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Self-heating characteristics of sub-bituminous coal C during spontaneous combustion in stockpiles

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ABSTRACT

Sub-bituminous coal C that is stored for extended periods in stockpile can lead to the occurrence of self-heating. This self-heating is a result of oxidation reactions involving coal, oxygen, and heat at low temperatures. Self-heating contributes to environmental quality decline due to the release of greenhouse gases, such as methane emissions, which significantly impact global warming. The purpose of this study is to explore the characteristics of self-heating, which is a stage in spontaneous combustion linked to the generation of methane emissions in coal piles with a calorific value below 6100 kcal/kg in stockpiles. The research methodology combines field data collection with literature review focusing on variables like temperature, time, and methane emissions, with data processing carried out through statistical analysis using Pearson correlation tests and linear regression. The characteristics of self-heating are studied by examining the relationships between time and temperature, temperature and methane emissions, as well as time and methane emissions. Research findings suggest that the self-heating characteristics in the study area are still at a latent stage, which can be divided into two categories: the traditional latent stage and the preparation latent stage. This stage has a temperature range of 43.98–54.19 °C and 58.84–61.27 °C, a time span of 32–46 minutes and 49–52 minutes, along with methane emissions that fall between 3192–17,319 ppm and 17,408–20,575 ppm, respectively. The emissions flux for temperature and methane during the traditional latent and preparation stage in the research area measures 44.14 °C/hour, 1371.55 ppm/°C, 60,544.20 ppm/hour, and 9.20 °C/hour, 6884.78 ppm/°C, 63,340 ppm/hour, respectively. This situation indicates that if self-heating is not properly managed, it can lead to an increase in methane emissions, negatively impacting global warming. Therefore, it is essential to implement preventive measures to mitigate methane emissions from self-heating by adjusting dimensions and installing temperature sensors on stockpiles.

Keywords: methane emissions, preparation stage, self-heating, stockpile, traditional latent stage.

INTRODUCTION

Jambi Province ranks second in coal production on Sumatra Island, following South Sumatra, and holds the fifth position nationwide in Indonesia. The majority of the coal produced has low to medium calorific value. The calorific value of coal in the study area falls between 5140–5270 kkal/kg, which is classified as mid-ranking coal, specifically sub-bituminous coal C, with a calorific value range of 5100–6100 kkal/kg [Riasetiawan et al., 2023; Umar et al., 2024]. The use of sub-bituminous coal C as an energy source for industrial activities and power generation is growing and becoming more widespread [Kusuma et al., 2023; Saletnik et al., 2025]. Continuous production growth may result in the accumulation of coal for extended periods, often leading to self-heating. This is a stages of spontaneous combustion that can negatively impact companies, particularly concerning the decline in both the quality and quantity of coal, as well as environmental issues that contribute to global warming [Thabari et al., 2023; Nursanto et al., 2024].

Research on the stages of spontaneous combustion of coal can be divided into two main categories: three stages and five stages. Most experts tend to categorize spontaneous combustion into three stages: incubation stage, self-heating stage, and self-combustion stage. The temperature ranges assigned to these three stages reveal vague boundaries between them. An alternative perspective in studying spontaneous combustion stages involves five stages: latent (55–70 °C), heat accumulation (70–90 °C), evaporation (90–105 °C), active (105–170 °C), and hypoxic (>170 °C), categorized based on laboratory experiments [Zhu et al., 2018].

Self-heating in sub-bituminous coal C is caused by an oxidation reaction that takes place between the coal, oxygen, and heat at low temperatures [Liu et al., 2023; Liu et al., 2024]. Self-heating is one of the stages in the spontaneous combustion process of coal which occurs at a temperature of 70 °C which is known as the self-heating temperature (SHT) of coal [Li et al., 2022]. The temperature of the SHT is mainly influenced by the type and grade of coal, with values between 40–140 °C. The stages of spontaneous coal combustion begins with the incubation stage, which occurs at temperatures ranging from 20–40 °C and experiences a significant increase. SHP temperatures for Polish coal range from 70–90 °C [Dariusz et al., 2021].

