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EFFECT OF THE HEAT TRANSFER SURFACE ON PREVENTION OF SPONTANEOUS COMBUSTION OF COAL

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ABSTRACT

The increased use of coal for power generation has increased the demand for low-rank coal, such as lignite and sub-bituminous coal, and during its supply, it may need to be stored for long periods. Because low-quality coal is more susceptible to spontaneous combustion than high-quality coal, its storage could potentially cause work-related accidents. One method being developed to control the temperature of stored coal to prevent spontaneous combustion is the immersion of heat exchangers in coal piles. This method can be used to control the temperature during both the storage and transportation processes. The purpose of this study was to test this method and, in particular, study the effect of changes in the heat-exchange surface area on the effectiveness of temperature control. An experiment was set up to control the temperature of a laboratory-scale coal pile using a heat exchanger made from copper tubes. Coal samples were placed in a cylindrical container with a spiral-shaped heat exchanger, placed in the center of the cylindrical container, and cooled with ~27^o seawater. Tests were carried out using several configurations of heat exchanger dimensions to determine the effect of changing the ratio of heat-exchange surface area to volume of combustible material. The test results showed that greater heat-exchange surface area produced a greater amount of cooling load and temperature difference.

Keywords: Coal; Heat exchanger; Heat transfer; Spontaneous combustion; Surface area ratio

1. INTRODUCTION

Coal is still used as a significant source of energy in most parts of the world (Benalcazar et al., 2017), especially for electricity generation. The high demand for coal worldwide has caused a shortage in the supply of high-quality coal. This has resulted in the increased use of low-quality coals, such as sub-bituminous coal and lignite, for combustion and gasification (Tristantini et al., 2015). In the coal supply chain process, some regions of the world still experience long storage times, whereby coal can remain stored in a ship for long periods. Especially for low-rank coal, this tends to lead to self-heating that can lead to spontaneous combustion, which has the potential to cause accidents (Nugroho et al., 2000; Singh, 2012; Onifade & Genc, 2018). Several methods have been used to reduce the spontaneous combustion of coal, including the compaction of coal piles, direct spraying of certain liquids onto the coal, periodic temperature checks, volcano traps, and trenching (Wan-xing et al., 2011). Different approaches have also been explored using

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laboratory-scale experiments, such as the use of water-sprays, mists, injections, showers, and gases (Tuomisaari & Baroudi, 1998; Goransson & Husted, 2007; Hadden & Rein, 2011). Each of these methods has advantages and disadvantages in their practice; so further research is required to find other methods that can more effectively prevent spontaneous combustion.

One such method under development for the indirect cooling of coal is the immersion of heat exchangers in coal piles (Mikalsen et al., 2018; Zhafira et al., 2018; Nugroho et al., 2019). This method can be used to control temperatures during both the storage and transportation processes. The purpose of this study was to test this method and determine the effect of the ratio of the heat-transfer surface area to the volume of the combustible material for the effectiveness of temperature control to prevent spontaneous combustion. Laboratory-scale tests were carried out using a heat exchanger made of copper pipe. Coal samples were placed in a cylindrical container and heated to certain temperatures in an oven. After the coal reached a certain temperature, saltwater was then flowed through the heat exchanger to maintain the temperature of the coal below a critical temperature. Previous experiments have used this identical method except for the method of water flow; Zhafira et al. (2018) and Nugroho et al. (2019) manually used a water bag while in the current experiment, a pump was used to automatically maintain a constant flow rate. Another similar experiment to study spontaneous combustion used a hotplate heater that was then cooled by flowing water after the sample reached a certain temperature (Mikalsen et al., 2018). Previous research determined the characteristics of spontaneous combustion by modeling heat distribution in heated coal (Saleh et al., 2017; Nugroho et al., 2019).

The current research explored this method because the transportation of coal by barges introduces new problems mainly due to the frequent occurrence of spontaneous combustion from coal being transported and the size of a heat exchanger impacts ship design and stability; additions to ships greatly affect the load, which in turn affects the stability of a vessel. Therefore, laboratory-scale experiments to determine the optimum dimensions of a heat exchanger were undertaken to ensure its effective use.

