Characterization of thermal distribution in 50-Liter biochar kiln at different heating times

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Abstract. Biochar has been known to be an excellent soil amendment. However, the biochar yield and its quality are both affected by the process parameter, such as temperature and heating time, and the production method from kiln type used. Therefore, the objective of this work was to characterize the thermal distribution inside the 50-liter kiln at different heating times of the biochar production. The experiments on the kiln with a dimension of 500 mm × 380 mm (height × diameter) including the fuel core with diameter of 115 mm with 5 rows of 6.35 mm drill puncture diameters were conducted. The biochar was produced from 7 kg of agricultural waste corncob. The pyrolysis temperature increased with increasing heating time and it was controlled not exceeding 600 °C by adjusting the briquette fuel quantity. The results showed that the highest temperature was found at the fuel core and decreased in radial direction outwards to the kiln wall. The heating time showed effect on the thermal distribution as well as the biochar yield. The lower thermal gradient and the higher biochar yield were obtained at the higher heating time. The biochar yield would, however, decrease after optimal heating time due to the decomposition and degradation of biochar derived from corncob during the pyrolysis process. The production cost of biochar was also determined. These findings propose agriculturists the optimal heating time along with the production cost to facilitate the biochar production.

Keywords: Anila stove, Biochar, Slow pyrolysis, Thermal characteristics, Simulation analysis

1. Introduction
Biochar is produced from biomass and agricultural waste materials such as agricultural crops. The different biomass materials and the type of pyrolysis process result in different physical and chemical properties of biochar [1, 2]. The pyrolysis process for biochar production is divided into 2 types: slow pyrolysis and fast pyrolysis. For the slow pyrolysis, biomass is heated to 500 °C with a heating time varying between 5 to 30 min while the fast pyrolysis depends on the higher temperature heating for less than 1 min [3, 4]. The biochar yield obtained from the slow pyrolysis was higher than that obtained from the fast pyrolysis (i.e., 35-50 wt. % for the slow pyrolysis and 12-25 wt. % for the fast pyrolysis) [5, 6]. The physical and chemical properties of biochar are suitable for cultivation; having ability to increase agricultural productivity and affecting soil biodiversity positively. Biochar increases the soil carbon content and provides long term carbon storage in soil. The alkalinity of biochar can help improve highly acidic soils [7, 8].
There have been the research reports about the pyrolysis process of biomass, including the simulation of the heat transfer and flow in the pyrolysis furnace and investigating the process in which biomass decomposed into gas, charcoal and tar [9-14]. Previous studies have shown the influence of heating time on biochar obtained from different biomass materials [15, 16]. The heating time did not only affect the biochar yield but also the biochar physical and chemical properties. However, temperature distribution inside the biochar kiln has not been reported under the different heating time conditions. The main objective of this study was to characterize and evaluate the temperature distribution inside the biochar kiln under different heating time conditions. In this study, the experiment on 50-liter biochar kiln was conducted under different heating time conditions and the results were compared with the numerical simulation results in order to validate the model. The temperature distribution inside the kiln was consequently evaluated at the different heating times.

2. Materials and methods

The biochar kiln material was carbon steel with the height of 467 mm, outer diameter of 384 mm, and thickness of 1.5 mm. The center hole of the kiln was punched with the diameter of 110 mm. The carbon steel cylinder pipe with the height of 467 mm, outer diameter of 115 mm, and thickness of 2.5 mm, with 5 rows of 6.35 mm drill puncture diameters was located at the center hole as the core of the kiln. The biochar kiln and its components are shown in figure 1.

![Figure 1. The biochar kiln and its components.](image)

The 7 kg of agricultural waste corncob with 10-20 mm length was dried to have the least moisture content about 10% wb and was loaded in the pyrolysis chamber of the biochar kiln. The 3 kg of fuel briquette was initially put into the core. In order to control the temperature not exceeding 600 °C, the fuel briquette was divided into small portions and was slowly filled into the core for each time. The combustion of fuel briquette had been continued at different heating times, i.e., 3 h, 5 h, 7 h, and 9 h. After the process was finished, the completed biochars were sorted out and weighed using digital weighing scale.

