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Drying Bananas with a Modified Hot Air Dryer Using Waste Heat from a 200 Liter Kiln

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Abstract

The purposes of this research are to modify hot air dryer by using waste heat from a 200 liter kiln for drying bananas and to investigate its drying performance by assessing its drying rate and specific energy consumption. The main parts of the dryer consist of drying chamber that has dimensions of 0.72 × 1.2 × 0.63 m^3, air circulation system and heat exchanger which receives waste heat from the exhaust tube and kiln surface. For the experiment, an initial moisture content of 30 kg bananas was prepared at 239.60±20.30 %dry basis. Drying temperature was set at 60±4°C while drying air velocity was set at 0.6 to 1.8 ms^{-1}. All experiments were carried out in triplicate and the drying period was measured from the initial moisture content less final moisture content, 59.06±6.77 %dry basis. An air velocity of 1.8 ms^{-1} was the optimal condition in this experiment. It had the highest drying rate at the lowest specific energy consumption. The results of the average drying rate and the average specific energy consumption were 0.87±0.004 kg_{water} h^{-1} and 51.12±0.70 MJ kg_{water}^{-1}, respectively.

Keywords: 200 Liter Kiln; Banana; Dryer; Biomass; Waste Heat

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Introduction

Fuel wood is a biomass which is a widely available renewable energy source. Wood is commonly available throughout Thailand. Wood has been used in combustion and heating. Charcoal is used for cooking in everyday life. A 200 liter tank is widely used in industry, such as the chemical, painting and oil industry. These tanks are therefore cheap and small. They can be modified to become a charcoal kiln [1]. This closed system technology is helpful in decreasing smoke pollution from open system charcoal production. This technology is easy to build, has a low cost and produces high charcoal quality. This research focuses on the waste heat from the kiln together with the exhaust heat to dry bananas.

Banana is a plant which is easy to grow. All parts of the banana plant can be used in products. Majority of people like to eat the dried banana. One way for drying banana is to use a solar heat source, just let them to dry in the sun. To speed up the drying a parabola dome was developed for drying clean banana [2] – [3]. This has the advantage of also protecting from dust and insects. Parabola dome drying usually takes about 4 – 5 days. This can be a problem during the rainy season. If the rain falls continuously for more than 2 days, the banana will be lost. Nowadays, banana dryers can be classified by heat sources such as LPG dryer [4], electric heater dryer combined with solar collector [5], and two cycle heat pump dryer [6]. The main source of power comes from the air temperature heating rate. In this research, a modified waste heat recovery system from a 200 liter kiln was used for drying peeled bananas. The drying kinetics of the bananas and the drying performance were investigated. The heating rate is heat per unit time in kW.

Materials and Methods

1. Experimental Unit

Figure 1 shows the experimental setup. The drying chamber had dimensions of 0.72 x 1.2 x 0.63 m^3. It could contain a maximum of 6, 0.63 x 0.72 m^2, trays. The air circulation system used a blower with 0.3 horse power motor. Two heat exchangers, one on the exhaust gas and another around the kiln surface were designed for waste heat recovery. The exhaust heat exchanger was made from a steel 4 inch diameter tube with rectangular fins for increased heat transfer area. The kiln surface and insulated six steel walls had a heat exchanger. At the front side of the kiln was an air valve and small door. The pocket was used to start burning wood in the kiln. At a high enough temperature the wood could fire itself. The air valve was used to control the temperature. Figure 2 shows a diagram of the air circulation system of the dryer.