2. METHODS

2.1. Sample Preparation

The coal samples used in this experiment were a sub-bituminous coal obtained from a coal mine in East Borneo, Indonesia. The proximate and ultimate analysis of the sample used is shown in Table 1.

2.2. Experimental Setup and Procedure

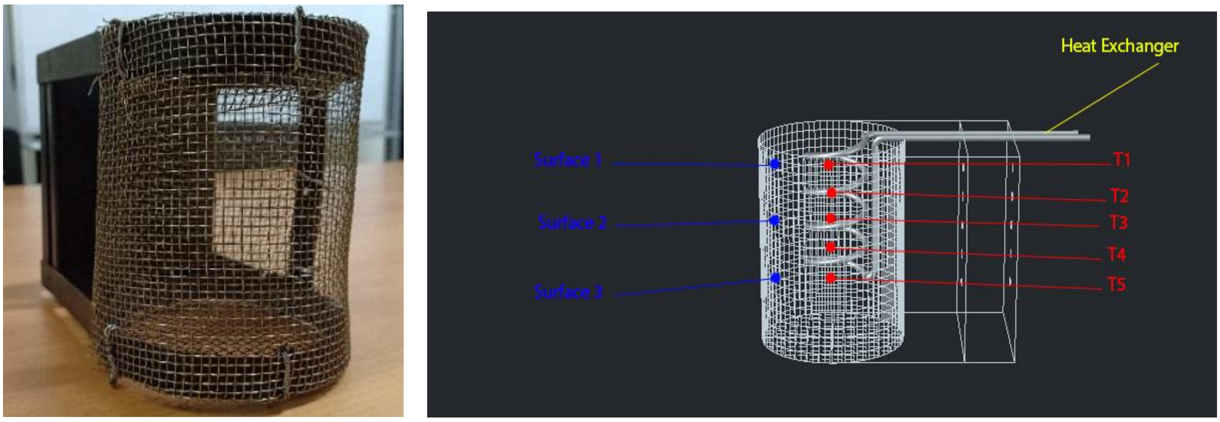
The general arrangement of the apparatus used in this experiment is shown in Figure 1. We used an oven (UN-55; Memmert) with an inner capacity of 53 L, a cylindrical reactor (85 mm diameter × 115 mm high) made from 1×1 mm^2 wire mesh (Figure 1a), and spiral-shaped heat exchangers made of copper pipes (2.3 mm outside diameter) with an outer-spiral diameter of 40 mm with several numbers of turns (2, 4, and 8) embedded in the center of the cylindrical container (Figure 1b). The coal sample was crushed and filtered using two sieves with mesh sizes of 2×2 mm^2 and 6×6 mm^2, respectively, so the sample was sized between 2 and 6 mm.

The cylindrical reactor was placed in the middle of the oven for the even distribution of heat to all points of the coal inside the reactor. The oven was set to re-circulate air at a rate controlled by 20% flap openings and 20% fan speed. Ten thermocouples were used in this study, with eight placed according to Figure 1.

Table 1 Proximate and ultimate analysis of the coal sample

Component	Unit	Value	Method
Total Moisture	%, ar	21.7	ASTM D 3302-17
Proximate Analysis	%, adb		
Moisture in Analysis	%, adb	11.8	ASTM D 3173-17
Ash Content	%, adb	4.6	ASTM D 3174-12
Volatile Matter	%, adb	44.2	ISO 562-2010
Fixed Carbon	%, adb	39.4	ASTM D 3172-13
Total Sulfur	%, adb	0.19	ASTM D 4239-17
Gross Calorific Value	Kcal/kg, adb	5914	ASTM D 5865-13
Bulk Density	g/cc	0.976	ASTM D 291-12
Ultimate Analysis			
Carbon (C)	%, adb	60.01	ASTM D 5373-16
Hydrogen (H)	%, adb	5.54	ASTM D 5373-16
Nitrogen (N)	%, adb	1.16	ASTM D 5373-16
Oxygen (O)	%, adb	28.50	ASTM D 5373-16

Notes; ar: as received; adb: air-dried basis



(a) (b)

Figure 1 Experimental setup: (a) The cylindrical reactor used in this experiment; (b) Placement of the thermocouples in the reactor

The ninth and tenth thermocouples were placed inside the oven outside the reactor to measure the oven temperature and at the water outlet to measure the water temperature exiting the heat exchanger, respectively. The distance between the thermocouples located in the center of the reactor was 1.6 mm between each point, while the three surface thermocouples (shown in Figure 1) were placed ~5 mm from the wire-mesh wall with a distance of 3.2 mm between each point. Each end of the heat exchanger was insulated with aluminum tape.

