Temperature Mapping on the Effectiveness of Heat Exchanger Submersion on Controlling Spontaneous Combustion of Coal Piles

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ABSTRACT

Self-ignition of low-rank coals leading to spontaneous combustion accidents remain a great challenge in coal transportation and storage for power generation. Piles compaction and removal of the hot spots are considered to be effective actions to control the hot spots during coal storage if the heavy equipment is available in stockpile area. However, more complex situations arise during coal transportation using coal barges for inter-island transports. Typical coal barges are not equipped with heavy equipment for removal of hot spots in coal self-heating situations. This work continues exploring the possibility of heat exchanger submersion in coal piles as a mean of reducing the temperature of coal piles to prevent the spontaneous combustion accident. Cylindrical reactors with different oven temperatures are used, and the temperature is mapped inside the coal bed. The effectiveness of submerging the heat exchanger in delaying and preventing heat accumulation (leading to spontaneous combustion of coal) is assessed. The method is found to be effective to prevent self-heating, which causes smoldering combustion in sub-critical and slightly super-critical conditions. Numerical modeling is undertaken, and the simulation results are compared with the experimental data. Cooling by the heat exchanger could be feasible for preventing smoldering fire accidents in coal barges.

KEYWORDS: Spontaneous ignition, heat exchanger, coal, COMSOL.

INTRODUCTION

Coal continues play a important role as one of the most widely used energy source in many countries. At the same time, self-ignition of low rank coals leading to spontaneous combustion accidents remain great challenges in coal transportation and storage for power generation [1-6, 9]. Depend upon the geographical locations of the coal mines and the power plants, coal shipment in barge could last within days or weeks. This event tends to lead to self-heating of the coal and progress to smoldering combustion [3, 10]. Smoldering combustion is the slow, low temperature, flameless burning of porous fuels and the most persistent type of combustion phenomena [10]. Several cases were reported regarding burning coal barges due to spontaneous combustion. Piles compaction and hot spots removal are considered effective measures to control the hot spots during coal storage due to the availability of heavy equipment in stockpile area. However, more complex situations arise during coal transportation using coal barges for inter islands transports. Typical coal barges are not equipped with heavy equipment for removal of hot spots in coal self-heating situations.

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This work explores further the possibility of heat exchanger submersion in coal piles as means of reducing the temperature of coal piles as a method to prevent the spontaneous combustion accident. In a previous work [7], a laboratory scale experimental was set up to study the smouldering combustion phenomenon of coal samples and means of control by using heat exchanger submersion in a coal bed. This method shows that the heat generated can be reduced to below the critical temperature for spontaneous combustion. The water flow rate has significant impact on temperature reduction of the coal inside the bed. This method has potential benefit for controlling spontaneous combustion problem during barge transportation of coal. Recently, R.F. Mikalsen et al. [8] explored heat extraction from the combustion zone as a method for extinguishing such flameless fires. Heat extraction from the sample was made feasible using water flowing through a metal pipe located inside the sample. Results from small-scale experiments of wood pellet fuel in a steel cylinder with insulated side walls, open at the top provide proof-of-concept of cooling as a new extinguishing method for smoldering fires [8].

The present work uses a spiral-shaped heat exchanger within the fuel bed in a cylindrical wire-mesh reactor placed in a temperature controlled oven, through which water flow is started after the coal temperature has reached the oven temperature. In particular, the current works explore the temperature mapping inside the coal bed as critical parameters to assess the effectiveness of submersion of heat exchanger as means to delay and to prevent heat accumulation leading to spontaneous combustion of coal. In this paper the self-heating process and the cooling effect has been modelled using COMSOL multi-physics software [11].

MATERIAL AND METHODS

Experimental set up and procedure

Figure 1 shows the general arrangement and a photo of the apparatus used in this work. It consists of a temperature-controlled oven of 53 L inner volume, a 3 mm x 3 mm wire-mesh cylindrical reactor with 85 mm diameter and 115 mm height. A heat exchanger of spiral shape was immersed inside the cylindrical wire-mesh reactor. The heat exchanger is made of copper tube of 3 mm outer diameter and shaped to a spiral coil with a 45 mm outer diameter. A wider wire-mesh cylindrical reactor with 100 mm diameter and 115 mm height was also used in this work. The volume % of heat exchanger versus coal volume is 0.7%. Meanwhile, the surface ratio of heat exchanger versus coal reactor surface is 14.6%.