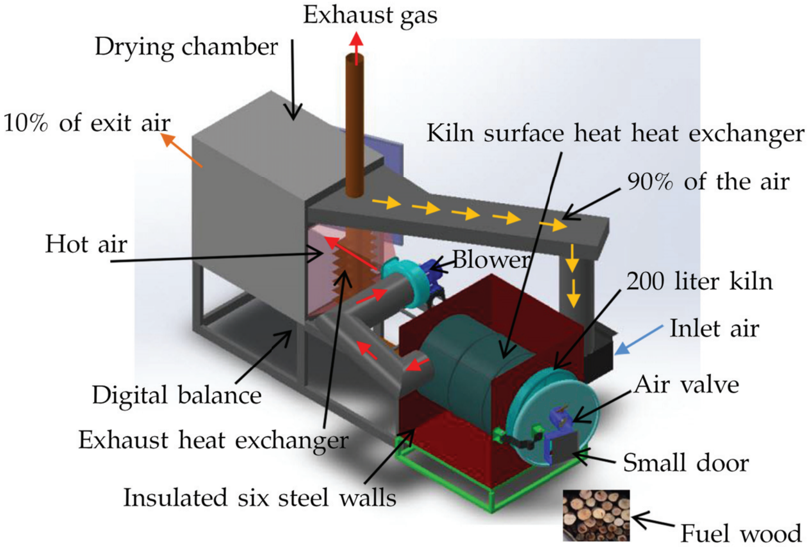

Figure 1 Apparatus of a 200 liter kiln waste heat recovery system

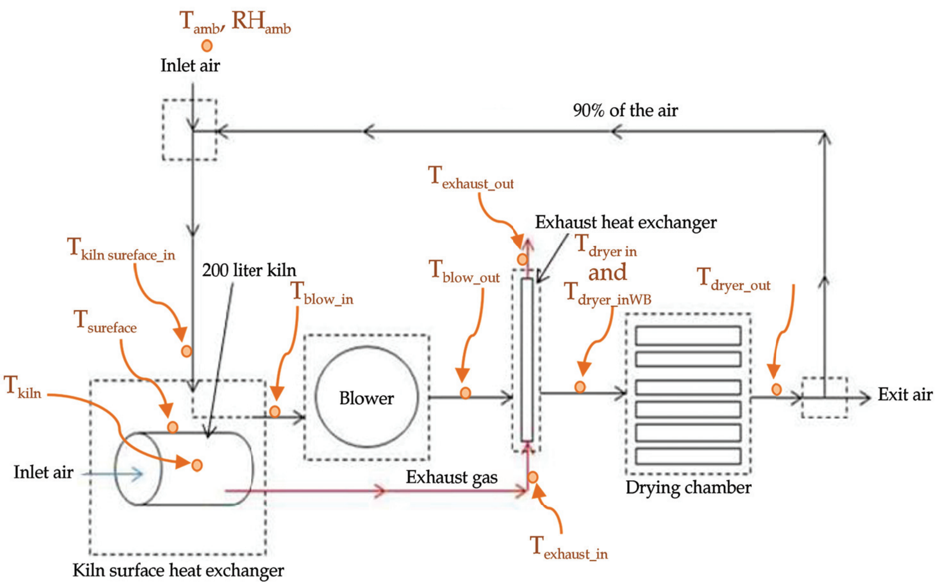

Figure 2 Diagram of the dryer air circulation system

2. Banana Drying

30 kg of peeled bananas were dried at a time. The initial moisture content of the peeled bananas was 239.60±20.30 % on a dry basis. They had dimensions of 90.1±4.0 mm in length, 29.3±0.9 mm in width and 28.9±1.2 mm in thickness. The bananas were shaken. Then, they were put on trays and placed in the drying chamber. They were dried for about 17 to 20 hours. The time period varied depending on the condition on the dried bananas. The dryer was stopped when the bananas were flat. The bananas were kept in a container for 12 hours and coated by honeyed fluid which came from the flat bananas. Finally, the bananas were dried until the final moisture content. Then, six bananas were selected from the tray and measured for their width, length and thickness and their drying time.

3. Eucalyptus

The trunk of the eucalyptus is the raw material for paper production. The small eucalyptus is waste from cutting the trunk. Usually, it is just combusted. The 200 liter charcoal kiln used the small eucalyptus as raw material.