All the thermocouples were linked to a data acquisition system (National Instruments) and personal computer modules to display the data collected during the experiments. After placing all the thermocouples, for each experiment, ~365 gm of coal sample was gently poured into the container to a height of ~110 mm. After the coal was poured into the container, the oven was maintained at 147°C until the experiment was complete.

For the heat exchange, we used seawater (with a density of ρ = 1.025 kg/m^3 and Cp = 3,993 J/Kg.C) flowed through the heat exchanger using a brushless DC pump type (Q_{max} = 240 L/hr and H_{max} = 300 cm), which was placed 100 cm below the inlet point of the heat exchanger. This arrangement produced a constant water flow rate of 4.8 L/hr. The water started to flow when the temperature at point T3 reached the oven temperature. At this point, the mass flow rate was measured by flowing the water into a measuring cup for 1 minute, which was then weighed. The mass flow rate obtained from these measurements was 0.00127 kg/s. The experiment was stopped when the temperature at point T3 stabilized after cooling to determine the difference between the temperature before cooling and the temperature after cooling.

2.3. Coal Characteristics

The coal sample was characterized to determine the nature of the coal sample when heated to certain temperatures. This process was also undertaken by Nugroho et al. (2019) and Saleh et al. (2017). Another purpose of this process was to determine the characteristics of the coal samples using the crossing-point method. In this study, dry-based coal was used. The temperatures used for the characterization of the coal were 390K, 400K, 410K, 420K, and 430K. The coal was placed in a cylindrical container and heated to a predetermined temperature in the oven. The coal was then allowed to continue heating to determine whether the ongoing test temperature was categorized as sub-critical or super-critical.

A sub-critical temperature is a temperature at which no spontaneous combustion reaction occurs. A super-critical temperature is a temperature at which a spontaneous combustion reaction occurs. Based on our characterizations of the coal sample (Figure 2), the sub-critical temperature was 117°C, while the super-critical temperatures were 127°C, 137°C, 147°C, and 157°C; therefore by taking the mid-point of the sub-critical and the first super-critical temperature, the super-critical temperature point was determined to be 122±5°C.

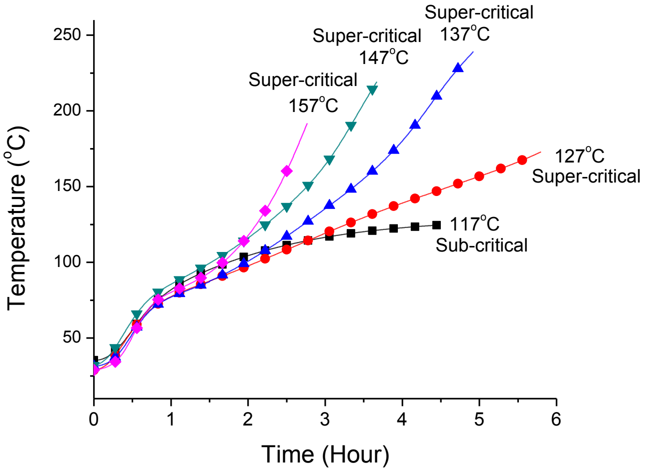


Figure 2 Characterization chart

3. RESULTS AND DISCUSSION

3.1. Effect of the Heat-Exchanger Surface Area on Coal Volume

One of the impacts of using heat exchangers is a reduction in the volume of coal that can be loaded onto barges. However, the configuration of the spiral-shaped heat exchanger used in this study would not significantly reduce the coal loading capacity; each heat exchanger, with a surface area of 7.52%, would reduce the coal loading capacity by only 0.2%.