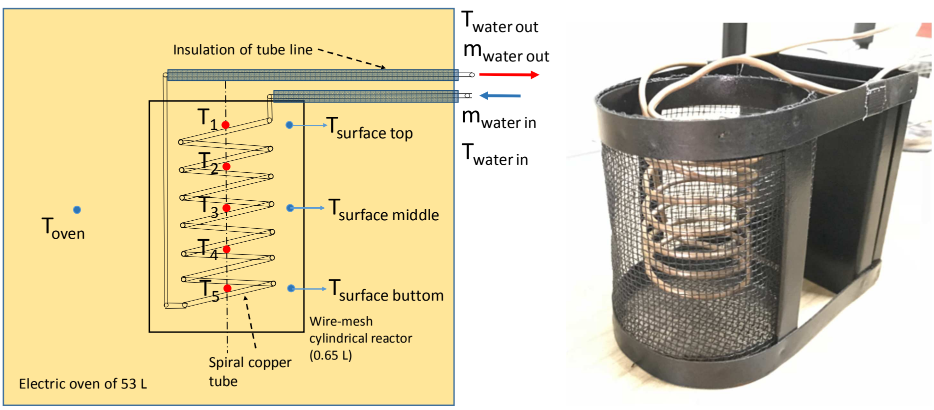

Fig 1. Experimental set-up.

The wire mesh cylinder was placed in the middle of a re-circulating air oven. Ten K-type thermocouples of 1.5 mm diameter were used in this experiment. Five thermocouple were placed in the middle of the cylindrical reactor to measure the temperature of coal (*the internal zone*), three thermocouple were placed about 3 mm from the surface of the reactor at 3 different height, one thermocouple was placed in the oven and another thermocouple was inserted to the water stream to measure the cooling water temperature leaving the oven. An insulation was wrapped at the in and out lines of the heat exchanger tube to minimise the effect of the oven temperature to the cooling water temperatures.

The thermocouple was connected to a National Instrument data acquisition system and the data were recorded to a personal computer for further analysis. Once the wire-mesh reactor, the heat exchanger and the thermocouples were set carefully inside the oven, then the coal sample was poured gently into the wire mesh reactor. No compaction was applied to the coal sample. For a run, the electric oven was set to a temperature and maintained at the same temperature until the experimental was finished. The oven temperature was set at 127^{o}C, 137^{o}C, 147^{o}C, and 157^{o}C to represent sub-critical and supercritical conditions for spontaneous combustion.

The heat exchanger tube was connected to a cooling water supply from a disposable infusion set with a 500 mL water bag, placed at 30 to 50 cm above the inlet point of the heat exchanger at the oven. This arrangement could maintain the flow rate of the cooling water stream at 4 L/hour. At least 10 water bags were prepared for water cooling stages. The cooling water was flowed into the heat exchanger tube when the coal temperature at the centre of the reactor (T_3) reached the oven temperature.

Sample preparation

This experiment uses a lignite from an Indonesian coal mine with the proximate and ultimate analyses were shown in Table 1. Prior to a test, the coal sample was crushed and sieved to size between 1 mm to 5 mm.

Table 1. Proximate and ultimate analyses of the coal sample

Components	As Received	adb(*)
	Proximate analysis	
Moisture Content (%)	37.98	9.94
Volatile Matter (%)	28.65	41.6
Fixed Carbon (%)	28.54	41.45
Ash Content (%)	4.83	7.01
	Ultimate analysis	
C (%)	39.87	57.9
H (%)	2.94	4.27
N (%)	0.54	0.84
S (%)	0.32	0.46
O (%)	13.48	19.58
Gross Calorific Value (MJ/kg)	3785	5496

*As dried basis.

Numerical modeling

COMSOL Multiphysics software [11] was applied in this investigation to simulate the heat transfer with the chemical reaction heat source in the coal pile reactor (porous media) and the cooling process using Nonisothermal Pipe Flow module.

The chemical reaction heat source of coal was simulated as a reaction of surface chemicals in which the oxidation reaction appeared on the surface of coal in the porous media. Heat as a product of the oxidation reaction is released into the environment by conduction and convection.

The mass and energy conservation equations leading to the mechanism of oxygen concentrations and heat transport in the reaction vessel of coal are described below.

