Using the Circulating Principle of Hot Air Flow for Accumulating the Energy of a Vertical Charcoal Kiln to Increase the Efficiency of the Charcoal Production Process in Thailand

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Abstract- This research aims to increase charcoal production efficiency by using the circulating principle of hot air flow to accumulate the energy of a vertical charcoal kiln by covering the kiln with double layers. The researchers developed a charcoal kiln from a traditional single-layer charcoal kiln to a double-layers charcoal kiln. It retains lost heat and heats the charcoal kiln. A 200 Litres charcoal kiln, a traditional one, and a 200 Litres with a cover are used as double-layer vertical kiln. The computational fluid dynamics (CFD) model was used for the analysis. Field tests were conducted with three types of firewood: Acacia siamensis, Eucalyptus, and Burma padauk. The diameters were divided into three sizes such as 1, 1.5 and 2 inches, respectively, to compare the charcoal burning time and to determine the burning capacity of the developed charcoal kiln and a traditional charcoal kiln. According to the test result, it was found that Acacia's highest burning temperature is 850 degrees Celsius, and the percentage of charcoal obtained from a traditional kiln is 23.75, while the developed kiln is 25.5. Eucalyptus' highest burning temperature is 890 degrees Celsius, and the percentage of charcoal obtained from a traditional kiln is 20, while the vertical kiln with a double layer to prevent heat loss is 22. Lastly, in Burma padauk, the highest burning temperature is 650 degrees Celsius, and the percentage of charcoal production from a traditional kiln is 25, while the vertical kiln with a double-layer kiln preventing heat loo is 26.25. The test results of the charcoal calorific value of the charcoal obtained from the developed kiln showed that the average value is similar to others biomass, 6,700 cal/g. According to the experiment of charcoal burning using a traditional kiln, the efficiency is 18.68 percent, the average charcoal production rate is 1.36 kg/hr per time, and the average ash rate is 1.83 kg per time. While the double-layer vertical kiln's efficiency is 21.94 percent, the average charcoal production rate is 3.84 kg/hr per time, and the average ash production is 1.1kg per time. Using a vertical kiln with a double layer to prevent heat loss can reduce the burning time by 50 percent. Therefore, as the experiment result of charcoal burning, using a vertical kiln with a double layer to prevent heat loss has a better charcoal burning efficiency than the traditional kiln.

Keywords Biomass, charcoal, vertical charcoal metal kiln, hot air flow.

1. Introduction

Global demand for energy and fossil resources is increasing [1]. Form the energy crisis, global warming and environmental pollution cause interest in renewable energy as a replacement for fossil fuels [2-5]. The invention of biomass energy as alternative energy from rice husks, straw, bagasse, sugarcane, palm shells, palm bunches, coconut shells, wood waste, grass waste, and so on has received much attention [6-7]. Currently, there are studies on biomass energy that can be used as fuel, especially the production of charcoal with different kiln types [8]. In many countries, the study on charcoal burning for energy utilization has been studied for a long time [9-17]. Thailand is a tropical country with diverse forests resulting in hardwood and softwood waste materials such as Burma padauk, Eucalyptus, and Acacia. These wastes can be processed into fuel [18-19]. Traditional charcoal burning cannot meet the market demand for quality and long burning time [20-22]. There are studies on improving a traditional charcoal kiln to increase efficiency by increasing the cooling zone [23] and developing a charcoal kiln that can be used along with electric power, resulting in a better burning result [24]. There are studies about log placement and log pile placement in charcoal kilns to increase the efficiency of charcoal burning and the concentration of charcoal obtained [25-27]. In addition, finding ways to strengthen the structure of the kiln will reduce the effect of damage to the kiln wall, resulting in a longer service life [28]. To increase the burning efficiency of a traditional kiln, thermal efficiency was studied using comparative mathematical models to analyse the optimum design of various kilns [29-31]. In many countries where charcoal is used as a fuel, many researchers are trying to develop high-efficiency charcoal burning kilns for the most efficient and effective charcoal burning.

For charcoal kilns in Portugal, there are studies about the main physical characteristics and operating conditions of a fireplace and a stove commonly used for domestic heating based on biomass combustion [32-33]. Moreover, there are studies about the technical feasibility of cotton stalk carbonization and torrefaction. The experiment used a metallic homemade cylindrical furnace 60 cm in diameter and 90 cm in height. A partial combustion process was used both for carbonization and torrefaction. From the experiment was found that the mass and energy yield, proximate analysis and the unburnt cotton stalks proportion (ratio of non-carbonized cotton stalks over carbonized cotton stalks) for each process were determined [34]. There are studies about charcoal burning using three kiln models for producing biochar slightly for the larger kilns. Biochar quality was mainly related to pyrolysis time [35]. The pyrolysis product is charcoal, wood or pyroligneous acid, vinegar, wood tar and wood [36 -38]. Currently, there are studies on biomass and charcoal analysis from various plants, for example, Acacia, eucalyptus, and other plants [39]. Biomass charcoal burning is the process of burning wood waste and waste from agricultural activities such as eucalyptus wood. Eucalyptus branches are commonly used for firewood and are very combustible firewood with low ash content [40]. The study of carbonization kiln with temperature control and outside air ventilation is another technology that can increase the efficiency of charcoal burning and reduce losses in the charcoal burning process. The development of various charcoal kilns and the thermal mathematical model of charcoal burning has also been studied [41] and has been used in the thermal analysis of various kilns [42-48]. A comparative study of single-layer and double-layer kilns using a mathematical model showed that the double-layer kiln is better at heat retention [49], including the loss at the kiln wall [50]. Moreover, there are studies on the environmental effects of charcoal burning [51-52]. Suppose the wood-burning system is effectively controlled using well-developed charcoal-burning technology. In that case, problems such as dust and smoke in the air, and also the problem in winter, the residual amount of wood-charcoal from burning will decrease or disappear [53]. Researchers in many countries are currently trying to develop efficient use of kilns to produce charcoal for cooking and selling for public income. According to the studies, it was found that there was no study on the prevention of heat loss and waste heat recovery of charcoal kilns in Thailand. As a result, carbonization efficiency is low due to heat loss on the surface of the chamber. Using the waste heat from burning charcoal at the chimney by recycling will cause heat to accumulate at a kiln. This can increase the efficiency of charcoal burning, shorten the burning time, and increase the burning temperature of charcoal.

