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Hoang Hung Thang

Quang Ninh University of
Industry, Quang Ninh,
Vietnam

Khuong Phuc Loi

Quang Ninh University of
Industry, Quang Ninh,
Vietnam

Evaluation of spontaneous combustion risks in Ha Lam anthracite seams using temperature-programmed oxidation and fire indices

Hoang Hung Thang and Khuong Phuc Loi

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Abstract

This study aims to evaluate the characteristics of gas emission and the evolution of fire indicators during the coal oxidation process through a heating experiment on the HLP-01 coal sample within a temperature range of 50 °C to 350 °C. The results indicate that as the temperature increases, the O₂ concentration gradually decreases, while the concentrations of CO₂, CO, H₂, and light hydrocarbons significantly increase. The sharp rise in CO levels when temperatures exceed 150 °C reflects the intensification of incomplete oxidation within the coal. Light hydrocarbons, including C₂H₄, C₂H₆, C₃H₆, and C₃H₈, also emerge prominently at high temperatures due to the thermal decomposition of the coal's organic structure. Fire indicators, including WP1, WP2, WP3, and the Graham Index, calculated from the emitted gas components, show an upward trend with temperature, reflecting the increasing oxidation intensity of the coal. The findings of this research provide a scientific foundation for utilizing indicator gases and fire indices in the monitoring and early warning of spontaneous combustion risks in coal mines.

Keywords: Spontaneous combustion, coal oxidation, indicator gases, fire indices, WP1, Graham index, Ha Lam coal mine

1. Introduction

In the mining industry, particularly in underground coal mining, spontaneous combustion (also known as the self-heating of coal) has long been considered one of the most severe and complex hazards^[1]. This phenomenon originates from the natural oxidation process of coal; when the heat generated from oxidation accumulates over time without being adequately dissipated, the temperature of the coal mass reaches a critical value, leading to self-ignition^[2]. Spontaneous combustion not only results in the loss of coal resources and economic damage but also directly threatens the safety of workers due to the emission of toxic gases, most notably carbon monoxide (CO)^[3, 4]. In Vietnam, alongside the roadmap to increase production for national energy security, mines under the Vietnam National Coal-Mineral Industries Holding Corporation Limited (TKV) are trending toward deeper extraction levels. Increasing mining depth implies facing higher strata pressure, elevated seam temperatures, and more complex ventilation conditions^[5]. Worldwide, spontaneous combustion is recognized as a primary cause of mine fires and catastrophic accidents^[2, 4]. According to numerous studies, the early detection of coal self-heating through the analysis of indicator gases produced during oxidation is one of the most effective methods for identifying spontaneous combustion risks at an early stage^[1, 6, 7]. Commonly used indicator gases for assessing coal self-heating include carbon monoxide (CO), carbon dioxide (CO₂), hydrogen (H₂), and light hydrocarbons such as ethylene (C₂H₄) and ethane (C₂H₆)^[8, 9]. The variation in the concentrations of these gases relative to temperature reflects the oxidation intensity of the coal and is widely applied in the monitoring and management of spontaneous combustion in underground coal mines^[10].

The phenomenon of coal spontaneous combustion is primarily explained by the slow oxidation of carbonaceous matter in coal when exposed to atmospheric oxygen. This oxidation is an exothermic reaction, with heat generation ranging from approximately 2.0 - 4.0 cal/ml of O₂ under standard conditions^[11]. When the generated heat accumulates within the coal mass and is not adequately dissipated into the surrounding environment, the coal

Corresponding Author:

Hoang Hung Thang

Quang Ninh University of
Industry, Quang Ninh,
Vietnam

temperature gradually rises, potentially leading to self-ignition ^[12]. In addition to the direct oxidation of coal, several other factors can influence heat generation within the coal mass, such as the presence of pyrite minerals, microbial activity, geothermal conditions, or water adsorption within the coal structure ^[13]. However, numerous studies have indicated that the oxidation of organic matter in coal remains the predominant mechanism leading to spontaneous combustion ^[1, 13, 14]. Globally, various methods have been proposed and applied to research the susceptibility of coal to self-ignition. These methods are typically based on laboratory-scale studies of coal oxidation and the analysis of gases evolved during the heating process. Countries have developed diverse evaluation methodologies, among which the most common are temperature-programmed heating of coal samples and gas composition analysis to identify indicator gases characteristic of the self-heating process ^[7, 15-17].