![Figure 2. The locations of thermocouple attachment.](image)

The temperature was measured at 7 different points using the K-type thermocouple. The locations of thermocouple attachment are shown in figure 2. The temperature was continuously recorded at each heating time during the pyrolysis process. The average of quasi-steady-state temperatures of 7 locations inside the biochar kiln along with the heating times of 3 h, 5 h, 7 h, and 9 h were chosen to compare with the numerical simulated temperature.
2.1. Parameter calculation

The percentage of the biochar yield was calculated according to the following equation:

\[
\text{Biochar Yield (\%)} = \frac{W_{\text{biochar}}}{W_{\text{initial}}} \times 100
\]  

(1)

where \(W_{\text{biochar}}\) is the weight of completed biochar after the pyrolysis and \(W_{\text{initial}}\) is the weight of raw material before the pyrolysis.

In order to characterize the temperature uniformity, the temperature difference inside the biochar kiln was defined as follow:

\[
\Delta T (^\circ\text{C}) = \frac{\sum_{i=1}^{n-1} \Delta T_i}{n-1}
\]  

(2)

where \(\Delta T\) is the average temperature difference, \(n\) is the number of thermocouple locations, and subscript \(i\) is the integer of different ordered pairs of thermocouple locations.

The production cost of biochar was calculated using the following equation:

\[
\text{Production Cost (Baht/kg)} = \frac{W_{\text{fuel}}}{W_{\text{biochar}}} \times \text{fuel cost per kg}
\]  

(3)

where \(W_{\text{fuel}}\) is the weight of fuel used during the process.

2.2. Computational model

The schematic of the biochar kiln and the boundary conditions is shown in figure 3. The domains of biochar kiln consist of three parts: the wall of the biochar kiln, the wall of the core of the biochar kiln, and the fluid of pyrolysis gas in the biochar kiln. Since the core of the kiln was used for loading fuel to combustion, the heat of combustion was radially transferred outwards to the kiln wall. The assumptions incorporated in the model to simplify the problem were detailed as below.

1) The model was considered in steady-state heat transfer.
2) The heat transfer from the inner core surface to outer core surface was conduction.
3) The heat transfer from the outer core surface to pyrolysis chamber was conduction and convection.
4) The heat transfer from the outer kiln wall to surroundings was free convection.

![Figure 3. The schematic of the biochar kiln and the boundary conditions.](image-url)
2.3. Numerical scheme
The temperature obtained from the numerical simulation was used to compare with that obtained from the experiment. The experiment was divided into conditions, i.e., the different heating times of the biochar production (3 h, 5 h, 7 h, and 9 h) affecting on thermal distribution inside the 50-liter kiln. From the numerical procedure, the material properties and initial condition were input first. The temperature and heat transfer coefficient were then applied to set the boundary condition. Finally, the temperature distribution in the kiln was calculated from the heat transfer formulations of the governing equations and boundary conditions using the finite element method.

3. Results and discussion
3.1. The comparison of temperature distribution of simulation results with the experimental results
The validity of the simulation results was evaluated by comparing to the experimental results.

3.1.1. The temperature distribution at different axial locations
The comparison of the temperature distribution of simulation results with the experimental results along radial direction at different axial locations (base: \( z_1 = 5 \) cm, middle: \( z_2 = 21.8 \) cm, and top: \( z_3 = 38.6 \) cm) is shown in figure 4. The simulation results were found to be in good agreement with the experimental results. The error of temperature averagely over radial locations at base, middle, and top of the kiln was found to be equal to \( 0.3 \pm 0.2\% \), \( 12.0 \pm 9.2\% \), and \( 0.7 \pm 0.2\% \), respectively.

![Figure 4](image1)

**Figure 4.** The temperature distribution obtained from the numerical simulation compared with the experiment at different axial locations of 3 h heating time.

3.1.2. The temperature distribution at different heating times

![Figure 5](image2)

**Figure 5.** The temperature distribution obtained from the numerical simulation compared with the experiment at different heating times of middle location (\( z_2 = 21.8 \) cm).
The comparison of the temperature distribution of simulation results with the experimental results along radial direction at different heating times (3 h, 5 h, 7 h, and 9 h) is shown in figure 5. The fairly good agreement with the experiment results was noted. The difference in the results occurred due to the model assumptions. The error of temperature averagely over three radial locations at heating time of 3 h, 5 h, 7 h, and 9 h was found to be equal to 12.0 ± 9.2%, 13.0 ± 9.3%, 12.7 ± 9.0%, and 14.5 ± 10.2%, respectively.