Therefore, this research is to develop a vertical charcoal kiln with a double layer to prevent heat loss. The waste heat from charcoal production at the chimney will be utilized by creating heat accumulation at the kiln causing higher heat between the outer and inner kiln walls. This will shorten the time of burning firewood to charcoal more quickly. The test of charcoal production between traditional and developed kilns (a vertical charcoal kiln with a double layer to prevent heat loss) aimed to increase the efficiency of charcoal burning, reduce the burning time, and can be used to develop a charcoal kiln that can be practically used in the community level in the future.

(a) A traditional kiln (b) A kiln showed hot air flow (c) CFD analysis showed air flow

Fig. 1. A traditional vertical charcoal kiln in Thailand

2. Methods and Methodology

2.1. Carbonization

Carbonization is a process of converting an organic substance into a carbon-containing residue. For wood, it means heating the wood with restricted airflow, resulting in the production of charcoal that has four main stages [54];

1. Initial dehydration was endothermic of the wood (200˚C).

2. Pre-carbonization that pyroligneous liquids can be condensed (170-250˚C)

3. Exothermic reaction, light tars and pyroligneous liquid come out steadily (250- 300˚C).

4. Drive off volatile components, increasing the carbon content of charcoal (>300˚C).

2.2. The traditional vertical charcoal kiln

A traditional vertical charcoal kiln in Thailand is made of a cylindrical metal tank with a capacity of 200 litres (0.2 m^3), a height of 89 centimetres, and a diameter of 56 cm. The bottom is drilled holes to transfer the heat. The top has a cover and a chimney with a diameter of 4 inches and 15 cm. long attached to the cover. When the firewood used to produce charcoal is placed, the cover and the kiln are covered with clay to prevent heat loss. The kiln base is about 60 cm. in diameter and is dug about 15 cm. into the ground. It will be surrounded by bricks to place the kiln at a distance of about 30 cm. from a firing mouth to feed firewood. Clay is then placed around 12 cm. in height to prevent heat loss. A traditional kiln, as shown in Figure 1(a), CFD model analysis showed hot air flow [49], as shown in Figure 1(b). When thermal imaging is performed, there is a hot air flow according to the CFD model, as shown in Fig. 1(c) a traditional kiln. It was found that the hot air flow accumulates heat at the bottom of the kiln and flows upward to the upper chimney.

2.3. The vertical charcoal kiln energy accumulation

The heat transfer among the gas, solid and kiln wall is considered with the energy balances for gas, solid and kiln walls [55-56]. The energy balances can be formulated following Equation 1-5;

$$\frac{1}{v_g}\frac{\partial(Q_g C_g T_g)}{\partial T} = \frac{\partial(Q_g C_g T_g)}{\partial Z} - C_1(T_g - T_s) - C_2(e_g T_g^4 - A_v T_s^4) - C_3(T_g - T_w) - C_4(e_g T_g^4 - A_v T_w^4) \quad (1)$$

The energy balance for the solid material following;

$$\frac{1}{v_s}\frac{\partial(Q_s C_s T_s)}{\partial T} = \frac{\partial(Q_s C_s T_s)}{\partial Z} - C_1(T_g - T_s) - C_2(e_g T_g^4 - A_v T_s^4) - C_5(T_w - T_s) - C_6(e_w T_w^4 - A_v T_s^4) - \frac{\partial Q_s}{\partial Z} H_v \quad (2)$$

The energy balance for the kiln wall following;

$$\frac{\partial(M_w C_w T_w)}{\partial T} = \frac{\partial(M_w C_w T_w)}{\partial Z} + C_3(T_g - T_w) + C_4(e_g T_g^4 - A_v T_s^4) - C_5(T_w - T_s) - C_6(e_w T_w^4 - A_v T_s^4) \quad (3)$$

The material balance for the solid is also given as;

$$\frac{1}{v_s}\frac{\partial Q_s}{\partial T} = -\frac{\partial Q_s}{\partial Z} - \frac{h_t A(T_g - T_s)}{H_v} \quad (4)$$

The balance for the gas is given as;

$$\frac{1}{v_g}\frac{\partial Q_g}{\partial T} = -\frac{\partial Q_g}{\partial Z} - \frac{h_t A(T_g - T_s)}{H_v} \quad (5)$$

When, A : Gas-solid surface (m^2/m)

A_v : Absorptivity

C : Model parameters

C_g : Specific heat of gas (kJ/(kg ºK))

C_s : Specific heat of solid (kJ/(kg ºK))

C_w : Specific heat of kiln wall (kJ/(kg ºK))

e_g : Gas emissivity constant

e_s : Solid emissivity constant

e_w : Emissivity of internal surface of wall constant

h_{sg} : Heat transfer coefficient between the solid and gas (W/m$^{2\circ}$K)

h_{wg} : Heat transfer coefficient between the wall and gas (W/m$^{2\circ}$K)

h_t : Convection coefficient between the gas and solid (W/m$^{2\circ}$K)

h_w : Heat transfer coefficient between the wall and solid (W/m$^{2\circ}$K)