Currently, in Vietnam, research methodologies for assessing coal spontaneous combustion susceptibility are primarily referenced from Russian and Polish standards. The Russian method is widely adopted due to its relatively straightforward experimental procedures and minimal equipment requirements. However, when applied to Vietnamese coal seams, certain characteristic parameters such as moisture content, gas content, and ventilation conditions require calibration to ensure site-specific accuracy ^[18]. The coal seams in the Quang Ninh region predominantly consist of Anthracite, characterized by high carbon content, low volatile matter, and a relatively stable structure ^[19]. Nevertheless, under underground mining conditions with high ventilation rates and significant strata pressure, slow oxidation can still occur, leading to self-heating ^[20]. In contrast, the Polish method is based on laboratory-scale coal sample heating and the analysis of gases evolved during oxidation. This methodology has been extensively applied in studies evaluating coal spontaneous combustion susceptibility across European mines ^[21]. Based on the collected gas compositions, specific fire indices are calculated to assess the coal's sensitivity to self-ignition. This method is currently being utilized by the Mine Safety Center in numerous studies to evaluate the spontaneous combustion potential of coal seams in the Quang Ninh region ^[18].

According to reports from the Vietnam National Coal-Mineral Industries Holding Corporation Limited, underground mining operations in the Quang Ninh region have recorded numerous instances of spontaneous combustion hotspots in longwall faces and goaf areas, particularly in thick seams with complex ventilation conditions. Ha Lam Coal Joint Stock Company - Vinacomin is a key subsidiary of the coal industry, operating modern mechanized longwalls in Seam 7 and Seam 11, which contribute millions of tons to annual production. However, the mining history of Seams 7, 10, and 11 has documented several areas requiring the construction of isolation seals and the injection of Nitrogen gas to mitigate spontaneous heating hotspots. Notably, the implementation of fully mechanized longwall top-coal caving technology in these thick seams results in a significant volume of residual coal fines being left in the goaf. This creates a favorable environment for coal oxidation and subsequent heat accumulation ^[18].

Despite numerous studies on coal spontaneous combustion

susceptibility in the Quang Ninh region, in-depth research regarding indicator gases and fire indices specifically for the Anthracite coal at Ha Lam mine remains limited. Notably, under the implementation of fully mechanized longwall top-coal caving technology, the accumulation of coal fines in the goaf can significantly alter the characteristics of the oxidation process and gas evolution ^[18].

Therefore, the objective of this study is to determine the gas emission characteristics during the oxidation of Ha Lam Anthracite through laboratory-scale heating experiments, while simultaneously calculating specific fire indices to evaluate the spontaneous combustion susceptibility of the investigated coal seams. Furthermore, the obtained results will serve as a foundational database for establishing risk assessment criteria and supporting mine gas monitoring efforts in underground coal mines with similar geological conditions.

2. The study area

The study area is the Ha Lam Coal Mine, located in Ha Lam Ward, Ha Long City, Quang Ninh Province. Situated approximately 7 km northeast of Ha Long's city center and near National Highway 18A, the mine benefits from favorable coal transportation and access to regional technical infrastructure. Ha Lam Mine belongs to the Quang Ninh Coal Basin, one of Vietnam's largest and most significant coal basins, dating back to the Late Triassic and primarily containing high-rank anthracite coal. The mine covers a total area of approximately 8.64 km², defined within the HN-72 coordinate system (X: 2,318,000-2,321,850; Y: 407,400-410,750) and VN-2000 (X: 2,318,309.544-2,322,222.043; Y: 719,207.384-722,484.969). The boundaries are established under Decision 1122/QĐ-HĐQT dated May 16, 2008, by the Vietnam National Coal-Mineral Industries Holding Corporation: bordered by the Nui Beo mine to the east, Suoi Lai mine to the north, Binh Minh mine to the west, and National Highway 18A to the south. The research scope extends from the outcrop down to a depth of approximately -800 m.