4. Experimental procedure

The experiments were performed under hot air temperature of 60±4 ^{o}C and air velocities from 0.6 to 1.8 ms^{-1} with a partial closed loop air system. 90 % of the air was recycled in these tests [7]. The air valve in the 200 liter kiln was used to control the burning eucalyptus temperature which also controlled the hot air temperature set in the drying chamber. The weight of the bananas was recorded every 0.5 hour with a digital balance (±0.01 kg). A temperature recorder (BTM-4208SD) was used to measure several temperatures in the dryer, such as the kiln temperature (T_{kiln}), kiln outside surface temperature ($T_{surface}$), inlet exhaust temperature ($T_{exhaust\_in}$), outlet exhaust temperature ($T_{exhaust\_out}$), inlet temperature of the heat exchanger on the kiln surface ($T_{kiln\ surface\_in}$), inlet blower temperature (T_{blow_in}), outlet blower temperature (T_{blow_out}), inlet drying chamber temperature (T_{dryer_in}) with wet-bulb temperature of inlet drying chamber (T_{dryer_inWB}), outlet drying chamber temperature (T_{dryer_out}), relative humidity of ambient (RH_{amb}) and ambient temperature (T_{amb}). An anemometer (Velocicalc plus model 8385-M-GB) was used to measure the air velocity. All experiments were carried out in triplicate.

5. Analytical methods

Processing dried banana involved dry air and vapor. The heating rate can be calculated as shown below:

$$\dot{Q}_h = \dot{m}_a\left(\left(C_{a2}T_2 + WC_vT_2\right) - \left(C_{al}T_1 + WC_vT_1\right)\right) \quad (1)$$

$$\dot{m}_a = \rho A v \quad (2)$$

where $\dot{Q}_h$ is heat transfer to air, $\dot{m}_a$ is mass flow rate of fluid flow, C_{a1} and C_{a2} are specific heat capacities of fluid flow for inlet and outlet of heat exchanger, respectively, W is the humidity ratio, C_v is specific heat capacity of vapor, T_1, T_2 are temperatures of inlet and outlet of fluid flow at heat exchanger, respectively, ρ is density of fluid flow, A is cross section area and v is velocity of fluid flow. The C_a will change with temperature (T) as shown in equation (3) [8] and the C_v is 1.88 kJ/kg °C [9].

$$C_a = 0.00000000037T^3 + 0.00000025095T^2 + 0.00003542694T + 1.003726 \quad (3)$$

The moisture ratio is used to determine the decreasing weight of bananas with drying time. The moisture ratio can be expressed as:

$$MR = \frac{M}{M_{in}} \quad (4)$$

where MR is moisture ratio, M is the moisture content and M_{in} is the initial moisture content.

The specific energy consumption (SEC) and the drying rate (DR) can be defined as:

$$SEC = \frac{((2.6P_b)DT(3.6)/1000) + (m_{wood}LHV)}{water\ \ evaporated\ \ from\ \ product} \quad (5)$$

$$DR = [water\ \ evaporated\ \ from\ \ product]/[drying\ \ time] \quad (6)$$

where 2.6 is an electrical factor for changing to primary energy [10], P_b is blower power, DT is drying time, 3.6 is constant for converting kWh to MJ, m_{wood} is mass of eucalyptus and LHV is low heating value of eucalyptus (17.64 MJ/kg [11]).

Results and Discussion

1. The time dependent temperature

The temperatures of the kiln, kiln outside surface, outlet blower, inlet drying chamber, outlet drying chamber, inlet exhaust of heat exchanger, outlet exhaust of heat exchanger and ambient temperature are presented in Figures 3 and 4. The air velocities ranged from 0.6 to 1.8 ms^{-1} at a drying temperature of 60±4 °C. The drying time was

0 - 20 hours. At a drying air velocity of 0.6 ms^{-1}, the temperatures of the kiln and kiln outside surface were more than the drying velocity of 1.8 ms^{-1}. At a velocity of 0.6 ms^{-1}, the transfer heating rate was lower than the velocity of 1.8 ms^{-1} because increasing velocity affected the mass flow rate following equation (1) - (2).