Energy conservation:

$$\left(\varepsilon\rho_g C_{pg} + (1-\varepsilon)\rho_s C_{ps}\right)\frac{\partial T}{\partial t} + \rho_g C_{pg}\frac{\partial u_i T}{\partial x_i} = \lambda_{eff}\frac{\partial^2 T}{\partial x_i \partial x_i} + (1-\varepsilon)Qr\,, \quad (1)$$

where ε is the porosity, ρ_g and C_{pg} are the gas density and gas specific heat, ρ_s and C_{ps} are the coal density and coal specific heat, r is the oxidation rate that calculated using Arrhenius equations, Q is the reaction heat for oxidation of coal, and λ_{eff} is the effective coal matrix thermal conductivity. This can be rewritten as:

$$\lambda_{eff} = \varepsilon\lambda_g + (1-\varepsilon)\lambda_s\,, \quad (2)$$

where λ_g and λ_s are the thermal conductivities for gas and coal, respectively.

The input data for the simulation are the boundary and initial conditions. As the initial conditions of booth coal and cooling water involved a temperature of 298.15 K, and the boundary condition used in this simulation was constant oven temperatures at 413.15 K. The physical and kinetic properties of coal used in this simulation were given in the following Table 2.

Table 2. The kinetic and physical properties of the coal as model inputs for simulation [1, 9]

Parameter	Value	Unit
Bulk density of coal	880	kg/m^3
Particle density of coal	1,260	kg/m^3
Conductivity of coal	0.1	W/(m·K)
Specific heat of coal	1,100	J/(kg·K)
Heat of reaction	350	kJ/mol-O_2
Activation energy	66.8	kJ/mol
Pre-exponential factor	2.88×10^6	1/s
Initial coal temperature	298.15	K
Coal particle diameter	2.38	mm
Cooling water flow rate	4	L/hr

The simulation was carried out in two steps. The first was a time dependent step without the cooling process. The second step involved time-dependent calculations, including the cooling process, and the time step was 60 s. Figure 2 shows the geometrical layout and mesh applied for this simulation. The element size was 1.15 mm, while the total element number was about 7,519 domain elements, 870 boundary elements, and 225 edge elements.

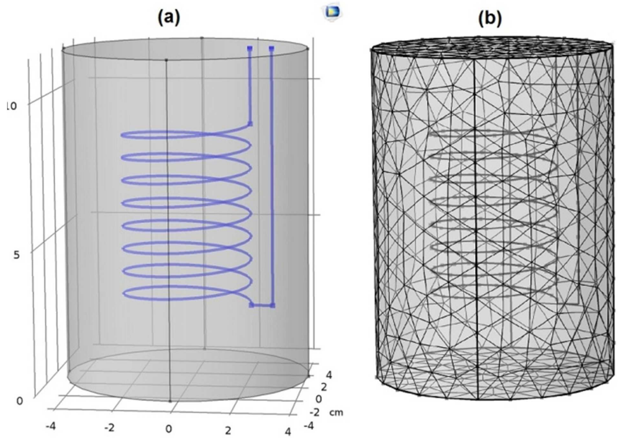

Fig. 2. The geometrical layout for the reactor vessel (a) and mesh used in the simulation (b)

RESULTS AND DISCUSSION

Experimental works

Self-heating behaviour

Figure 3 shows a time-temperature history of the experiment at a set oven temperature of 127^{o}C. The response time of the electric oven was excellent as it could reach the set temperature within 40 minutes. The measured overshoot temperature was ± 1^{o}C of the set temperature.

