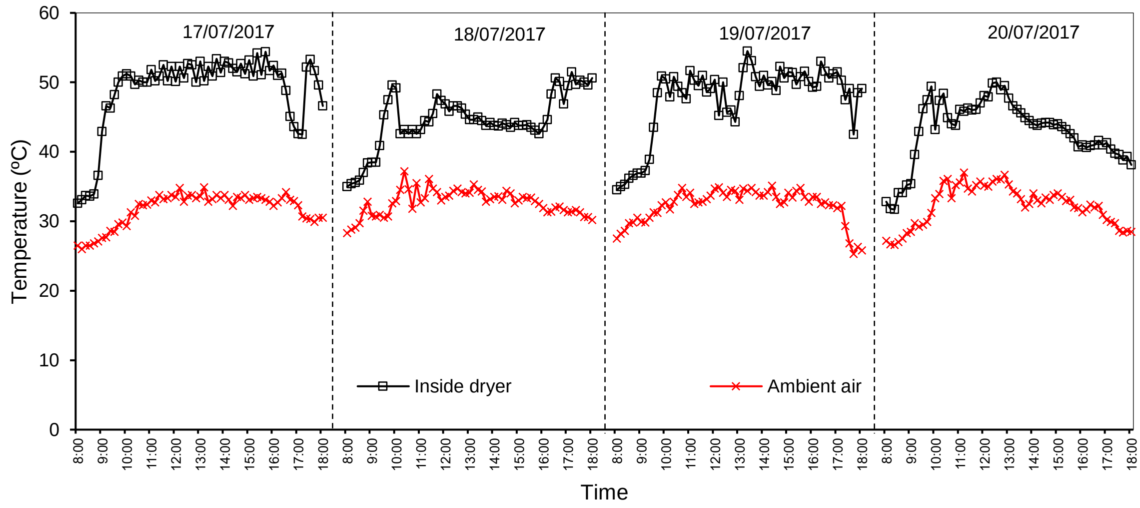


Fig. 6 Comparison of temperature variations inside the greenhouse dryer with the burning system and the ambient air temperature.

The variations of the relative humidity of the air inside the greenhouse solar dryer equipped rice husk burning system and the ambient air outside the dryer are shown in Fig. 7. The relative humidity (%) of the air inside the dryer decreased when the temperature increased. The relative humidity outside the dryer was always 40 % higher than the humidity inside the dryer. The relative humidity of the air at the noon was always less than those of the morning and afternoon.