This research used three heat exchangers, each with different dimensional configurations and distinguished by different numbers of heat-exchanger turns, resulting in different heat-exchange surface areas. This was used to determine the effect of different heat-exchanger surface area to coal surface area ratios.

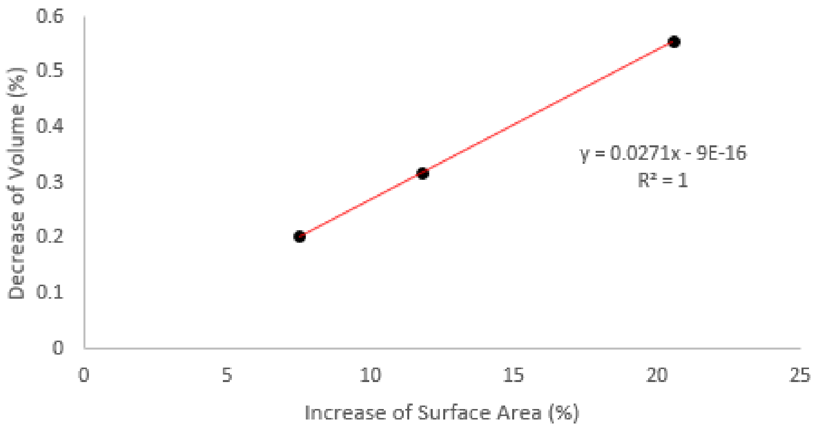


Figure 3 Increasing the heat-exchanger surface area vs. volume decrease

The three heat-exchanger surface-configuration ratios used in this study were 0.752, 0.118, and 0.205. Heat-exchanger surface ratios defined in this research is the division between heat exchanger surface area and the coal surface area. The coal surface area and volume were considered to be the same as the cylindrical reactor because the cylinder was filled with coal, which had a surface area of 3.07×10^4 mm^2 and a volume of 6.52×10^5 mm^3. The height of the spiral-shaped heat exchanger was 80 mm. The number of heat-exchanger turns used in this study was 2, 4, and 8. The following table shows the three heat-exchanger-configuration calculations used in this study.

Table 2 Heat exchanger configurations

Configuration	n	d	Leng/+th (mm)	Area (mm^2)	Volume (mm^3)	Surface Ratio	Volume Ratio
I	2	2.3 mm	319.7	2308.7	1327.5	0.752	0.0020
II	4		500.2	3612.4	2077.2	0.118	0.0030
III	8		872.8	6303.6	3624.6	0.205	0.0055

The equation used to calculate the length of the heat exchanger is shown below:

$$L = \sqrt{(\pi \frac{h}{h_1} D)^2 + h^2} + L' \tag{1}$$

3.2. Effect of the Heat-Exchanger Surface Area on Heat Transfer

The heat transfer effect was determined by the heat loss produced and the temperature difference at the heat exchanger center point 3 which is located at the center point of the heat exchanger. The heat released from the system was determined by referring to the following equation:

$$Q = m.C_p.\Delta T_{water} \tag{2}$$

Changes in the surface area of the heat exchanger compared with the resulting heat loss are shown in Figure 4, which demonstrates that heat loss increases with increasing heat-exchanger surface area.