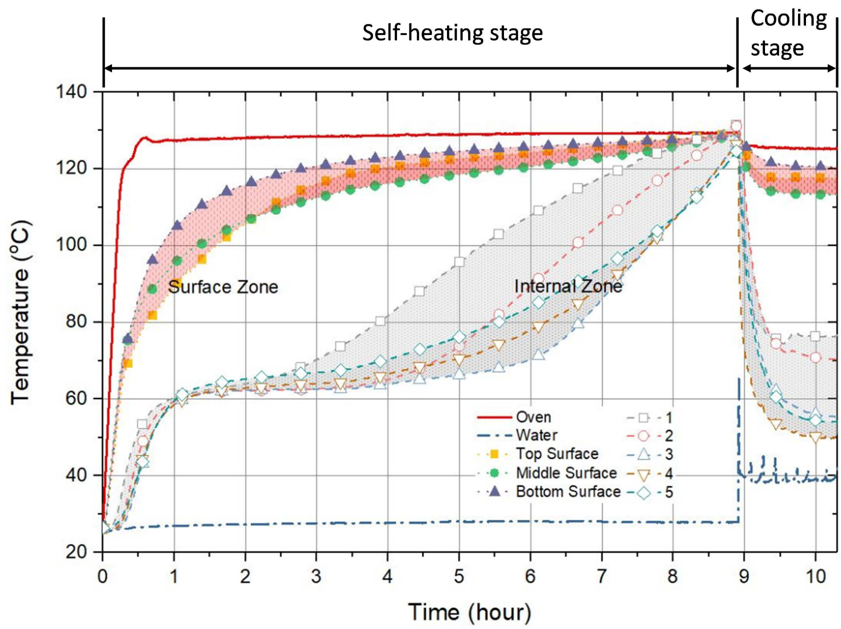

Fig. 3 Temperatures time history of a typical run at 127 °C oven temperature, using a 100 mm diameter wire-mesh cylindrical reactor.

The temperatures near the surface of the wire-mesh reactor rapidly response to the oven temperature. Although the coal sample is considered having high moisture content (Table 1), no significant delay was observed in the heating process of the coal temperature near the reactor surface, i.e. the surface zone. A contrast situation was observed when considering the temperature measurement results near the centreline of the cylindrical wire-mesh reactor. The temperature rise in this zone, the so called internal zone, represented by T_1 to T_5, was considerably delayed by heat conduction process and the drying process of the coal sample. During the period of initial heating from room temperature to oven temperature, the sample shows important features in this early stage of coal oxidation.

Firstly, the heat provided by coal oxidation brings the temperature of coal particles to about 60^{o}C, before moisture evaporation starts to affect the heating significantly. Secondly, a relatively large quantity of water is removed by the air stream when the temperature rises from about 60^{o}C to 100^{o}C. During this period, the drying process significantly delays the temperature rise. After this stage, if coal oxidation is still capable of evaporating all the water in the basket of coal, the temperature rises above 100^{o}C. Comparison of experimental results from larger wire-mesh reactor of 100 mm diameter (Fig. 3) to smaller wire-mesh reactor of 85 mm diameter (Fig. 4) clearly suggests the effect of pile size on the times for coal temperatures in the internal zone to reach the oven temperature. For both reactors, the coal temperatures at the outer locations of the reactor, represented by T_1 and T_5 rise slightly faster compared to compared to T_2 and T_4.

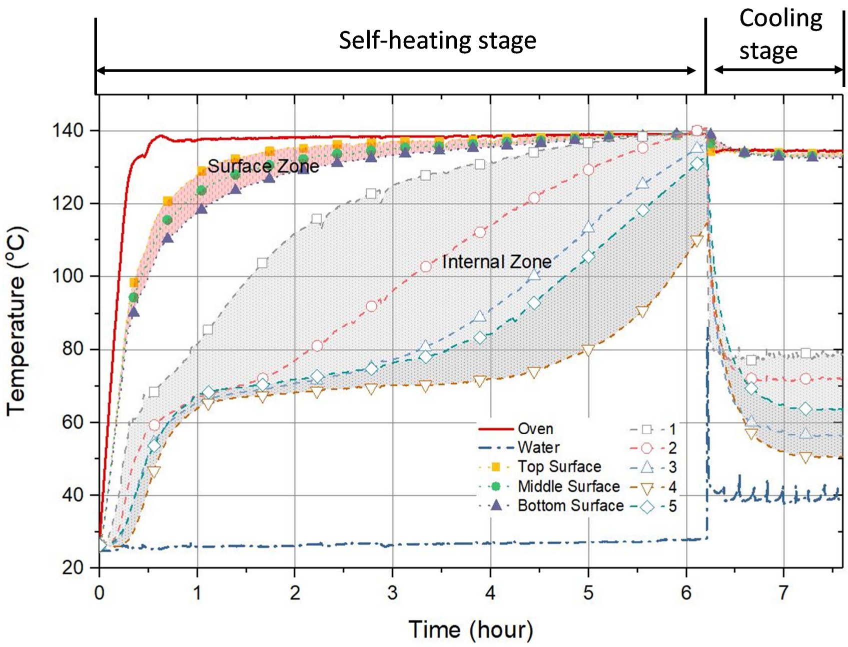

Fig. 4. Temperatures time history of a typical run at 137 °C oven temperature, using a 85 mm diameter wire-mesh cylindrical reactor.