H_v : Latent heat of vaporization of VOC (kJ/kg)

M_w : Wall mass per unit kiln length (kg/m)

Q_g : Gas flow rate (kg/s)

Q_s : Solid flow rate (kg/s)

T_g : Gas temperature (ºK)

T_s : Solid temperature º(K)

T_w : Temperature of internal surface of the wall (ºK)

t : Time (s)

V_g : Gas velocity (m/s)

V_s : Solid velocity (m/s)

z : Kiln tall (m)

2.4. The vertical charcoal kiln with double-layer to prevent heat loss

The principle of energy accumulation in a vertical kiln by circulating hot air flow inside the kiln is used to design a vertical charcoal kiln with a double layer to prevent heat loss, as shown in Figure 2(a). An analysis based on the CFD model found that when the charcoal kiln cover is installed, there is a gap between the kiln wall and the cover that blocks the hot air from burning charcoal, thus causing a hot air flow around the gap until the heat accumulation occurred. CFD model analysis found a hot air circulation, as shown in Fig. 2(b). The average temperature of the double-layer vertical charcoal kiln is higher than that of a traditional charcoal kiln by 51.47% [49]. Installing a double layer charcoal kiln cover causes the temperature to spread throughout the kiln, which also increases the temperature inside the kiln.

The main components of the vertical charcoal kiln with a double layer to prevent heat loss are 1) the chamber made of a cylindrical metal tank, height of 89 cm., a diameter of 56 cm., and a capacity of 200 litres. (0.2 m^3); 2) a cover insulator made of fiberglass insulation, a diameter of 65 cm., a height of 100 cm., thickness of 10 cm., and covered with steel sheet thickness of 2 mm.; 3) a grate set made of ¼ inch steel bars with spaced 2 cm apart forming a circle shape and steel bars of ½ inch diameter and 60 cm long, with a lock to secure the steel grate with a chamber; 4) a kiln stand made of steel with a diameter of 110 cm. It is made to fill fuel and can be opened and closed. On the top is a groove for placing a chamber and a cover. The groove is about 5 cm deep, so sand can be fed while burning charcoal to prevent heat loss. Inside a kiln, there is a channel for hot air to flow through the chimney; and 5) a chimney made of steel, a diameter of 4 inches, a thickness of 2 mm., and 2 meters high, connected to the base of a kiln. Once completed, it will look as shown in Figure 2(C). According to the image of a thermal imaging camera, the vertical charcoal kiln with a double layer to prevent heat loss has hot air flowing from the bottom to the top and accumulates at the top of the cover and spreads down to the bottom of the kiln resulting in maximum heat at the top of the kiln and is transferred throughout the kiln as shown in Figure 2(d). The carbonization process of the developed kiln is faster than a traditional kiln. As a result, it has a higher temperature and shorter burning time.

(a) charcoal kiln design (b) CFD analysis showed air flow (c) A kiln showed hot air flow (d) vertical charcoal kiln

Fig. 2. The vertical charcoal kiln with double-layer to prevent heat loss

2.5. Methodology

In the field test, two types of charcoal kiln, a traditional kiln and the vertical charcoal kiln with a double layer to prevent heat loss, were tested for charcoal production capacity and efficiency. There are three different types of firewood which are Acacia siamensis, Eucalyptus, and Burma padauk and three different dimensions of about 1 inch (2.54 cm.), 1.5 inches (3.81 cm.), and 2 inches (5.08 cm.), respectively, were used in the test. The number of charcoal burning was set at 27 times. In the preparation phase of the test, the firewood used in the charcoal burning test was wood obtained from various community sources that were dried in the sun to reduce the moisture content to below 15%. The wood used in the test was Acacia siamensis , Eucalyptus, and Burma padauk. When the wood is dry, cut the wood to the size of the kiln, length 30-35 cm., as shown in Figure 3.

(a) Acacia siamensis (b) Eucalyptus (c) Burma padauk

Fig. 3. Three types of firewood.

Logs should be arranged vertically to allow smoke to pass through easily. Temperature and gas were measured by thermocouple TYPE R and gas analyzer, respectively. Data Logger was used for data collection. As a test, once the wood has been stacked into a kiln, the cover must be completely closed. Then, fire a kiln at the fuel inlet. Place the kiln on the stand. A double-layer cover insulator maintains the heat between the first and second kiln walls. After firing, keep adding firewood, which will take about 2-4 hours, depending on the wood's moisture content. The smoke in the chimney during dehumidification should be observed. The smoke from the chimney is white and has a foul odour because of a substance in the wood. The temperature at the mouth of the chimney is about 55-60 degrees Celsius, while the temperature inside the kiln is about 150 degrees Celsius. When the moisture has been expelled and the wood starts firing (about 2-4 hours after the furnace is fired), a large amount of grey-white smoke will be seen from the chimney.

When the smoke starts to clear, only hot steam coming out of the chimney opens the kiln about 50% to allow the air to interact with the charcoal, purifying the charcoal and reducing carcinogens. This process takes about 30 minutes. At the end of 30 minutes, cover all chimneys with the cover insulator or clay. Cover the front of the kiln with clay to prevent air from entering. (If there are leaks at other places, all leaks must be sealed) as shown in Figure 2. After the wood in the kiln has turned into charcoal, leave the kiln to cool down for about 3-4 hours. The charcoal can be obtained, and the kiln can be prepared for the next charcoal-burning round.