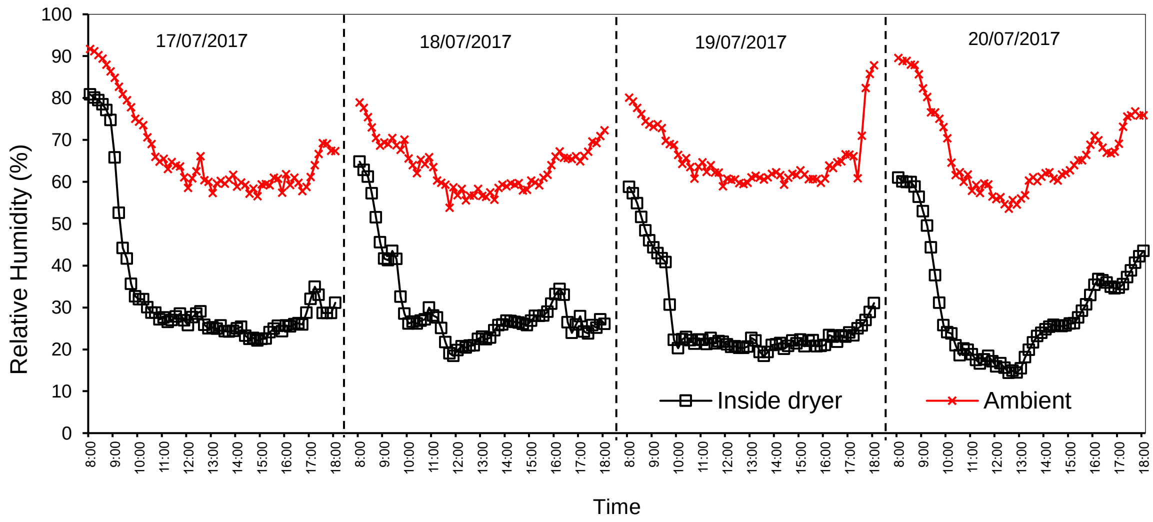


Fig. 7 Comparison of relative humidity inside the dryer and ambient air.

Fig. 8 shows the comparison of moisture content changes of banana inside the greenhouse dryer with the burning system and natural sun drying. Banana inside the greenhouse dryer coupled with the biomass burning system was dried to a final moisture content of 15 % (w.b.) within 4 days from an initial moisture content of 68% (w.b.) while the drying in natural sun drying took 6 days to achieve the final moisture of about 15%. The banana dried in the greenhouse dryer supported by the rice husk burning system was a better quality dried banana compared to the sun dried banana (Fig. 9). Commercially, the dried banana has a moisture content less than 20% (w.b.) [28, 29] while the dried banana in this study was 15% (w.b.), which has a better shelf life. The overall efficiency of the solar greenhouse dryer was 12.6%. Fudholi et al. [30] also reported the overall efficiency of the solar greenhouse dryer to be 12.7%.

More than half of the dried banana from natural sun drying was deteriorated due to fungus attack. But banana dried inside the greenhouse dryer was very good quality both in color and pungency.

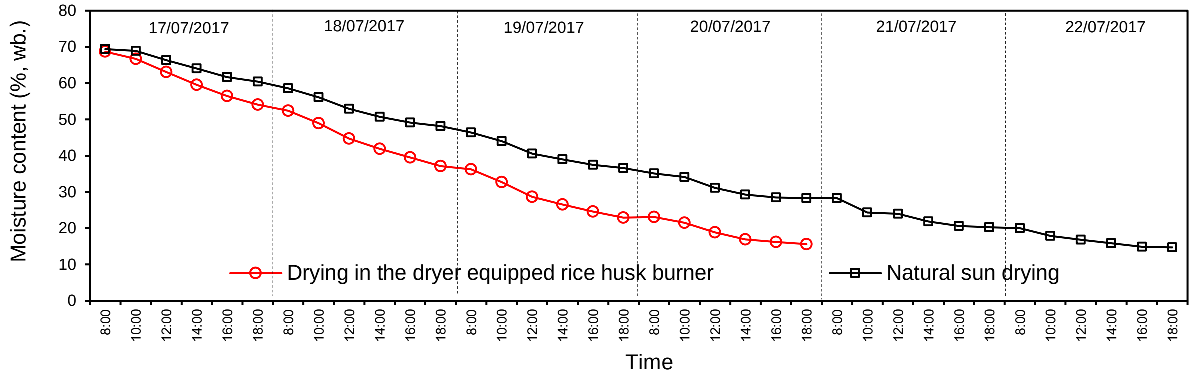


Fig. 8 Moisture contents of banana drying in greenhouse dryer with the burning system in comparison with the natural sun drying.

Fig. 9 (a) Banana inside the dryer (b) Banana dried by natural sun.

3.3. Economic evaluation

The economic evaluation of the parabolic greenhouse solar dryer equipped with the rice husk burning system was carried out based on economic data in Thailand during the past 5 years (2012-2017) and experimental data undertaken in this study. These data are shown in Table 1.

Table 1 Economic and dried banana production data used for the economic evaluation.