Within the mine field, 12 coal seams with industrial value have been identified, notably Seams 14, 13, 11, 10, 9, 7, 6, 5, and 4. Reserves are primarily concentrated in the northern block of the F.L Fault within the Ha Lam anticlines and synclines. The mining area is heavily influenced by a tectonic fault system oriented NW-SE, where the F.L fault serves as the primary structural divide and governs the distribution of coal seams. Seams 7, 10, and 11 vary from medium to very thick, with relatively complex to complex structures, an average dip angle of 20 - 45°, and variability coefficients for thickness and dip angle generally below 35%. The coal seams are characterized by a high degree of metamorphism, low volatile matter, and high fixed carbon content, which are typical of anthracite in the Quang Ninh basin.

The engineering geological conditions are characterized by roof and floor rocks consisting mainly of siltstone, sandstone, and claystone, interbedded with weak carbonaceous clay layers. These conditions facilitate underground mechanized mining but also pose risks of floor heave and roof collapse. Furthermore, during underground operations, particularly in mechanized areas employing top-coal caving, a certain amount of coal fines can accumulate in the goaf, promoting slow oxidation and increasing the

risk of spontaneous combustion. The coal in this region, categorized as anthracite and semi-anthracite, is primarily used for energy production. Specifically, the Seam 11

mechanized longwall face is a key focus of this study. The geological structural characteristics of the study area are illustrated in Figure 1.

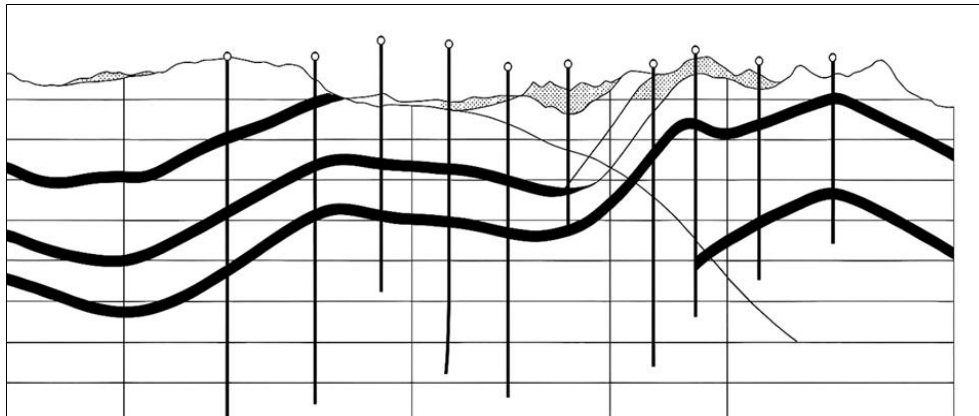


Fig 1: Geological cross-section of the borehole at the Seam 11 mechanized longwall face

3. Methodology

The sampling and determination of coal spontaneous combustion susceptibility were conducted in accordance with Decision No. 1583/QĐ-TKV (dated August 25, 2017) issued by the Vietnam National Coal-Mineral Industries Holding Corporation, regarding the regulations for sampling to determine the self-ignition levels of coal seams in underground mines. Coal samples were collected directly from the longwall faces of Seams 7, 10, and 11 at the Ha Lam mine. The samples are designated as HLP A-01, HLP A-02, HLP A-03, HLP A-04, and HLP A-05, corresponding to their respective sampling locations within the study area. These samples were gathered from the coal face and the top-coal area, strictly following the sampling protocols prescribed by TKV. After collection, the coal samples were crushed and screened to achieve the required particle size. The samples were then dried under laboratory conditions prior to testing. The experiments were performed using a coal sample heating system integrated with a gas composition analysis system, allowing for the monitoring of evolved gas variations during the coal oxidation process relative to temperature. The gases monitored during the experiment include CO, CO₂, CH₄, H₂, C₂H₄ and C₂H₆. Based on the gas components evolved during coal oxidation, specific indices for evaluating the oxidation degree and spontaneous combustion risk were determined. In this study, the Graham Index and WP indices were utilized to assess the progression of the coal oxidation process. The Graham Index is defined by the following formula:

$$\text{Graham} = \text{CO} / \text{O}_2 \quad (1)$$

Where:

- **CO:** Carbon monoxide concentration (% or ppm).
- **O₂:** Oxygen concentration (%).

The WP index (Wskaźnik Pożarowy) is determined using the following formulas:

$$\text{WP} = \text{CO} / \text{CO}_2 \quad (2)$$

Where:

- **CO:** Carbon monoxide concentration (% or ppm).
- **CO₂:** Carbon dioxide concentration (%).