2.6. Indicator

2.6.1 Charcoal production capacity

The kiln's capacity is tested by weighing the firewood used for charcoal burning before burning. The moisture content of the firewood must not exceed 15%, and the weight value must be recorded. Once the kiln is fired, set a timer until the kiln is closed. The capacity of the kiln can be calculated using Equation 6;

$$C = \frac{W_c}{t} \tag{6}$$

When, C = Capacity of charcoal production (kg/hr)

Wc = Total weight of charcoal (kg)

t = Carbonization time (hr)

2.6.2 Charcoal Production Efficiency

The efficiency of charcoal burning by considering firewood, charcoal, ash, and charcoal residue from carbonization can be calculated from Equation 7;

$$e = \left(\frac{W_c}{W_f}\right) \times 100 \tag{7}$$

When, W_c = Total weight of charcoal (kg)

W_f = Total weight of firewood (kg)

e = Charcoal Production Efficiency (%)

2.7. Charcoal Heating value

Three different types of firewood, Acacia, Eucalyptus, and padauk, were tested for the calorific value of biomass according to ASTM standards. The diameter is divided into three sizes, about 1, 1.5, and 2 inches. The test was performed ten times to obtain the average calorific value of the fuel. The amount of heat must be transferred from the fuel in a complete carbonization system by burning hydrocarbon fuels with oxygen. The products obtained in the complete carbonization process are carbon dioxide and water. Bomb Calorimeter is used to test the calorific value of fuel according to ASTM standards [57-58].

3. Results

3.1. Charcoal Production Performance s

To compare the charcoal production performance between a vertical traditional charcoal kiln and the vertical charcoal kiln with a double layer to prevent heat loss, three types of wood, including Acacia siamensis, Eucalyptus, and Burma padauk, were used in the experiment. The diameter of each wood was 1, 1.5, and 2 inches. The average initial weight of each wood was 40 kilograms. The test result is shown in Table 1.

3.2. The results of the comparative test of the charcoal production rate and efficiency of a vertical traditional charcoal kiln and the vertical charcoal kiln with a double layer to prevent heat loss

The test used three different types of firewood, namely Acacia siamensis wood, Eucalyptus wood, and Burma padauk wood, with a diameter of 3 sizes: 1, 1.5, and 2 inches to determine the capacity of charcoal production and the efficiency of charcoal production of each kiln type. The test of burning charcoal with developed and traditional kilns was set at 27 times (3 types of firewood x 3 diameter of firewood x 3 repeat) to find the mean value. The test results obtained from calculating the ratio of charcoal weight to carbonization time showed that the vertical charcoal kiln with a double layer to prevent heat loss has a greater burning capacity than a traditional kiln in all test trials.

3.2.1 Acacia siamensis

In the case of charcoal burning with three different sizes of Acacia siamensis by the vertical charcoal kiln with a double layer to prevent heat loss and a traditional kiln, it was found that the average kiln burning capacity of developed charcoal kilns of the three sizes of wood is higher than the average charcoal burning capacity of traditional charcoal kilns by 55.53, 51.83 and 52.27 percent, respectively, as shown in Figure 4. According to the experiment, charcoal burning by the traditional method (vertical shaft kiln) took about one time longer to become charcoal than the developed charcoal kiln. Therefore, if charcoal is burned in the vertical charcoal kiln with a double layer to prevent heat loss, it can reduce the time of burning charcoal by 50%.

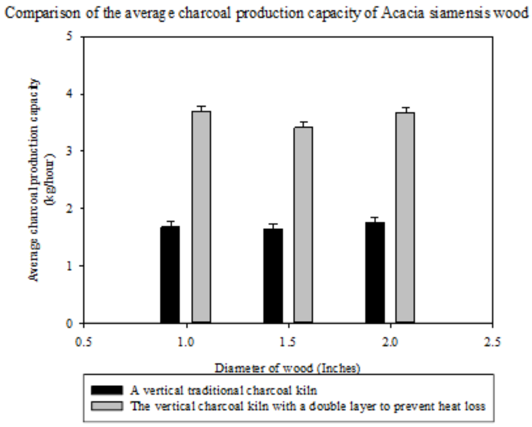


Fig 4. The results of the comparative test of the charcoal production rate and efficiency of a vertical traditional charcoal kiln and the vertical charcoal kiln with a double layer to prevent heat loss of Acacia siamensis

3.2.2 Eucalyptus

The charcoal burning with three sizes of Eucalyptus by the developed charcoal kiln and a traditional kiln found that the average charcoal burning capacity was consistent with that of acacia wood. The charcoal burning capacity of the developed charcoal kiln is higher than that of a traditional charcoal kiln by 57.81, 61.36 and 51.58 percent, respectively, as shown in Figure 5. According to the experiment, charcoal burning by the traditional method (vertical shaft kiln) took about one time longer to become charcoal than the developed charcoal kiln. Therefore, if charcoal is burned in the vertical charcoal kiln with a double layer to prevent heat loss, it can reduce the time of burning charcoal by 50%.