Effect of cooling

In this experiment, the primary measurement was conducted to measure the temperature drop that occurred when the cooling process was carried out continuously for more than 1 hour. The different temperature pattern can be observed clearly in Figs. 3-6. The fluctuation in the outlet water temperature was due to delays of water flow due to changing of water bags every time a 500 mL of water was finished.

As shown in Figs. 3 and 4, the cooling process can effectively reduce the coal temperatures within the spiral zone of the immersed heat exchanger (T_1 to T_5) to below the critical temperature for spontaneous combustion. However, no significant temperature reduction was observed at the surface zone. The temperature at the surface zone remains constant close to the oven temperature with no spontaneous combustion process commences.

To represent a delay in starting the cooling water flow, Fig. 5 show the temperatures time history of a run at 147°C oven temperature. At this oven temperature, the coal bed is super-critical conditions, as the critical temperature was about 129.5 °C, for no cooling tests. Cooling process was started when central temperature reaches 50°C above the oven temperature. Although the coal temperature had reached a temperature of 200°C, a significant reduction in coal temperature at all zone was observed. This suggests that the cooling mechanism still work properly and could maintain the coal temperature at a safe zone.

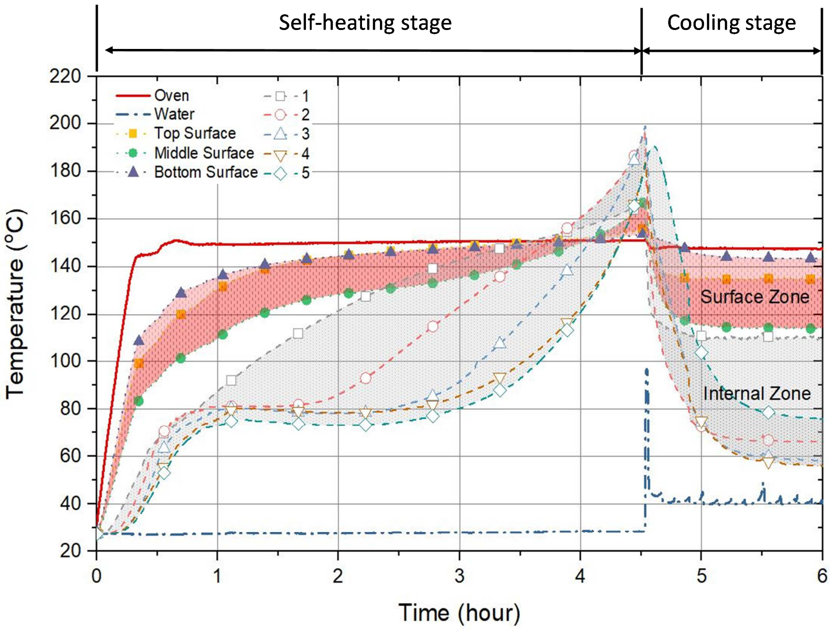

Fig. 5. Temperatures time history of a typical run at 147 °C oven temperature, using a 85 mm diameter wire-mesh cylindrical reactor. Cooling begins when central temperature reaches 50°C above the oven temperature.

Figure 6 shows the evolution of the spatial temperature profile for the coal sample as it warms up from room temperature to oven temperature of 157°C. Self-heating above the oven temperature is clearly shown on the surface zone of the coal sample, and this phenomenon commences either before the centre of the sample reaches the oven temperature or before the sample exhibits self-heating at its centre. This is qualitatively in agreement with the numerical work carried out by B.F. Gray et al. (1992) [12]. The coal temperatures inside the wire-mesh reactor (T_1 to T_5) arise following the increase of surface temperatures. On the contrary with conditions at lower oven temperatures (137°C and 147°C), at super critical condition (oven temperature at 157°C), cooling effect with similar cooling water stream rate at 4 L/hr provides delay for spontaneous combustion process for a period of time only at the internal zone. However, the cooling effect could not reduce the coal temperature at the surface to a safe condition for preventing the spontaneous combustion. From the temperature data at the surface layer zone, the temperature was decrease shortly followed by a sharp increase especially for the thermocouples close to the surface of the reactor. This indicates the increase of the rate of combustion. The thermal runaway phenomenon was observed in Fig. 6 although the cooling water was flowed continuously.