Conducting a thorough analysis during the incubation stage at the site is quite challenging since this process has been underway for a significant period, potentially lasting several weeks or even months [Wang et al., 2023]. Research on spontaneous coal combustion in areas with high potential focuses on the self-heating stage associated with time, temperature, and methane missions. This latent or self-heating stage occurs at temperatures ranging from 40–70 °C. The self-heating process occurring in the study area can be divided into two classifications: (1) the traditional latent stage, which includes physical changes and minimal chemical alterations, and (2) the preparation stage, which involves chemical changes.

Significant changes in the traditional latent stage involve physical adsorption, while in the preparation phase, this is characterized by chemical adsorption that occurs as the temperature rises [Anghelescu and Diaconu, 2024]. Nations recognized for coal production, especially sub-bituminous coal, frequently encounter spontaneous combustion occurrences. This includes countries such as the United States, China, Turkey, Indonesia, India, Australia, South Africa, Germany, Poland, and others, leading to detrimental effects on social, economic, and environmental factors [Zhao et al., 2023]. Instances of self-heating coal lead to the release of methane, which is a greenhouse gas that plays a role in global warming [Gorka et al., 2022].

Emissions of methane will absorb and reflect the radiation waves emitted by the Earth, resulting in a rise in the planet's surface temperature. Methane has a warming potential over a century that is approximately 27–30 times more significant than that of CO_2, contributing about 25% [Chen et al., 2024]. Since 2007, there has been a notable rise in methane emissions, increasing at a rate of 0.006 ppm/year. This acceleration has become more pronounced since 2014, with a rise of 0.01 ppm/year, marking a growth of 66.67% over seven years or 9.52% annually [Nisbet et al., 2020]. Recent research from experts indicates that the Earth's average temperature is expected to increase by approximately 0.5–1 °C over the past century, while estimates from the International Commission on Climate Change predict a rise of 6 °C if fossil fuel usage and deforestation are not addressed [Mikhaylov et al., 2020]. The Paris Agreement has specified that the rise in global temperatures should not exceed 2 °C [Ivanova et al., 2020].

With the significant rise in temperatures each year, extensive research on self-heating is essential as part of efforts to minimize methane emissions caused by the spontaneous combustion of coal in the mining industry. Various researchers with a specific interest in this area have conducted studies on self-heating and spontaneous combustion, particularly concerning methane emissions, both in laboratory settings and in the field. These studies can be categorized into several segments, including self-heating and self-combustion stages, intrinsic and extrinsic characteristics, development of measurement tools, testing methods, and models related to self-heating and spontaneous combustion of coal in connection with methane emissions. Typically, findings from laboratory research are more satisfactory, while field studies often face numerous difficulties due to the lengthy processes involved in spontaneous combustion, which begins with incubation, latent, heat accumulation, evaporation, activity, and ends with hypoxia.

The study on the impact of temperature and duration on methane emissions has been carried out by experts to demonstrate self-heating and spontaneous combustion of coal, both in real-world settings and in laboratory environments [Wang et al., 2023]. However, the study has not thoroughly connected its findings to the emission flux related to self-heating, particularly in examining its characteristics during the latent stage. The emission flux in self-heating must be addressed from the mining sector, as currently, the contribution of methane emissions from this sector accounts for 16% [Olczak et al., 2023]. By examining the traits of self-heating and implementing preventive measures, it is hoped that methane emissions in the mining sector can be minimized.

The aim of this study is to examine the characteristics of self-heating in sub-bituminous coal C, particularly in relation to temperature, duration, and methane emissions, which are connected to prior research conducted in both laboratory and field settings.

MATERIALS AND METHODS

Data collection location

The research site is located at a company in Jambi Province that holds a Mining Business License (IUP) for production operations covering an area of 199.10 hectares. The company's coal production is stored in a stockpile occupying 1 hectare, which serves to manage the input and output of coal as part of the stockpile management system. The selection of this location for the study is based on several considerations regarding self-heating, namely: (1) the type of coal at the research site is medium-calorific coal, specifically sub-bituminous C, with a calorific value below 6.100 kcal/kg, (2) there are hotspots indicated by the presence of smoke, particularly associated with self-heating, and (3) the number of hotspots related to self-heating is quite significant. Seven self-heating hotspots are sampled in this study, labeled as KAI-1 – KAI-7.