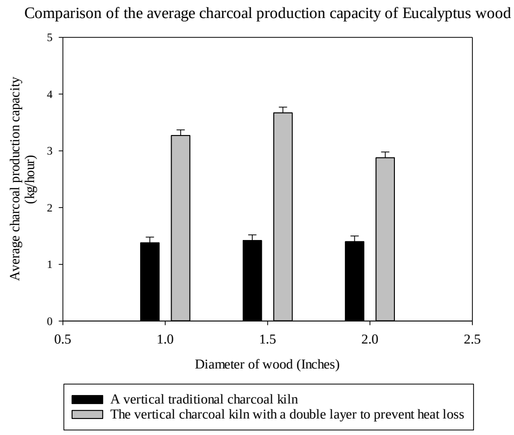


Fig 5. The results of the comparative test of the charcoal production rate and efficiency of a vertical traditional charcoal kiln and the vertical charcoal kiln with a double layer to prevent heat loss of Eucalyptus

3.2.3 Burma padauk

The charcoal burning with three sizes of Burma padauk by the developed charcoal kiln and a traditional kiln found that the average charcoal burning capacity was consistent with that of acacia wood. The charcoal burning capacity of the developed charcoal kiln is higher than that of a traditional charcoal kiln by 61.77, 58.83 and 53.11 percent, respectively, as shown in Figure 6. According to the experiment, charcoal burning by the traditional method (vertical shaft kiln) took about one time longer to become charcoal than the developed charcoal kiln. Therefore, if charcoal is burned in the vertical charcoal kiln with a double layer to prevent heat loss, it also can reduce the time of burning charcoal by 50%.

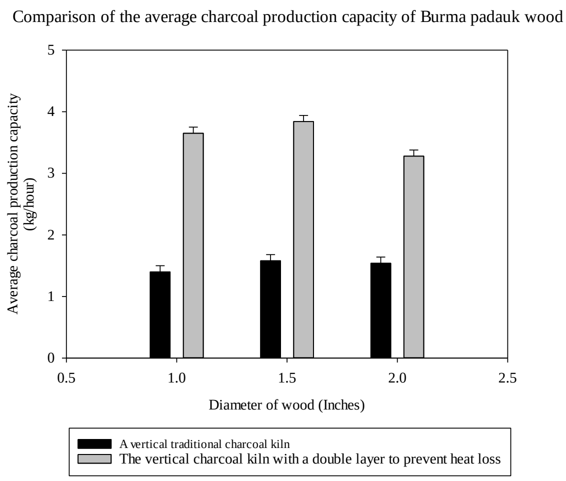


Fig 6. The results of the comparative test of the charcoal production rate and efficiency of a vertical traditional charcoal kiln and the vertical charcoal kiln with a double layer to prevent heat loss of Burma padauk

3.2.4 Comparison of the charcoal production capacity of each type of firewood between the two kilns

The experimental data from Figure 7 shows the result of the experiment of charcoal burning to determine the efficiency of the vertical charcoal kiln with a double layer to prevent heat loss and a traditional kiln using three different types of firewood such as Acacia siamensis, Eucalyptus, and Burma padauk, with different three diameter sizes: 1, 1.5, and 2 inches, respectively. The experiment with acacia wood found that the vertical charcoal kiln with a double layer to prevent heat loss had an average charcoal production rate of 3.68 kg/hr, and a traditional charcoal kiln's average charcoal production rate is 1.75 kg/hr. For Eucalyptus, it showed that the vertical charcoal kiln with a double layer to prevent heat loss had an average charcoal production rate of 3.67 kg/hr, and a traditional charcoal kiln's average charcoal production rate is 1.42 kg/hr. For Burma padauk, the vertical charcoal kiln with a double layer to prevent heat loss had an average charcoal production rate of 3.84 kg/hr, and a traditional charcoal kiln's average charcoal production rate is 1.58 kg/hr. The kiln's capacity depends on the wood type and size, as shown in Figure 8. The reason for the capacity to produce more charcoal is that the production time per round decreased so that it could produce more rounds.

Table 1. Comparative experiment of burning charcoal

Kiln type	Wood	The average diameter of firewood (inch)	Maximum average carbonization temperature (degree Celsius)	Average carbonization time (hours)	The average weight of firewood before burning (kg)	Average charcoal weight after burning (kg)	Charcoal Production Efficiency (%)	Charcoal production capacity (kg/hour)
A vertical traditional charcoal kiln	Acacia siamensis	1.0 ±0.25	740 ±25	5.5 ±0.2	40 ±0.1	9.0 ±0.1	22.50	1.67
		1.5 ±0.25	670 ±25	5.8 ±0.2	40 ±0.1	9.5 ±0.1	23.75	1.64
		2.0 ±0.25	605 ±25	6.0 ±0.2	40 ±0.1	10.5 ±0.1	26.25	1.75
	Eucalyptus	1.0 ±0.25	835 ±25	5.8 ±0.2	40 ±0.1	8.0 ±0.1	20.00	1.38
		1.5 ±0.25	850 ±25	6.0 ±0.2	40 ±0.1	8.5 ±0.1	21.25	1.42
		2.0 ±0.25	800 ±25	6.6 ±0.2	40 ±0.1	9.2 ±0.1	23.00	1.40
	Burma padauk	1.0 ±0.25	525 ±25	6.3 ±0.2	40 ±0.1	8.8 ±0.1	22.00	1.40
		1.5 ±0.25	515 ±25	6.0 ±0.2	40 ±0.1	9.5 ±0.1	23.75	1.58
		2.0 ±0.25	520 ±25	6.5 ±0.2	40 ±0.1	10.0 ±0.1	25.00	1.54
The vertical charcoal kiln with a double layer to prevent heat loss	Acacia siamensis	1.0 ±0.25	855 ±25	2.5 ±0.2	40 ±0.1	9.2 ±0.1	23.00	3.68
		1.5 ±0.25	730 ±25	3.0 ±0.2	40 ±0.1	10.2 ±0.1	25.50	3.40
		2.0 ±0.25	750 ±25	3.0 ±0.2	40 ±0.1	11.0 ±0.1	27.50	3.67
	Eucalyptus	1.0 ±0.25	890 ±25	2.6 ±0.2	40 ±0.1	8.5 ±0.1	21.25	3.27
		1.5 ±0.25	850 ±25	2.4 ±0.2	40 ±0.1	8.8 ±0.1	22.00	3.67
		2.0 ±0.25	855 ±25	3.3 ±0.2	40 ±0.1	9.5 ±0.1	23.75	2.88
	Burma padauk	1.0 ±0.25	650 ±25	2.6 ±0.2	40 ±0.1	9.5 ±0.1	23.75	3.65
		1.5 ±0.25	650 ±25	2.6 ±0.2	40 ±0.1	10.0 ±0.1	25.00	3.84
		2.0 ±0.25	640 ±25	3.2 ±0.2	40 ±0.1	10.5 ±0.1	26.25	3.28