Item	Value
1) Cost of the parabolic greenhouse dryer (C_{dryer})	550,000 Baht
2) Cost of rice husk burning system (C_{burner})	120,000 Baht
3) Labor cost per batch for handling banana and operating the dryer equipped with the burning system (C_{labor})	1,200 Baht
4) Number of drying batch per year	90 batches
5) Drying time per batch	4 days
6) Quantity of fresh banana per batch (M_f)	300 kg
7) Quantity of dried banana obtained from the dryer per batch (M_d)	100 kg
8) Average number of cloudy or rainy days per year, when auxiliary heat from the rice husk burning system are needed*	57days
9) Quantity of rice husk required per batch (during cloudy or rainy days)**	61 kg
10) Unit cost of rice husk	1.7 Baht·kg^{-1}
11) Electricity required per batch (for operating various blowers and feeders of the burning system during cloudy and rainy days)	45 kWh
12) Unit cost of electricity ($C_{unit\ electricity}$)	2.76 Baht·kWh^{-1}
13) Price of fresh banana (P_f)	15 Baht·kg^{-1}
14) Price of dried banana (P_d)	100 Baht·kg^{-1}
15) Interest rate (i_{in})***	7.83%
16) Inflation rate (i_f)***	2.1%
17) Life span of the dryer equipped with the burning system (N)	10 years

* It was estimated from the level of solar radiation and sky condition routinely recorded by a pyranometer and a sky camera at a nearby solar radiation monitoring station.

** It was estimated from experimental data during the study period.

*** Average values (2012-2017) from the National Bank of Thailand

(1 USD = 31.72 Baht)

Three economic parameters were calculated as follows.

1) Drying cost

The following steps were carried out to estimate the drying cost. Firstly, the capital cost (C_T) of the parabolic greenhouse dryer equipped with the rice husk burning system was computed from

$$C_T = C_{dryer} + C_{burner} \tag{6}$$

where C_{dryer} is the cost of the parabolic greenhouse dryer and C_{burner} is the cost of the rice husk burning system.

Then, the annual cost (C_{annual}) of the dryer equipped with the burning system for banana drying was estimated using the formula proposed by Audsley and Wheeler [32] as follows:

$$C_{annual} = \left[C_T + \sum_{i=1}^{N} (C_{main,i} + C_{op,i})\omega^i \right] \left[\frac{\omega - 1}{\omega(\omega^N - 1)} \right] \tag{7}$$

and
$$\omega = \frac{(100 + i_{in})}{(100 + i_f)} \quad \ldots\ldots \tag{8}$$

where $C_{main,i}$ and $C_{op,i}$ are the maintenance cost and operating cost at year i, respectively. i_{in} is interest rate and i_f is inflation rate. The maintenance cost was assumed to be 1% of the capital cost.

The operating cost comprises the rice husk consumption cost (C_{husk}), electricity consumption cost ($C_{electricity}$) and labor cost (C_{labor}) for handling banana and operating the dryer equipped with the burning system. Therefore the operating cost can be written as follows:

$$C_{op} = C_{husk} + C_{electricity} + C_{labor} \tag{9}$$

The cost of rice husk (C_{husk}) was calculated from

$$C_{husk} = C_{unit\_husk} \cdot M_{husk} \tag{10}$$

where C_{unit_husk} is the unit cost of the rice husk, M_{husk} is the amount of rice husk used per year and it is estimated from solar radiation level and sky condition routinely recorded at Nakhon Pathom solar monitoring station during 2012-2017. The amount of rice husk required by the burning system during cloudy and rainy days was estimated from the drying experiments.

The cost of electricity consumption ($C_{electricity}$) can be computed from

$$C_{electricity} = C_{unit\ \ electricity} \cdot M_{electricity} \tag{11}$$

where $C_{unit\ \ electricity}$ is the unit cost of the electricity and $M_{electricity}$ is the amount of electricity consumed per year.

Finally, the drying cost (Z) was calculated from

$$Z = \frac{C_{annual}}{M_d} \tag{12}$$

where M_d is the amount of dried product estimated per year. From the above–mentioned equations and the related data in Table 1, the drying cost was calculated to be 20.5 Baht/kg.