The experiment was conducted using the Olpinski method, in which the coal sample is heated in an airflow. The temperature change of the sample over time is monitored to determine the self-ignition index (Sza) and the activation energy (Ea) of the coal oxidation process. During the experiment, the coal sample is subjected to a programmed heating rate within a temperature range of 30 °C to 350 °C at a constant rate. Air is continuously supplied to the reaction chamber to ensure a stable oxidation process. The experimental results are used to classify the coal's spontaneous combustion susceptibility according to the Polish standard PN-90/G-04558 and the assessment guidelines of the Vietnam National Coal-Mineral Industries Holding Corporation (TKV). Based on the determined self-ignition index (Sza) and activation energy (Ea), the spontaneous combustion susceptibility of the coal is classified according to the Polish standard PN-90/G-04558 (Table 1).

Table 1: Classification of coal based on spontaneous combustion susceptibility

Self-ignition index Sz ^a , [°C/min]	Activation energy E, [kJ/mol]	Coal self-ignition classification	Spontaneous combustion susceptibility level
≤ 80	> 67	I	Very low
	46 ÷ 67	II	Low
	< 46	III	Medium
80 ÷ 100	> 42		
100 ÷ 120	< 42	IV	High
	> 34		
	< 34	V	Very high

In addition to classifying the spontaneous combustion susceptibility, other parameters such as the oxidation heat of the coal sample, the incubation period (induction time), and the standard characteristic curves of the coal samples were also determined. These parameters serve as a foundational database for evaluating the specific self-heating characteristics of the coal within the study area.

4. Results and Discussion

4.1. Classification of coal spontaneous combustion susceptibility:

Based on the analysis of the self-ignition index (S_{za}) and activation energy (E_a) according to the Polish standard PN-90/G-04558, the results for coal samples collected from longwall faces in Seams 7, 10, and 11 at Ha Lam Coal JSC - Vinacomin indicate that characteristic parameters, such as moisture, volatile matter, ash content, and self-ignition indices vary within a relatively narrow range (Table 2). This minimal variation suggests that the coal composition across different sampling locations is

consistently similar, reflecting the relative homogeneity of the coal seams within the study area. The moisture content of the coal samples ranges from 2.36% to 4.34%, volatile matter from 6.85% to 8.30%, while the ash content varies between 3.37% and 12.38%. The self-ignition indices of the coal samples, determined through the parameters S_{za} and S_{za}' , yield values in the ranges of 12.16-14.69 °C/min and 2.78-3.52 °C/min, respectively, corresponding to an activation energy (E_a) of 55.42 to 61.70 kJ/mol. According to the spontaneous combustion susceptibility classification standards, all coal samples are categorized into Group II - Low susceptibility. These results indicate that the anthracite coal in the Ha Lam mine possesses relatively high thermal stability and a lower tendency for self-ignition compared to coal types with higher volatile matter content. This finding is consistent with previous studies on anthracite in the Quang Ninh region, where the spontaneous combustion potential is typically assessed as low due to low volatile content and a stable coal structure.

Table 2: Classification of spontaneous combustion susceptibility for coal samples in Seams 7, 10, and 11 at Ha Lam Mine - Vinacomin

Seam	Sampling location	Sample ID	Moisture W (%)	Volatile matter V _k (%)	Ash content A _k (%)	Self-ignition index		Activation energy E (kJ/mol)	Susceptibility Group	Spontaneous combustion level
						S_{za} °C/min	S_{za}' °C/min			
7	Mechanized longwall face 7-3.1, Seam 7	HLPA-01	2.43	6.85	10.28	12.16	2.78	61.70	II	Low
11	Mechanized longwall face 11-1.16	HLPA-02	3.94	8.30	11.03	13.13	3.48	55.42	II	Low
10	Longwall face10-2 - KT5	HLPA-03	2.36	8.24	4.27	12.69	2.99	60.46	II	Low
10	Longwall face10-3-T-13 - KT8	HLPA-04	3.06	7.35	3.37	14.69	3.52	59.65	II	Low
11	Longwall face11-3-T-14 - KT1	HLPA-05	4.34	7.89	12.38	13.70	3.24	60.26	II	Low

However, despite being classified as having low susceptibility to spontaneous combustion, the risk of endogenous fires persists under actual underground mining conditions. This risk is primarily attributed to residual coal remaining in the goaf, the accumulation of coal fines after extraction, the disruption of coal structures due to strata pressure, and prolonged exposure to oxygen within the ventilation environment. These factors can accelerate the low-temperature oxidation of coal, leading to the evolution of indicator gases such as CO and CO₂. Simultaneously, this process causes localized heat accumulation within the coal mass, creating favorable conditions for the development of spontaneous combustion.