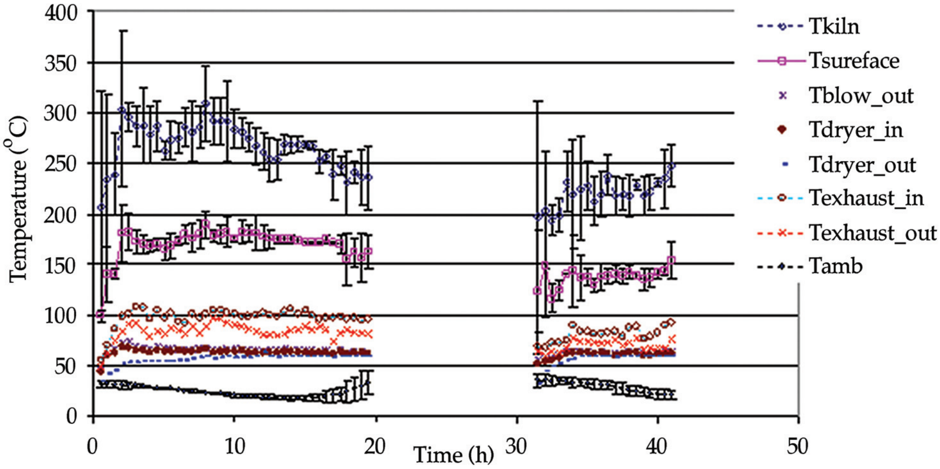

Figure 3 Experimental temperatures versus time at an air drying velocity of 0.6 ms^{-1} and temperature of 60±4 °C

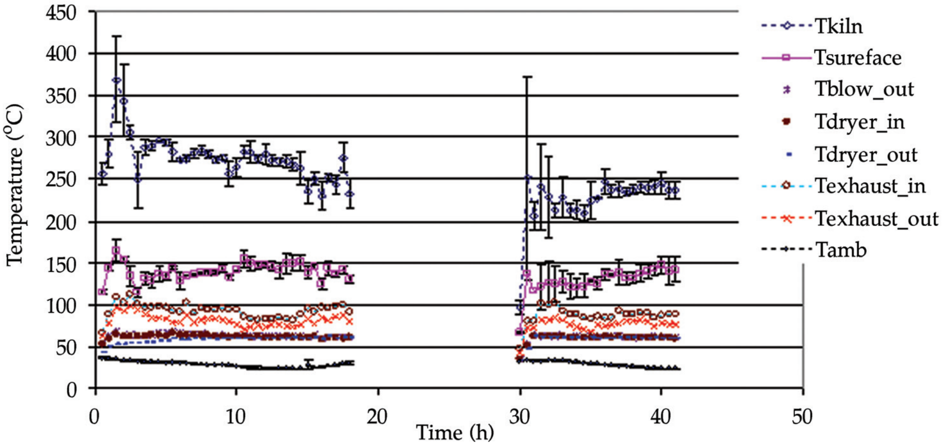

Figure 4 Experimental temperatures versus time at an air drying velocity of 1.8 ms^{-1} and temperature of 60±4 °C

2. The heating rate from the 200 liter kiln

Figure 5 shows the heating rate of the kiln surface heat exchanger. The air drying velocity of 0.6 ms^{-1} had a higher heating rate than the velocity of 1.8 ms^{-1}. The structure of kiln was steel and the dryer structure was stainless so the heat loss through these structures was very high. The heat transfer occurred in three stages, the first stage was the transfer of heat to the dryer structure; the second stage was to increase the product temperature and the third stage was the banana drying.

Figure 6 shows the average heat transfer in the exhaust heat exchanger for drying air velocities of 0.6 and 1.8 ms^{-1}. The average heating rate was 0.06 kW. The kiln surface heat exchanger had a higher average heating rate than the exhaust heat exchanger because the kiln surface temperature was higher as shown Figure 3 – 4.

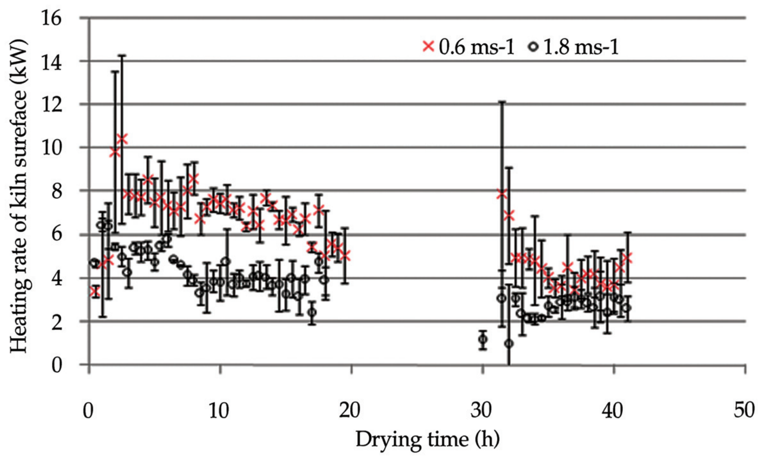

Figure 5 Heat transfer in the kiln surface heat exchanger versus time at two different air velocities and a drying temperature of 60±4 °C