2) Payback period

The payback period (PB) was estimated using the following equation adopted from Fudholi et al. [33] and Dhanushkodi et al. [34]

$$PB = \frac{C_T}{M_d P_d + M_f P_f + M_d Z} \tag{13}$$

where M_f is the amount of fresh banana used per year and P_f is the price of fresh banana. Based on the evaluation data in Table 1 and Eq. 13, the payback period of the parabolic greenhouse dryer equipped with the rice husk burning system was estimated to be 2.2 years.

3) Internal rate of return

The internal rate of return (IRR) was estimated using a formula adopted from Park [35] as follows:

$$\sum_{i=1}^{N} \frac{C_i}{(1+IRR)^i} = 0 \tag{14}$$

where C_i is the cash flow at year i due to the investment on the dryer equipped with the burning system. By using the iteration method and the related data in Table 1, IRR was found to be 45%.

4. Conclusions

Rice husk burner with a heat exchanger was designed to provide flue gas free clean heated air for the greenhouse solar dryer and the maximum effectiveness of the rice husk burner and heat exchanger was 87.7%. Field-level drying experiments of banana was carried out using the solar greenhouse dryer equipped with a rice husk burning system for drying of banana. Banana was dried in this dryer to 15% (w.b.) of moisture content from an initial moisture content of about 68% (w.b.) during 4 days of drying while the moisture content of similar samples in the open sun drying method took 2 more days. Thus, there is a considerable reduction in drying time in the greenhouse solar dryer equipped with a rice husk burning system in comparison to natural sun drying. The overall energy efficiency of the solar dryer was 12.6%. Finally, this study demonstrates that the dryer equipped with the burning system is fully capable of providing clean heat to maintain the desired temperature during cloudy and rainy days and also thereby it can produce high quality dried bananas.

Nomenclature

A_{dryer}	dryer area, m^2
C_{annual}	annual cost, Baht
C_{burner}	cost of rice husk burning system, Baht
C_{dryer}	cost of the parabolic greenhouse dryer, Baht
$C_{electricity}$	electricity consumption cost, Baht
C_{husk}	rice husk consumption cost, Baht
C_i	cash flow at year i
C_{labor}	labor cost, Baht
C_{main}	maintenance cost, Baht
C_{op}	operating cost, Baht
C_{op}	specific heat of air, $J{\cdot}kg^{-1}\,{}^{o}C^{-1}$
C_T	capital cost of the dryer equipped the burning system, Baht
$C_{unit\ electricity}$	unit cost of electricity, $Baht{\cdot}kWh^{-1}$
E_{dryer}	dryer output, J
E_{PV}	energy output from solar cell panel, J
$E_{rice\ husk}$	energy output from rice husk burner, J
E_{solar}	solar energy input to the dryer, J
h_f	heating value of rice husk, $J{\cdot}kg^{-1}$
i_f	inflation rate, %
i_{in}	interest rate, %
IRR	internal rate of return, %
L_g	latent heat of vaporization of moisture, $J{\cdot}kg^{-1}$
m_a	mass flow rate of air, $kg{\cdot}s^{-1}$
m_f	mass flow rate of rice husk, $kg{\cdot}s^{-1}$
M_f	Quantity of fresh banana, kg
M_d	Quantity of dried banana, kg
m_r	moisture removed, kg
N	life span of the dryer, years
P_f	price of fresh banana, $Baht{\cdot}kg^{-1}$
P_d	price of dried banana, $Baht{\cdot}kg^{-1}$
PB	payback period, year
$S_r(t)$	solar radiation at time t, $W{\cdot}m^{-2}$
t	time, s
T_{out}	temperature of hot air input from the heat exchanger, ^{o}C
T_{in}	ambient air temperature, ^{o}C
x_i	actual value
x_{mean}	measure value (mean value of the measurement)
Z	drying cost, $Baht{\cdot}kg^{-1}$
δx_i	uncertainly in a measurement
ε	overall effectiveness
ε_{eff}	efficiency of the dryer equipped with the burning system, %

ω economic parameter defined in Eq. 8

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