4.2. Gas emission characteristics during the coal heating process

The heating process of sample HLP-01 from 50 °C to 350 °C shows a distinct variation in the composition of evolved gases (Table 3). Note that the total gas content may appear less than 100% because several components are represented in ppm (parts per million). The oxygen (O₂) concentration decreased sharply from approximately 19.96% to 1.65%, reflecting the consumption of oxygen during the coal oxidation reaction. Conversely, the carbon dioxide (CO₂) concentration increased steadily from 0.19% to 11.53%, as it is the primary product of the complete oxidation of carbon. The high CO₂ values recorded at elevated temperatures may be attributed to the accumulation of oxidation products within the reaction chamber and the relatively low gas flow rate during the experiment. A significant rise in carbon monoxide (CO) concentration was also recorded as temperature increased. At 50 °C, the CO concentration was only about 67 ppm, but it surged to 22,481 ppm at 350 °C. The rapid increase of CO between 150 °C and 250 °C indicates that the oxidation reaction has entered an intensive stage, characteristic of the coal's self-

heating process. Simultaneously, the hydrogen (H₂) concentration rose from 15.75 ppm to 1,167.88 ppm, reflecting the occurrence of thermal decomposition and cracking of the organic structures within the coal at high temperatures. Light hydrocarbons such as ethylene (C₂H₄), ethane (C₂H₆), propane (C₃H₈), and propylene (C₃H₆) also appeared and increased with temperature. Among these, ethylene (C₂H₄) and propylene (C₃H₆) are considered critical indicator gases for spontaneous combustion during the medium-temperature stage; specifically, C₂H₄ is often used as a characteristic indicator for the thermal decomposition phase of coal. The emergence of these gases from approximately 150-200 °C indicates that the thermal breakdown of the coal's organic structure has become significant.

These trends align with the general mechanism of the coal self-heating process, which consists of three main stages:

- 1. Low-temperature oxidation:** Characterized by oxygen consumption and CO₂ generation.
- 2. Temperature acceleration and CO evolution:** Reflecting the acceleration of the oxidation reaction.
- 3. Thermal decomposition and light hydrocarbon evolution:** Occurring once the temperature exceeds the critical threshold.

4.3. Trends of fire indices

Based on the results of the gas composition analysis, the fire indices WP₁-WP₄ and the Graham index were calculated to describe the progression of the coal self-heating process (Table 4). The WP₁ index exhibits a strong upward trend, rising from 380 at 50 °C to a peak of approximately 5,255 at 175 °C, before gradually decreasing as the temperature continues to rise. This trend is illustrated in Figure 2. The initial surge in WP₁ reflects the rapid increase in CO evolution during the intensive oxidation stage.

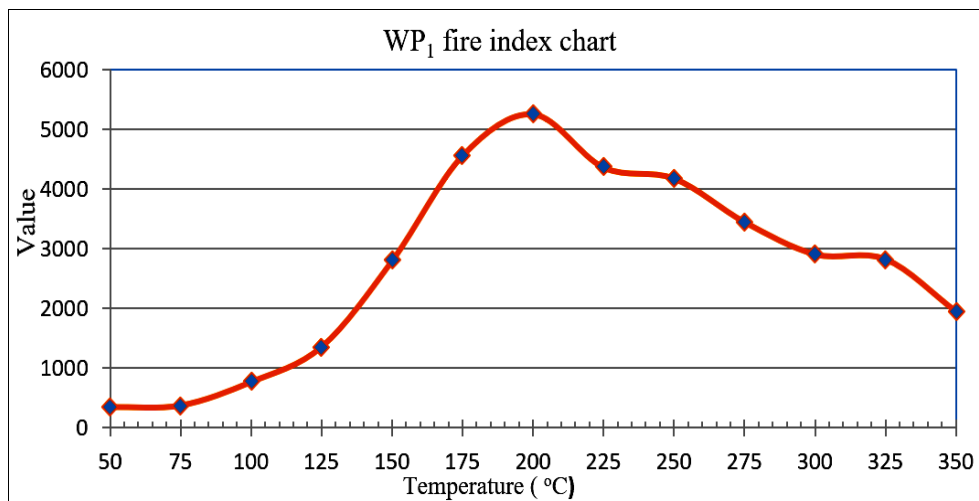


Fig 2: Variation of the WP₁ fire index for the coal sample at mechanized longwall face 7

The WP₂ index reflects the relationship between CO and CO₂. The WP₂ values increase progressively with temperature, reaching approximately 0.52 at 350 °C (Figure

3). This trend indicates an intensifying coal oxidation process, leading to a significant increase in CO production relative to CO₂ within the gas mixture.