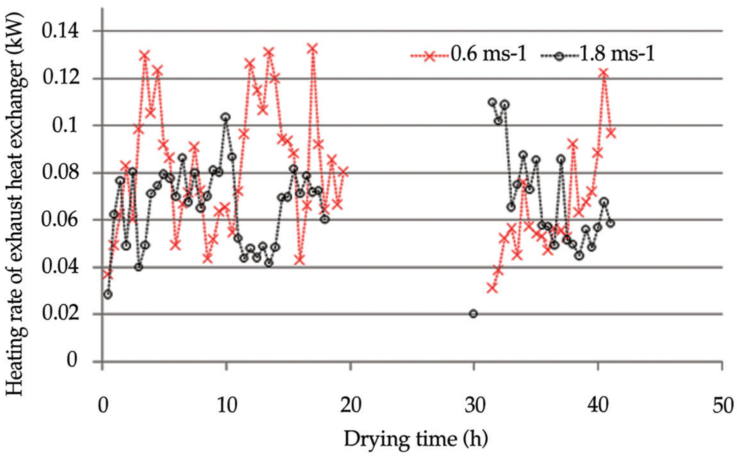

Figure 6 Heat transfer in the exhaust heat exchanger versus time at two different air velocities and a drying temperature of 60±4 °C

3. Drying kinetics of bananas

Figure 7 shows that the air velocity of 1.8 ms^{-1} decreased the moisture ratio more than the air velocity of 0.6 ms^{-1}. Increasing air velocity increased the mass transfer from bananas to hot air. At a temperature of 60±4 °C with an air velocity of 0.6 ms^{-1}, the bananas were dried from an initial moisture content of 235.44±26.85 % dry basis (MR = 1) to a final moisture content of 61.50±3.12 % dry basis (MR = 0.26). The final moisture content was similar to a previous research on leaf stove dryer [7]. At a temperature of 60±4 °C with an air velocity of 1.8 ms^{-1}, the bananas were dried from an initial moisture content of 242.37±20.86 % dry basis (MR = 1) to a final moisture content of 38.33±10 % dry basis (MR = 0.15). From this study, the drying rate of bananas increased with increasing air velocity because the higher heating rate of the air velocity at 1.8 ms^{-1}.

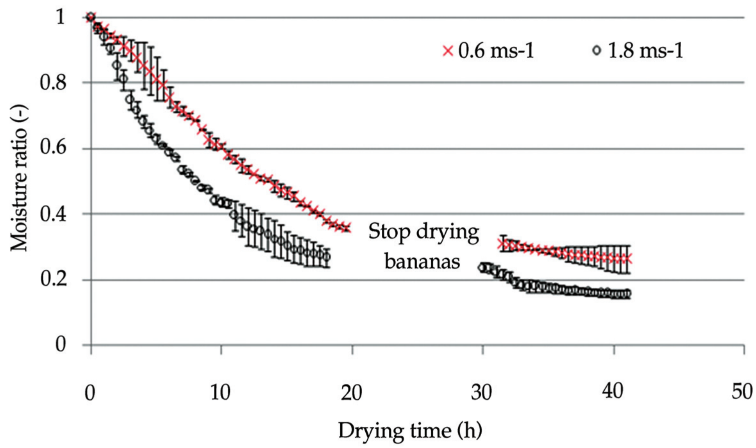

Figure 7 Comparison of the change in moisture ratio at hot air velocities of 0.6 and 1.8 ms^{-1} at a drying temperature of 60±4 °C.