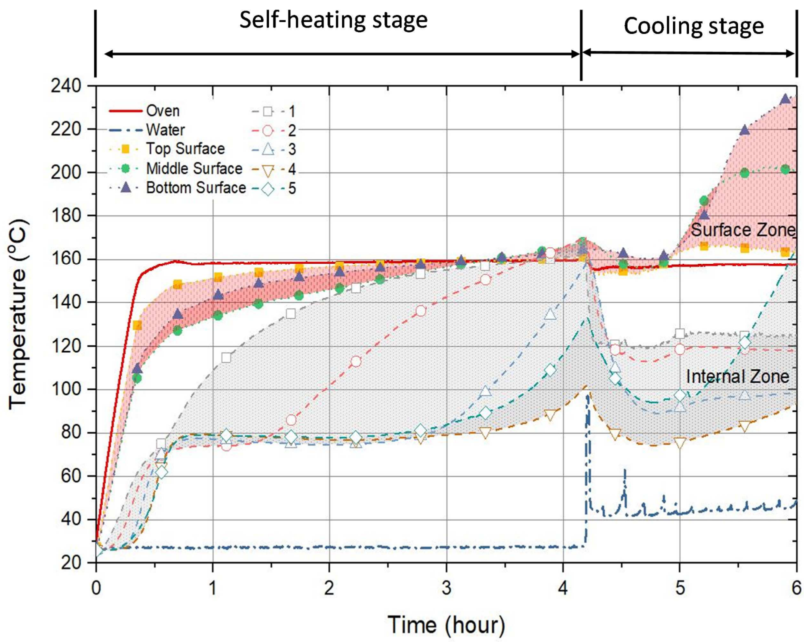

Fig. 6. Temperatures time history of a typical run at 157 °C oven temperature, a super-critical condition for spontaneous combustion.

Numerical modeling

Self-heating phenomenon of coal bed heated in a wire-mesh cylindrical reactor is a complex numerical modeling problem that requires experimental data such as the activation energy and the pre-exponential factor. By means of the crossing-point temperature method [1], one can derive the values of activation energy and the product of exothermicity (*Q*) and the pre-exponential factor (*A*) from a wire-mesh basket experimental method. For this coal the overall activation energy was about 66.8 kJ mol^{-1}, and $QA = 3.6 \cdot 10^9$ J kg^{-1} s^{-1}. These values were considered in the modeling work.

The problem is becoming more complex when heat removal mechanism by means of heat exchanger submersion is added into the system. The simulation was conducted in two step studies where step 1 was simulated during the heating process of coal until the center of coal temperatures matched the oven temperatures. Meanwhile, step 2 was the cooling processes of coal with a heat exchanger using water as a cooling medium. During this study it was assumed that all basket surfaces (tubes) were at constant temperature conditions (i.e. oven temperature), coal density was uniform in all parts of the stack and coal conductivity was not affected by temperature (constant).

In order to have better understanding of the heat transfer within the system, surface and contour of the coal temperatures were retrieved and presented as Figs. 7 and 8. These figures demonstrated the distribution of temperature throughout the vessel during the simulation step 1 and step 2.

It can be seen in Fig. 7, that heat transfer occurs uniformly (symmetrically) from all directions of the basket reactor = surface towards the center of the coal bed. While in Fig. 8 it can be seen that in the cooling step (step 2) the temperature distribution becomes slightly asymmetrical especially along the heat exchanger output pipe from the bottom up on the right side of the basket. Meanwhile, Fig. 9 shows the development of cooling water temperatures resulted from simulation in step 2. An increase of cooling water temperature of about 5°C to 10°C is confirmed by the experimental data shown in Figs. 3 and 4.

In addition, by considering the heat loss to the heat exchanger ($\dot{q}_{cooling}$) is given by $\dot{q}_{cooling}$ =

$\dot{m}_w C_{p,w} \Delta T_w$, where $\dot{m}_w$ is the water flow rate, $C_{p,w}$ is the specific heat capacity, and ΔT_w the temperature difference of the water entering and leaving the heat exchanger, thus the heat loss to the heat exchanger is in the range of 40 to 65 W.