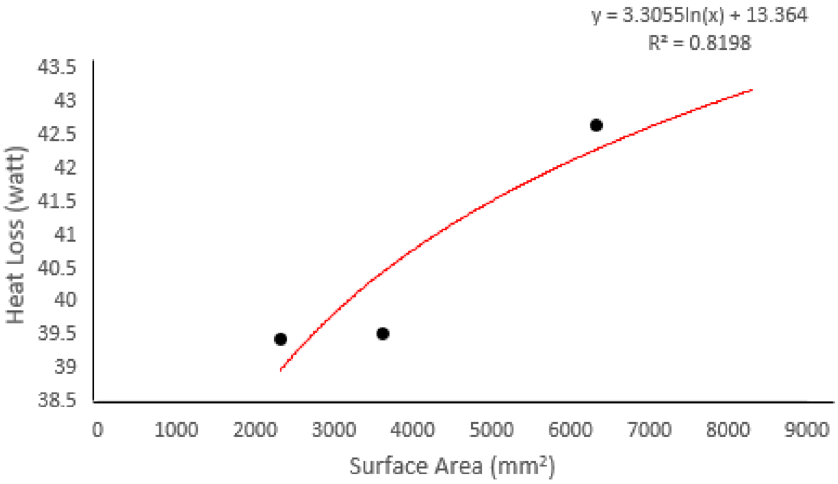


Figure 4 Effect of the heat-exchanger surface area vs. heat loss

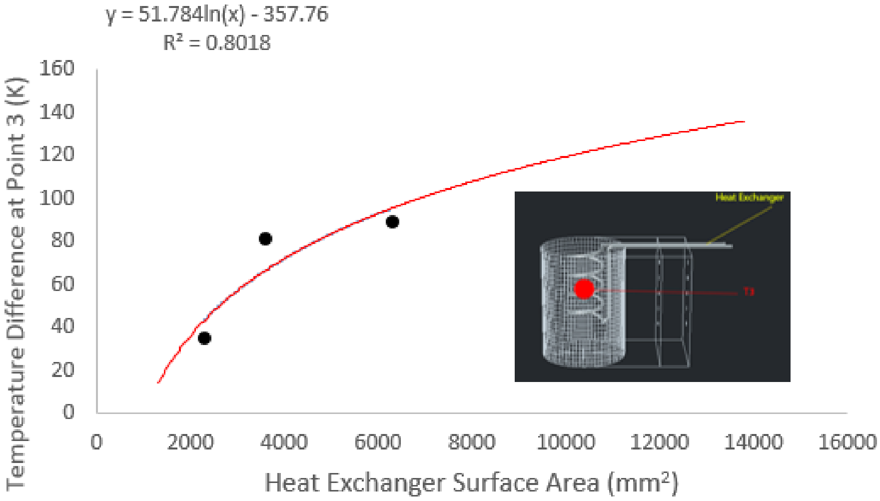


Figure 5 Effect of changes in the heat-exchanger surface area on the temperature in the center of the heat exchanger at point 3

The temperature differences in the center of the heat exchanger at point 3 are shown in Figure 5. The temperature increased with increasing heat-exchanger surface area. However, the graphs shown in Figures 4 and 5 are logarithmic, indicating that the resulting effects were not linear and did not show an optimal point before finally exhibiting a diminished effect, thereby reducing the effectiveness of this method. Therefore, further work is required to determine the optimal size for the maximum effectiveness of an immersed heat exchanger for the control of coal pile temperature. For future works, a high-performance heat exchanger based on the use of a heat-pipe system (Winarta et al., 2019) is being considered for future studies. Meanwhile, the drying kinetics of the samples (Palamba et al., 2018) and their corresponding blending properties (Nugroho et al., 2000) should be taken into account in the field application.

4. CONCLUSION

While the effect of increasing a heat-exchanger surface area on heat transfer has been generally examined, this study carried out an in-depth exploration of a heat exchanger immersion method to control coal pile temperatures to avoid spontaneous combustion. For the sub-bituminous coal used in this experiment, the critical temperature was determined to be 122.5±5°C, which was lower than the work undertaken by Nugroho et al. (2019) because of the different coal samples used in the experiments. The spiral-shaped heat exchanger used in this experiment was quite effective because of its small impact on the coal loading volume compared with the additional heat-exchange surface area. This eliminates reducing the volume of coal that can be loaded onto barges that use heat exchangers, one of the drawbacks of using immersion heat exchangers on coal barges. Spiral-shaped heat exchangers can reduce coal temperatures to below critical spontaneous combustion temperatures. The experimental results showed that additional heat-exchange surface area increased the heat loss and reduced the temperature difference. All other similar, previous work has reported the same results; immersed heat exchangers can effectively prevent the spontaneous combustion of coal (Zhafira et al., 2018; Nugroho et al., 2019). However, the current study did not determine an optimal value for the surface area ratio for this method; it ranged between 0.118 to 0.205. The results of this research can be combined with the distribution of coal temperatures (Nugroho et al., 2019) to identify critical points of spontaneous heating before continuing research on the implementation of this method for coal barges. Therefore, further research related to this method must be undertaken to discover other possibilities for optimal configurations.

5. ACKNOWLEDGEMENT

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