3.3. Comparison test of the inner kiln temperature between a vertical charcoal kiln (traditional) and the vertical charcoal kiln with a double layer to prevent heat loss

3.3.1 Acacia siamensis

In the case of charcoal burning with three different sizes of acacia wood by the vertical charcoal kiln with a double layer to prevent heat loss and a traditional kiln, the results of the study showed that the average temperature of the inner kiln of the developed kiln is higher than a traditional charcoal kiln in all three sizes of woods. The maximum temperature of the vertical charcoal kiln with a double layer to prevent heat loss and a traditional kiln is 850 and 780 degrees Celsius, respectively, as shown in Figure 9. The experiments also found that charcoal burning with the traditional method (vertical shaft kiln stove) takes longer to become charcoal than the developed charcoal kiln. From firing the kilns to obtaining charcoal, the vertical charcoal kiln with a double layer to prevent heat loss and a traditional charcoal kiln take 5 and 7 hours, respectively. Therefore, if charcoal is burned in the vertical charcoal kiln with a double layer to prevent heat loss, it can reduce the time of burning charcoal by 50%.

3.3.2 Eucalyptus

In the case of charcoal burning with three different sizes of eucalyptus wood by the vertical charcoal kiln with a double layer to prevent heat loss and a traditional kiln, the results of the study showed that the average temperature of the inner kiln of the developed kiln is higher than a traditional charcoal kiln in all three sizes of woods. The maximum temperature of the vertical charcoal kiln with a double layer to prevent heat loss and a traditional kiln is 850 and 800 degrees Celsius, respectively, as shown in Figure 10. The experiments also found that charcoal burning with the traditional method (vertical shaft kiln stove) takes longer to become charcoal than the developed charcoal kiln. From firing the kilns to obtaining charcoal, the developed kiln and a traditional charcoal kiln take 4.5 and 7 hours, respectively. Therefore, if charcoal is burned in the vertical charcoal kiln with a double layer to prevent heat loss, it can reduce the time of burning charcoal by 50%. The trend is similar to acacia wood.

3.3.3 Burma padauk

In the case of charcoal burning with three different sizes of eucalyptus wood by the vertical charcoal kiln with a double layer to prevent heat loss and a traditional kiln, the results of the study showed that the average temperature of the inner kiln of the developed kiln is higher than a traditional charcoal kiln in all three sizes of woods. The maximum temperature of the vertical charcoal kiln with a double layer to prevent heat loss and a traditional kiln is 650 and 590 degrees Celsius, respectively, as shown in Figure 11. The experiments also found that charcoal burning with the traditional method (vertical shaft kiln stove) takes longer to become charcoal than the vertical charcoal kiln with a double layer to prevent heat loss. From firing the kilns to obtaining charcoal, the developed kiln and a traditional charcoal kiln take 4.5 and 7 hours, respectively. Therefore, if charcoal is burned in the vertical charcoal kiln with a double layer to prevent heat loss, it can reduce the time of burning charcoal by 50%. The trend is similar to Acacia siamensis and eucalyptus wood.

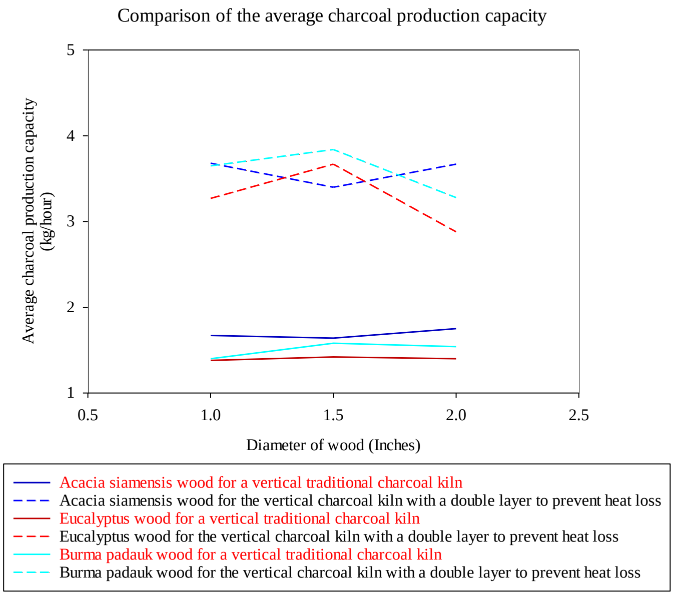


Fig 7. Comparison of the average charcoal production capacity between the developed kiln and a traditional kiln.