The research was conducted directly at the self-heating hotspot using equipment to measure methane emissions, which included a calibrated multigas detector and a 50 × 50 × 50 cm cube-shaped chamber equipped with a stainless steel prism on the top. Additional tools included an infrared thermocouple for temperature measurements and a stopwatch for time tracking. The dimensions of the chamber were established to facilitate easier measurement and control of methane emissions in the field during equipment mobilization. The chamber designed to isolate methane gas emissions also considered heat conduction, maintaining a state where no heat enters or exits, or a semi-adiabatic process [Yusuf and Rendana, 2024].

Data processing and analysis

Data collection techniques carried out directly in the self-heating hotspot area involve monitoring temperature, time, and methane gas emissions. The data collection process is executed using a chamber that has an opening on the top to connect the multigas detector to the chamber via a hose. Temperature, time, and methane gas emissions are recorded every minute until each KAI-1 – KAI-7 reaches its peak methane emissions, and then the averages are computed.

Data processing is carried out utilizing tables, graphs, and statistical analysis through Pearson correlation and linear regression [Smith and Sam, 2020; Yadav, 2022; Magazzino et al., 2024]. The data processing procedure is a vital component linked to research outcomes, as well as the patterns and trends that arise. These patterns and trends are then examined within the discussion of the results derived from data processing, especially in relation to comparisons with earlier studies.

Before measuring methane emissions in the field, the multigas detector must be calibrated according to guidelines provided by the manufacturer or the operating instructions, following the Multigas Detector Bump Test Procedure for the MSA Altair 4X. Once calibration is complete, an on-site test is performed outside the stockpile area to verify that the initial (ambient) conditions are fulfilled, such as: O_2%, temperature, time, and methane emissions. If these values meet the ambient conditions, the multigas detector is then employed to measure methane emissions during self-heating. The temperature measuring equipment used is the GM 550 infrared type, calibrated with various other temperature measurement tools, specifically for ambient temperature. If the temperature readings are confirmed to be appropriate, measurements are then taken for self-heating. Research on self-heating at the coal stockpile is conducted at seven hotspots, each possessing data totals below 60. This data is subjected to a normality test using the Shapiro-Wilk test to assess whether it follows a normal distribution. Subsequently, the data is averaged to determine the temperature, time, and methane emissions for each hotspot labeled KAI-1 - KAI-7. The collected data undergoes Pearson correlation testing and linear regression analysis using SPSS Version 22 software.

RESULTS AND DISCUSSION

Analysis of the relationship between time and temperature

Analysis of self-heating characteristics in methane emissions formation is largely influenced by the stages involved in the process. The initial stage of self-heating includes minor changes in chemistry and physical alterations, followed by chemical changes as the coal, air, and heat interact, leading to a gradual increase in temperature due to oxidation reactions occurring in adiabatic conditions. The self-heating process in coal, particularly the physical aspects, is significantly determined by temperature and time variables. This physical process is preceded by an incubation stage that takes place at temperatures ranging from 20–40 °C, prior to the self-heating stage that occurs between 40–70 °C [Booth et al., 2020]. The air temperature around the mine at the research site reaches 30 °C in summer, while during the rainy season, the temperature can drop to around 20 °C. This temperature significantly influences the incubation stage. The air temperature around the research site in the stockpile and samples KAI-1 – KAI-7 recorded 30 °C during the measurement period, which is indicative of summer. The incubation stage for samples KAI-1 – KAI-7 is challenging to forecast since this process had already taken place. Consequently, this study focuses solely on examining the characteristics of self-heating that occur by utilizing Pearson correlation analysis and linear regression for each hotspot. The field data concerning temperature, time, methane emissions, and the latent stage of self-heating for samples KAI-1 – KAI-7 can be referenced in Table 1.