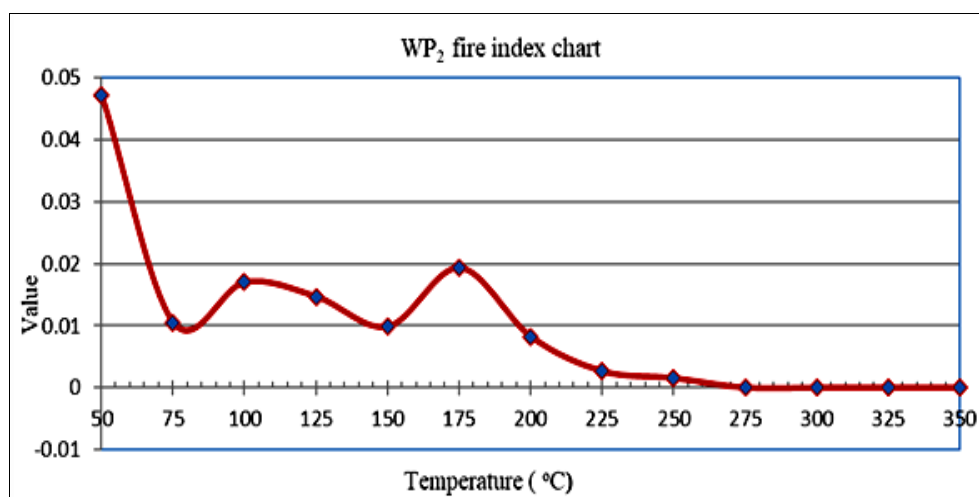


Fig 3: WP₂ fire index chart for the coal sample at mechanized longwall face 7-3.1

Meanwhile, the WP₃ (Figure 4) and WP₄ indices increase with temperature, reaching their peak values between 150 °C and 200 °C. This indicates a stage of rapid development in the self-heating process. These indices can serve as

characteristic parameters for the early detection of spontaneous combustion phenomena under actual mining conditions.

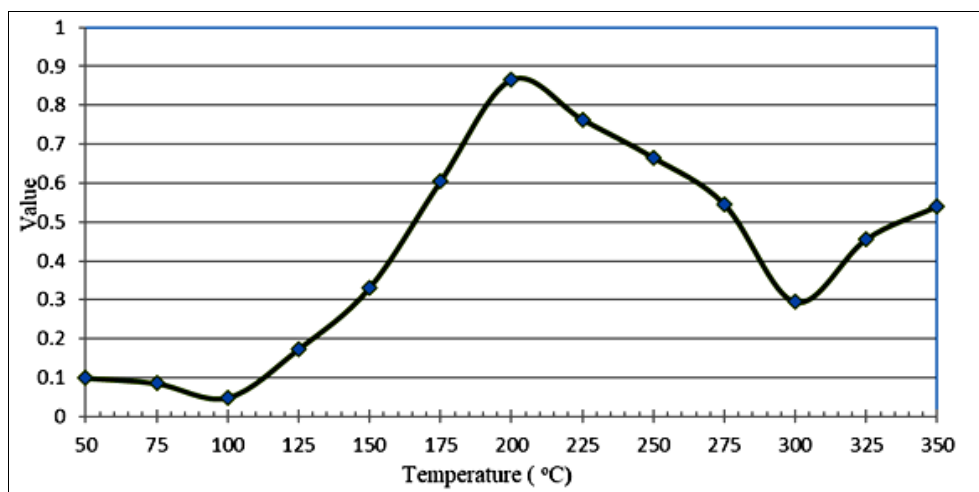


Fig 4: WP₃ fire index chart for the coal sample at mechanized longwall face 7-3.1

The Graham index (Graham's ratio) also exhibits a continuous upward trend with temperature, rising from 0.0062 at 50 °C to approximately 0.1136 at 325 °C, reflecting the increasing oxidation level of the coal. In actual mining conditions, Graham index values are significantly lower than laboratory results due to the dilution effect caused by the ventilation air stream. Nevertheless, the

rising trend of this index remains a crucial indicator for the early identification of spontaneous combustion. This trend is illustrated in Figure 5. The increase in the Graham index indicates a progressively intensifying oxidation stage and reflects the growing risk of endogenous fires under high-temperature conditions.