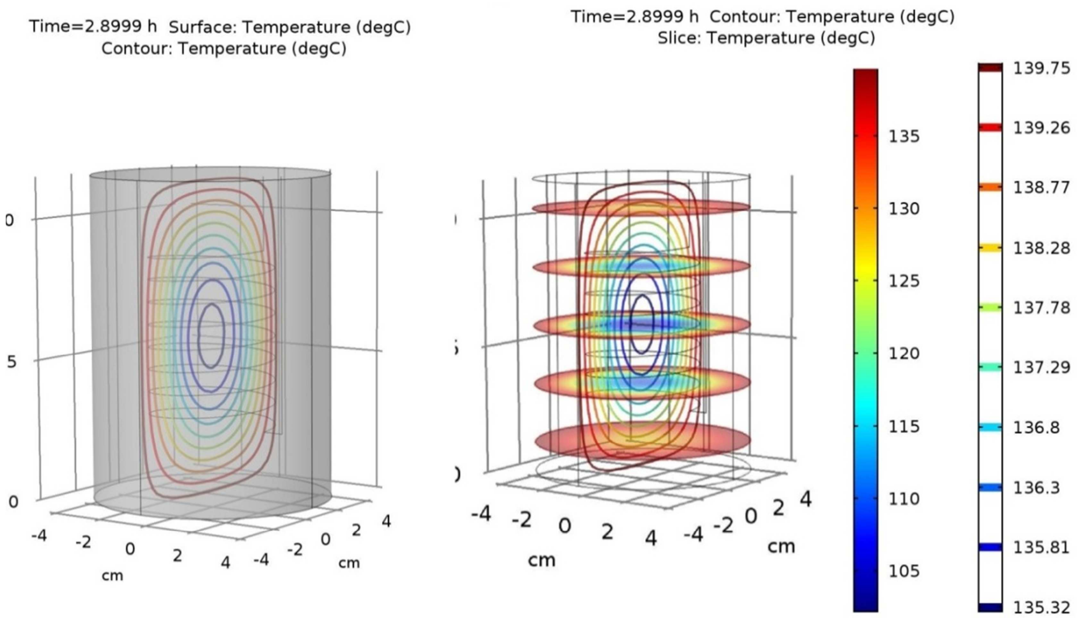

Fig. 7. Surface and Contour Temperatures during simulation in step 1.

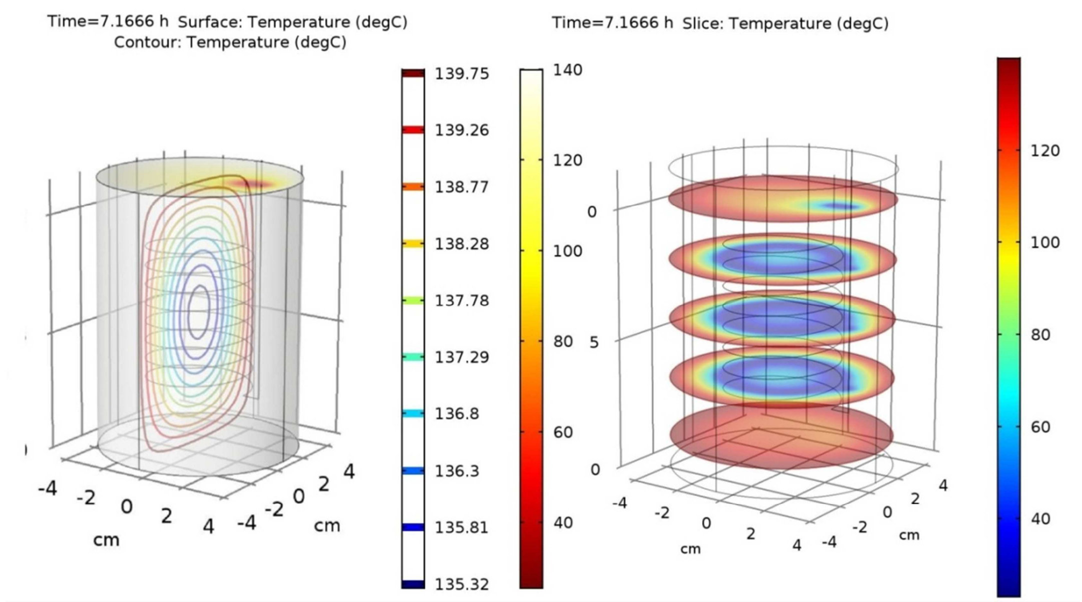

Fig. 8. Surface and contour temperatures during simulation in step 2.