Table 1 shows that the latent stage of self-heating at the site can be divided into two categories: (1) the traditional latent stage occurring in the temperature range of 43.98–54.19 °C associated with hotspots KAI-5, KAI-1, KAI-7, KAI-6, and KAI-2, and (2) the preparation stage taking place in the temperature range of 58.84–61.27 °C with hotspots KAI-3 and KAI-4. In the traditional latent stage, there are physical changes along with minor chemical changes, while in the preparation stage, chemical changes occur along with an increase in temperature and duration that trigger the production of methane emissions. Figure 1 illustrates a linear correlation between temperature and self-heating time at each hotspot in the research area, showcasing a very strong correlation coefficient (r) of 0.9820.

Figure 1 illustrates the relationship pattern during the latent stage of self-heating, showing a linear regression trend that continues to advance into the next stage, which is the accumulation stage within the temperature range of 70–90 °C, marking the self-combustion stage, and beyond [Lei et al., 2023]. Field observations clearly indicate that the hotspots detected are still in the latent stage characterized by self-heating, as evidenced by the presence of smoke but no fire (Figure 2). The oxidation process occurring between the coal, oxygen, and heat in the conventional latent stage at the hotspots takes place at a relatively slow rate, within the temperature range of 43.98–54.19 °C over 14 minutes. The temperature flux during the traditional latent stage observed in the field is recorded at 0.736 °C/minute, equating to 44.14 °C/hour. Conversely, the preparation stage occurs within the temperature range of 58.84–61.27 °C over 3 minutes. The temperature flux during this preparation stage is 0.153 °C/minute, which translates to 9.20 °C/hour.

Table 1. Data on temperature, time, and methane gas emissions

Sample	Temperature (°C)	Time (minute)	Methane emissions (ppm)	Latent stage
KAI-1	46.10	36	7715	Traditional latent
KAI-2	54.19	46	17319	Traditional latent
KAI-3	58.84	49	17408	Preparation
KAI-4	61.27	52	20575	Preparation
KAI-5	43.98	32	3192	Traditional latent
KAI-6	51.80	40	16601	Traditional latent
KAI-7	48.10	37	14050	Traditional latent

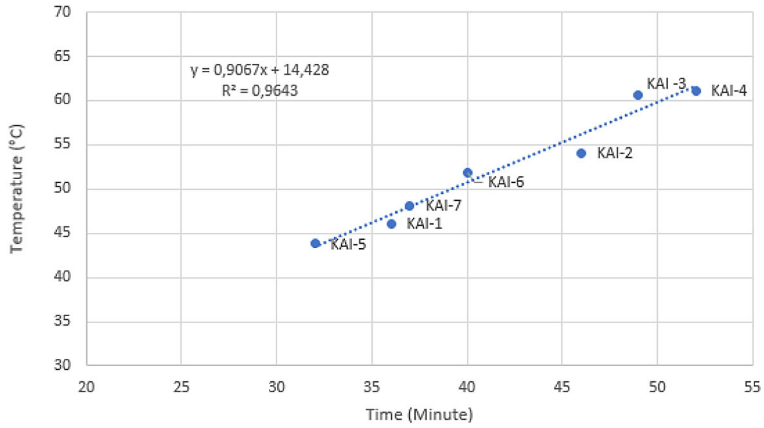

Figure 1. The relationship between time and temperature during the latent stage of the self-heating process

Figure 2. Hotspots in self-heating generate smoke due to latent stage

Temperature flux during the conventional latent stage, measured at 44.14 °C/hour, must be monitored closely to prevent the onset of the preparation and self-combustion stages proactively. The self-heating process occurring in coal significantly impacts the environment, particularly by increasing greenhouse gas emissions like methane. The characteristics of self-heating observed in the field indicate a strong correlation between time and temperature rise throughout the coal oxidation process. These factors are heavily influenced by the calorific value, rank, moisture content, and organic sulfur content of the coal [Xi et al., 2022; Yusuf, 2023; Nursanto et al., 2024]. The calorific value and rank of the coal at the research site reveal it to be medium-calorific coal, classified as sub-bituminous C, which is prone to self-heating.