Fig 8. Charcoal obtained from the vertical charcoal kiln with a double layer to prevent heat loss

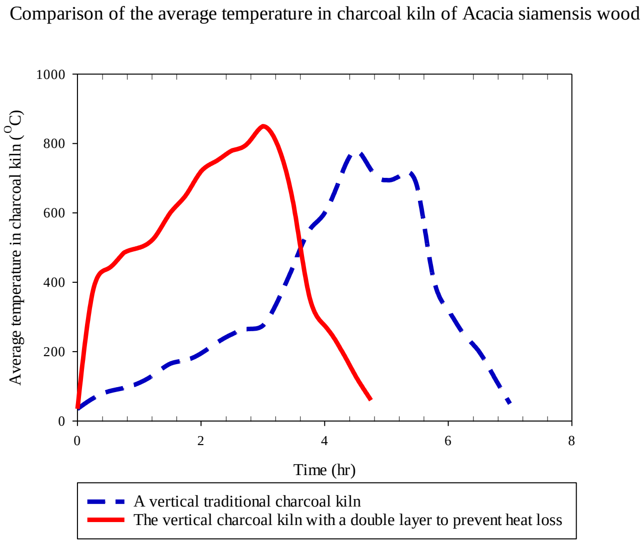


Fig 9. Comparison of the inner kiln temperature between a vertical traditional charcoal kiln and the vertical charcoal kiln with a double layer to prevent heat loss of Acacia siamensis.

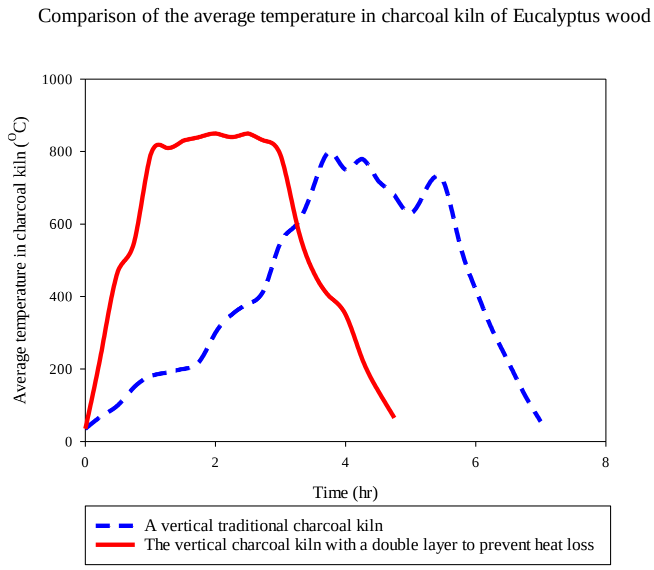


Fig 10. Comparison of the inner kiln temperature between a vertical traditional charcoal kiln and the vertical charcoal kiln with a double layer to prevent heat loss of Eucalyptus.

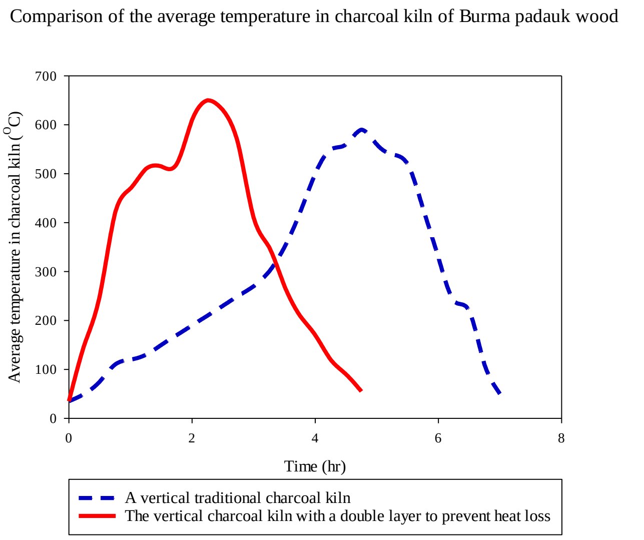
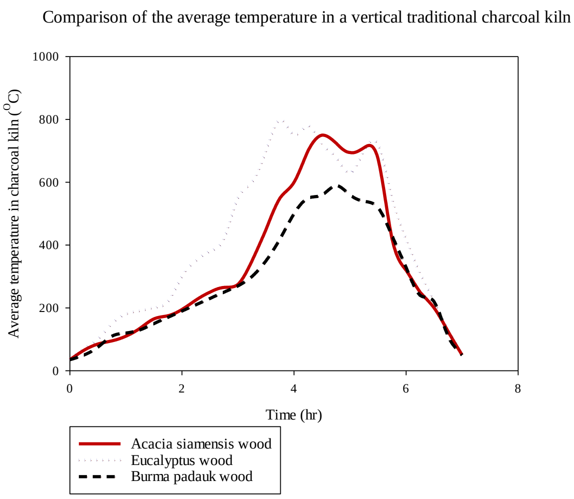
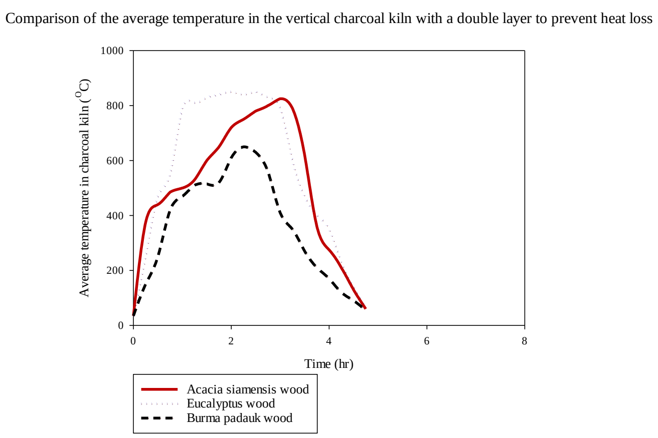


Fig 11. Comparison of the inner kiln temperature between a vertical traditional charcoal kiln and the vertical charcoal kiln with a double layer to prevent heat loss of Burma padauk.