3.2. The effect of heating times on the temperature distribution

The temperature distribution has been investigated by our group [17]. Figure 6 displays the temperature distribution inside biochar kiln at the different heating times. The temperature distributions for any heating time were numerically simulated corresponding to the variation of temperature along radial direction as exemplified in figures 4 and 5. The temperature distribution of simulation and experimental results followed the similar trend in all axial locations, i.e., the highest temperature was found at the fuel core and decreased in radial direction outwards to the kiln wall. Furthermore, the temperature along radial direction at the middle axial location was found to be higher than that at upper and lower axial locations, respectively, resulting from the combustion of fuel briquettes occurred in the middle region. Regarding the middle axial location, at the middle radial location (x2 = 12.3 cm) to outer kiln wall (x3 = 18.2 cm), the temperature along radial direction slightly increased when the heating time increased. Whereas, at the inner kiln wall (x1 = 5.4 cm), the highest temperature was observed at 3 h heating time and it decreased with time variations due to the thermal equilibrium. At the outer kiln wall, the temperature did not shift up to be the uniform temperature since heat loss occurred from the non-insulated kiln wall due to convection.

Figure 6. The characterization of temperature distribution inside biochar kiln at the different heating times: (a) 3 h, (b) 5 h, (c) 7 h, and (d) 9 h.

3.3. The effect of heating times on the temperature difference and biochar yield

Figure 7. The average temperature difference and biochar yield at different heating times.
Figure 7 shows the variations of average temperature difference inside the biochar kiln and biochar yield at different heating times. The heating time of 3 h was higher in temperature difference than that of 5 h, 7 h, and 9 h, i.e., 178.5 ± 9.7 °C, 171.2 ± 18.6 °C, 169.7 ± 24.9 °C, and 167.8 ± 29.8 °C, respectively. However, regarding the statistical analysis, the temperature difference did not significantly decrease when heating time increased (p > 0.05). Although it was not statistically significant, the decrease of temperature difference and the increase of decomposition for corncob could be contributed to the increasing completed biochar yield up to around 42% during the heating time of 3 h to 7 h, i.e., increased from 17.1 wt. % to 24.3 wt. %. Above 7 h to 9 h, the biochar yield decreased as the corncobs continued decomposition and degradation. The trend of heating time affecting on biochar yield was similar to previous studies [18]. Additionally, the weight loss of completed biochar could be caused by the converting carbon to CO₂, CO, and CH₄ [19].

3.4. The effect of heating times on the production cost
Figure 8 shows the production cost of biochar produced from agricultural waste corncob using the present 50-liter biochar kiln. The assumed price of fuel briquette used was 10 Baht/kg. The weight of fuel used during the process was 3 kg, 5 kg, 7 kg, and 9 kg for 3 h, 5 h, 7 h, and 9 h, respectively. The production cost was gradually increased during the heating time of 3 h to 7 h, i.e., 25.0 Baht/kg, 35.7 Baht/kg, and 41.2 Baht/kg, respectively. After that, at heating time of 9 h, the production cost was dramatically increased up to 90 Baht/kg due to the increasing ratio of fuel briquette to biochar yield quantities. The results can be used as a guideline to improve the heating method in order to increase the efficiency of the biochar kiln by reducing the rate of fuel consumption. In the next study, the insulated biochar kiln should be tested.

![Figure 8. The production cost at different heating times.](image)

4. Conclusions
The temperature distributions inside the 50-liter biochar kiln at the different heating times were characterized in this study. The numerical simulation to calculate the temperature distribution inside the kiln was used. The simulation results were found to be in good agreement with the experimental results. The accuracy range of the simulation results was found to be equal to ± 12.8%. The temperature difference did not significantly decrease when heating time increased. The maximum biochar yield was optimized at the heating time of 7 h. The higher heating time resulted in the increase of production cost.

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Acknowledgment
This research was supported by the Faculty of Engineering and Agro-Industry and the Graduate School, Maejo University, Chiang Mai, Thailand.