Although the volume % of heat exchanger is only 0.7% of the coal volume, the surface ratio of heat exchanger versus coal reactor surface could be significant and reach up to 14.6%. The surface ratio of 14.6% suggests the importance of adding the surface area for coal to cooling mechanism in order to increase heat losses to prevent the system from approaching the critical condition for spontaneous combustion and uncontrolled smoldering combustion.

Figure 10 presents the validation and comparison of the numerical modeling results with the experimental data. In general, the numerical modeling results are in good agreement with the experimental data, although discrepancy occurs during the drying stage. This could be due to at this stage of the numerical modeling work, changes in the specific heat and moisture content of the coal bed during the self-heating processes are neglected.

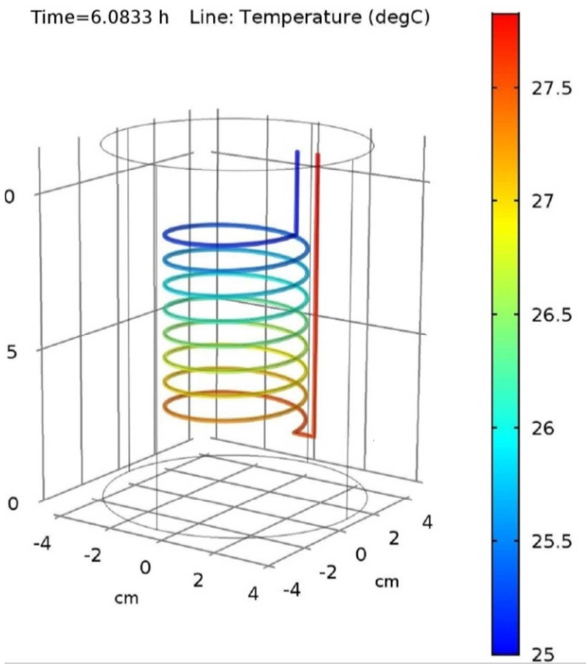

Fig. 9. Increase of cooling water temperatures during simulation in step 2.

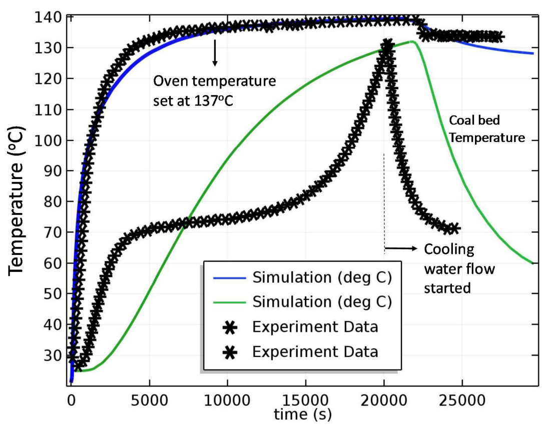

Fig. 10. Comparison between the simulation and experimental results at oven temperature 137 °C.

CONCLUSIONS

A series of bench-scale experiments on self-heating behaviour of lignite (low rank coal) and the effect of cooling by means of spiral coil heat exchanger submersion have been carried out using a cylindrical wire-mesh reactor at various oven temperatures. Temperature mapping of self-heating process within the reactor suggests that the coal temperature at the surface zone and at the internal zone of the spontaneous combustion process behave differently due to heat and mass transfer processes during low temperature oxidation of the coal. The surface zone will follow the oven temperature rigorously. Meanwhile, the internal zone of the coal bed inside the wire-mesh reactor is greatly affected by heat and mass transfer between coal and the oven conditions. The effectiveness of cooling mechanism depended upon the self-heating stage of the coal sample. The cooling process can effectively reduce the coal temperatures within the spiral zone of the immersed heat exchanger to below the critical temperature for spontaneous combustion. However, no significant temperature reduction was observed at the surface zone. Similar condition was observed even when there was a delay in cooling process leading to coal sample temperature went above the oven temperature. However, when a super-critical temperature for spontaneous combustion was reached, the cooling effect could not reduce the coal temperature at the surface zone to a safe condition for preventing the spontaneous combustion. Numerical modeling for small scale tests of self-heating and cooling process shows a good agreement with the experimental data. Both numerical modeling and experimental works are critical to define the best position of the heat exchanger submersion inside the coal bed for real applications of this method in coal barge design. Heat exchanger cooling method could be feasible for preventing smoldering fire accidents in coal barges.

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