(a)



(b)

Fig 12. Comparison of the inner kiln temperature of (a) the vertical traditional charcoal kiln and (b) the vertical charcoal kiln with a double layer to prevent heat loss

According to the charcoal burning experiments using a traditional charcoal kiln found that the average initial burning temperature is 120 °C at 20 min, the maximum temperature is 850 °C at 5 hr, as shown in Fig. 12(a), percent of efficiency is 18.68, the average charcoal production rate is 1.36 kg/hr per time, and the average ash rate is 1.83 kg per time. For the vertical charcoal kiln with a double layer to prevent heat loss, it found that the average initial burning temperature is 300 °C at 20 min, the maximum temperature is 890 °C at 2 hr, as shown in Fig. 12(b), percent of efficiency is 21.94, the average charcoal production rate is 3.84 kg/hr per time, and the average ash rate is 1.1 kg per time. In addition, when measuring the wind speed and exhaust gas emitted from the end of the chimney, it was found that a traditional charcoal kiln has an average combusted air speed of 3.32 m/s, the exhaust gas consists of CO_2 of 16.4% and O_2 of 2.86%. While the vertical charcoal kiln with a double layer to prevent heat loss has an average combusted air speed of 4.86 m/s, the exhaust gas consists of CO_2 of 18.5% and O_2 of 0%. It showed that the vertical charcoal kiln with a double layer to prevent heat loss burns faster due to its more complete carbonization, without oxygen (pyrolysis), than a traditional kiln. Therefore, based on the experiment of charcoal burning, using the vertical charcoal kiln with a double layer to prevent heat loss has a better temperature efficiency than a traditional charcoal kiln because it can retain heat, so the average inner temperature of the developed kiln is higher than a traditional charcoal kiln.

3.4. Heating value of charcoal

Table 2. The heating value of the charcoal

Biomass	Size of charcoal (inch)	Heating Value (cal/g)
Acacia siamensis	1.0	6,780±50
	1.5	6,762±50
	2.0	7,030±50
Eucalyptus	1.0	6,725±50
	1.5	7,075±50
	2.0	6,764±50
Burma Padauk	1.0	6,784±50
	1.5	6,315±50
	2.0	6,711±50

The test to determine the calorific value of charcoal obtained by burning charcoal with the vertical charcoal kiln with a double layer to prevent heat loss of all three wood types found that the average calorific values of charcoal, as shown in Table 2, are similar to the previous study [18,58].

4. Conclusion

This research is the vertical charcoal kiln with a double layer to prevent heat loss for charcoal burning. It is a development from the traditional single-layer charcoal kiln to the vertical kiln with a cover resulting in a double layer kiln.

The outer kiln wall can retain the loss of heat at the inner wall, thus increasing the heat of the chamber. To compare the carbonization time between a traditional charcoal kiln and the vertical charcoal kiln with a double layer, a traditional kiln used a 200-litre tank, and the developed kiln used a 200-litre tank with a cover insulator. Three kinds of firewood, such as Acacia siamensis, Eucalyptus, and Burma padauk, with three diameters of 1, 1.5, and 2 inches, respectively, were used in the test of this study. Charcoal burning experiments were performed to determine the charcoal burning capacity of both kilns. The results of the Acacia siamensis wood test showed that the developed kiln took an average of 5 hours for the carbonization process while the traditional kiln took 7 hours. The maximum burning temperature is 850 degrees Celsius, and the charcoal obtained from a traditional kiln is 23.75%. Because the vertical charcoal kiln has a double layer to prevent heat loss, resulting in 25.5 percent of the charcoal obtained, which is 1.75 percent better than the traditional one. The results of the Eucalyptus wood test showed that the developed kiln took an average of 4.5 hours for the carbonization process while the traditional kiln took 6 hours. The maximum burning temperature is 890 degrees Celsius, and the charcoal obtained from a traditional kiln is 20.00%. Because the vertical charcoal kiln has a double layer to prevent heat loss, resulting in 22 percent of the charcoal obtained, which is 2 percent better than the traditional one. The Burma padauk wood test results showed that the developed kiln took an average of 4.5 hours for the carbonization process, while the traditional kiln took 6 hours. The maximum burning temperature is 650 degrees Celsius, and the charcoal obtained from a traditional kiln is 25.00%. Because the vertical charcoal kiln has a double layer to prevent heat loss, resulting in 26.25 percent of the charcoal obtained, which is 1.25 percent better than the traditional one. According to the calorific value test of the charcoal obtained from the developed kiln found that the average calorific value of charcoal is similar to other types of biomass. From the experiment of charcoal burning by a traditional charcoal kiln, the efficiency is 18.68%, the average charcoal production rate is 1.36 kg/hr per time, and the average ash rate is 1.83 kg per time. While the experiment of charcoal burning by the vertical charcoal kiln with a double layer to prevent heat loss, the efficiency is 21.94%, the average charcoal production rate is 3.84 kg/hr per time, and the average ash rate is 1.1 kg per time. Therefore, if charcoal is burned in the vertical charcoal kiln with a double layer to prevent heat loss, it has a better charcoal burning efficiency than a traditional kiln and can reduce the time of carbonization time by 50%. From the information mentioned above, the knowledge of this vertical charcoal kiln with a double layer to prevent heat loss can be transferred to local people in Thailand for further use.

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