Analysis of the relationship between temperature and time on methane emissions

The temperature flux that occurs over time during the self-heating of coal produces greenhouse gases, particularly methane emissions. The latent stage of self-heating observed in the field displays a similar pattern to earlier studies, where rising temperatures in conjunction with time yield methane emissions as illustrated in Figures 3 and 4. Figure 3 shows that during the traditional latent stage, a temperature rise between 43.98–54.19 °C results in methane emissions ranging from 3192–17319 ppm, with an emission flux of 1371.55 ppm/°C. In contrast, during the preparation stage, a temperature rise between 58.84–61.27 °C yields the emission flux approximately of 6884.78 ppm/°C. The rise in temperature in relation to methane emissions during self-heating is notably significant and intense, posing a substantial risk for global warming originating from the mining sector. This pattern aligns with previous research findings, especially occurring during self-heating prior to self-combustion [Li et al., 2024; Liu et al., 2025]. Regulating temperatures to prevent self-heating and its subsequent stages is crucial and requires proactive measures.

Figure 4 illustrates a similar linear pattern between time and methane emissions, indicating a strong correlation between temperature and methane emissions production in the field [Ma et al., 2023]. The emissions flux during the traditional latent stage reaches 1009.07 ppm/minute or 60544.20 ppm/hour. Meanwhile, in the preparation stage, it rises to 1055.67 ppm/minute or 63340.00 ppm/hour. This emissions flux has a highly significant effect on the rise of greenhouse gases from the coal mining sector.

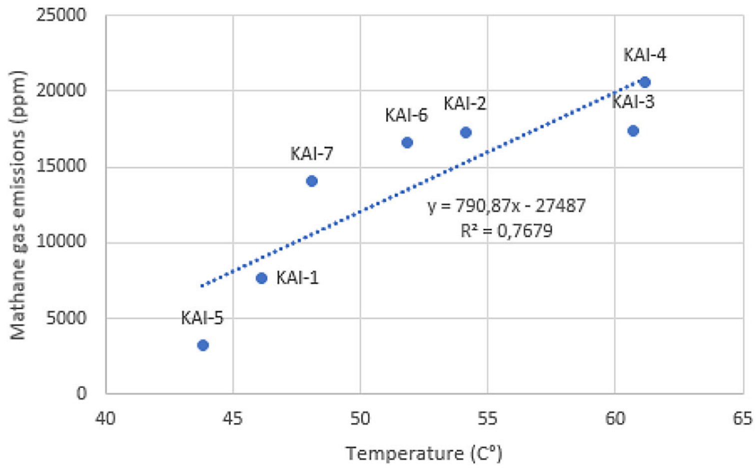

Figure 3. The relationship between temperature and methane emissions

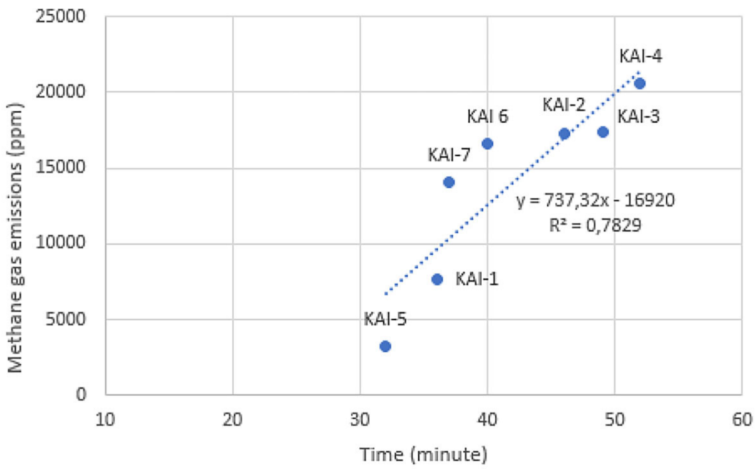

Figure 4. The relationship between time and methane emissions

Table 2 illustrates that self-heating falls within the latent stage with temperatures ranging from 40–70 °C, which can be divided into two categories: the traditional latent stage with an emission flux approximately of 1371.55 ppm/°C and 60,544.20 ppm/hour, and the preparation latent stage with an emission flux approximately of 6884.78 ppm/°C and 63,340.20 ppm/hour. This situation indicates that during the traditional latent stage, the increase in methane emissions occurs at a slower rate, whereas, in the preparation latent stage, the spike in methane emissions happens more rapidly. Therefore, it is crucial to implement preventive measures to avert self-heating at earlier stages, particularly within the traditional latent stage with temperature ranges of 40–55 °C.