4. Change in banana dimensions

The change in width, length and thickness of bananas are presented. Table 1 shows reducing banana dimensions of width, length and thickness because the water in the banana evaporates. The dried bananas were flat so the width and the length increased but the thickness decreased. The bananas were kept in a container about 12 hours and they were coated by honeyed fluid. Finally, the bananas were dried to their final moisture content. It was found that the width, the length and the thickness of bananas decreased with decreasing moisture content.

The end color of the dried banana is not presented in this paper. The color of dried bananas at the final moisture content had the same color result as drying bananas by using LPG and solar energy cabinet dryer [4] because the hot air used was at the same temperature of 60 ^{o}C as shown in Figure 8.

Table 1 Changing banana dimensions of width, length and thickness at four time periods

Dimension	v = 0.6 ms^{-1}	v = 1.8 ms^{-1}
Width of before dry (mm)	29.0±1.0	29.5±0.8
Length of before dry (mm)	91.0±4.3	89.6±3.7
Thickness of before dry (mm)	28.9±3.7	28.8±1.1
Width of before flat banana (mm)	24.0±4	23.2±3.6
Length of before flat banana (mm)	82.9±4.9	81.8±4.0
Thickness of before flat banana (mm)	20.4±1.8	21.6±2.2
Width of flat banana (mm)	35.0±3.1	32.0±1.5
Length of flat banana (mm)	93.0±5.0	92.0±4.5
Thickness of flat banana (mm)	9.4±0.6	9.6±0.4
Width of dried banana (mm)	33.1±2.8	30.6±1.7
Length of dried banana (mm)	88.1±5.1	87.8±4.4
Thickness of dried banana (mm)	8.8±0.8	9.0±0.5

5. Drying performance

The optimal drying condition is the one where the specific energy consumption (SEC) is the lowest. The average drying rate is the second value of interest and it is desired to have the highest drying rate. Table 2 shows that the velocity of 1.8 ms^{-1} had the lowest average specific energy consumption because this velocity had a higher heating rate in the drying chamber. Therefore this velocity could remove the water more efficiently. The average drying rate of 1.8 ms^{-1} velocity was also higher than the velocity of 0.6 ms^{-1}. The results are in agreement with previous a research on eggplant [12].

Table 2 The calculation values of experimental results for dried banana

Description	Data of 0.6 ms^{-1}	Data of 1.8 ms^{-1}
Initial weight of product (kg)	30	30
Initial moisture content (% dry basis)	235.44±26.85	242.37±20.86

Table 2 The calculation values of experimental results for dried banana (Cont.)

Description	Data of 0.6 ms^{-1}	Data of 1.8 ms^{-1}
Final moisture content (% dry basis)	61.50±3.12	57.43±8.7
Drying time of drying bananas (h)	29	18.5
Drying time of stopping dried bananas (h)	12	12
Total electric power consumption of blower (kWh)	5.5	3.5
Eucalyptus amount (kg)	68±2.20	45.8±0.77
An average drying rate, DR (kg_{water} h^{-1})	0.56±0.0034	0.87±0.004
An average specific energy consumption, SEC (MJ kg_{water}^{-1})	75.46±3.41	51.12±0.70

Figure 8 The dried bananas from air velocity of 1.8 ms^{-1} with drying temperature of 60±4 ^{o}C

Conclusions

This research modified a 200 liter kiln for waste heat recovery to use for banana drying. The performance of the dryer was evaluated. The used air velocities were 0.6 and 1.8 ms^{-1} and a drying temperature was set at 60±4 ^{o}C. Eucalyptus was selected to use for the generated heat. All experiments were carried out in triplicate. It was found that the kiln surface heat exchanger had a higher heat rate than exhaust heat exchanger. The drying period from the initial moisture content to the final moisture content was 59.06±6.77 on a %dry basis, the drying rate and specific energy consumption were analyzed. It was found that the air velocities of 0.6 and 1.8 ms^{-1} had average drying rates of 0.56±0.0034 kg_{water} h^{-1} and 0.87±0.004 kg_{water} h^{-1}, respectively. The average specific energy consumptions of the air velocities of 0.6 and 1.8 ms^{-1} were 75.46±3.41 MJ kg_{water}^{-1} and 51.12±0.70 MJ kg_{water}^{-1}, respectively. The air velocity of 1.8 ms^{-1} was the best condition.

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