The temperature ranges of 43.98–54.19 °C and 58.84–61.27 °C are categorized based on the research conducted by Zhu et al., 2018 and Booth et al., 2020, where the latent stage occurs within a temperature ranges of 40–70 °C. Previous studies on the spontaneous combustion stages of coal have identified two categories for the latent stage: the traditional latent stage, which falls between

Table 2. Analysis of temperature range, time range, methane gas emission range, and emission flux

Sample	Temperature range (°C)	Time range (minute)	Methane gas emissions range (ppm)	Emission flux		Standard temperature (°C)	Latent stage (40–70 °C)
				ppm/°C	ppm/jam		
KAI-5, KAI-1, KAI-7, KAI-6, KAI-2	43.98–54.19	32–46	3192–17319	1371.55	60544.20	40–55	Traditional latent
KAI-3, KAI-4	58.84–61.27	49–52	17408–20575	6884.78	63340.00	55–70	Preparation

40–55 °C, and the preparation stage ranging from 55–70 °C. Research on self-heating places the temperature interval of 43.98–54.19 °C in the traditional latent stage and 58.84–61.27 °C in the preparation stage. Consequently, physical changes along with minimal chemical changes take place during the traditional latent stage, while chemical alterations start during the preparation stage. The emissions flux during the preparation stage is reflected in the emission flux data, revealing values approximately of 6884.78 ppm/°C compared 1371.55 ppm/°C, and 63340.00 ppm/hour compared to 60,544.20 ppm/hour. The need to mitigate the emissions flux during the traditional latent stage, which records approximately 60,544.20 ppm/hour, can be addressed by preventing self-heating through effective stockpile management and the installation of temperature sensors on stockpiles. The escalation of self-heating in stockpiles leads to increased emissions not only of methane but also of carbon dioxide, both of which are greenhouse gases. Indonesia has established a policy to reduce greenhouse gas emissions by 31.89% below normal levels by the year 2030 [Al Ahmad et al., 2025]. Through better stockpile management in the future, it is hoped that a reduction in greenhouse gas emissions, particularly methane emissions, can be achieved.

The approach needed to lessen the occurrence of self-heating in stockpiles involves managing the stockpile, which includes not just controlling its size but also processing coal to avoid long-term storage issues. Additionally, it is essential to install temperature sensors on each stockpile to monitor and prevent excessive temperature rise and to avert self-heating events.

CONCLUSIONS

Characteristics of self-heating at the research site include a latent stage categorized into two stages: the traditional latent stage, which has a temperature range of 43.98–54.19 °C, and the preparation stage, with temperatures between 58.84–61.27 °C. Consequently, there are physical changes and minor chemical alterations during the traditional latent stage, while chemical changes occur during the preparation stage. The emissions flux during the preparation stage is evident from the emission flux data, which shows values of 6884.78 ppm/°C, compared to 1731.55 ppm/°C in the traditional latent stage, as well as 63,340.00 ppm/hour compared 60,544.20 ppm/hour. The emissions flux during the traditional latent stage, recorded at 60,544.20 ppm/hour, requires mitigation through proactive measures to prevent self-heating, which can be achieved via effective stockpile management and temperature sensor installation on the stockpile. The rise in self-heating concerning the stockpile includes not just methane emissions but also CO_2, both classified as greenhouse gases. Indonesia has implemented a policy to reduce greenhouse gas emissions by 31.89% from baseline conditions by the year 2030. With proper stockpile management in the future, it is hoped that reductions in greenhouse gas emissions, particularly methane emissions, can be accomplished.

Self-heating monitoring needs to be conducted regularly to ensure that the temperature of the stockpile does not rise dramatically, and for mining companies, stockpile management along with the installation of temperature sensors should be incorporated into company regulations for implementation. This study is limited to sub-bituminous coal C that is commonly found in Jambi Province, and it will be expanded to include lignite, sub-bituminous, bituminous, and anthracite coals, with a specific focus on examining the self-heating characteristics of each coal grade and observing the stockpile dimensions for each coal rank.

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