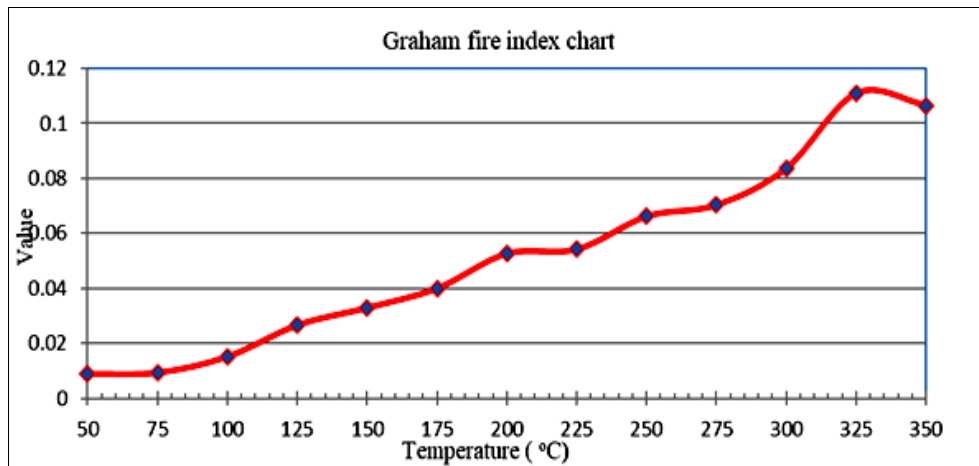


Fig 5: Graham's ratio chart for the coal sample at mechanized longwall face 7-3.1

Table 3: Analysis results of composition and concentration of evolved gases during the heating process of coal sample HLP-01 (Mechanized longwall face 7-3.1, Seam 7)

No.	Temperature (°C)	Gas concentration										
		H ₂ ppm	O ₂ %	N ₂ %	CO ₂ %	CO ppm	CH ₄ %	C ₂ H ₄ ppm	C ₂ H ₆ ppm	C ₂ H ₂ ppm	C ₃ H ₆ ppm	C ₃ H ₈ ppm
1	50	15.75	19.9596	78.1766	0.1906	67	0.4027	0.019	15.319	0.009	0.010	0.705
2	75	22.44	15.4875	80.3556	1.4241	541.70	1.4337	0.122	68.253	0.015	0.099	1,514
3	100	29.88	13.2468	82.8629	1.7041	1319.07	2.6467	0.084	145.986	0.029	0.030	2,551
4	125	39.57	10.6655	82.4324	2.1792	2973.27	4.5147	0.379	342.124	0.032	0.156	8,437
5	150	46.31	7.4792	87.0019	1.8257	5123.80	4.3805	0.605	363.898	0.018	0.232	10,099
6	175	67.47	5.7489	88.5352	1.5511	7083.02	3.5150	0.939	378.700	0.030	0.276	10,087
7	200	66.75	3.9831	88.4192	1.9466	10229.30	3.5762	1.686	478.309	0.016	0.435	14,881
8	225	100.81	2.9501	91.0978	2.6305	11475.40	2.3359	2.009	508.888	0.007	0.511	20,206
9	250	131.11	3.3831	90.0486	3.2419	13544.50	1.0025	2.159	409.128	0.005	0.483	19,759
10	275	125.75	3.0704	92.5106	4.3713	15071.40	0.4085	2.387	296.032	0.000	0.516	16,365
11	300	109.46	2.0822	91.5763	6.3845	18577.00	0.0138	1.883	75.023	0.000	0.379	6,899
12	325	264.18	2.2736	88.9145	8.3517	23609.60	0.0279	3.813	62.391	0.000	0.685	7,045
13	350	1167.88	1.6498	85.8698	11.5286	22481.10	0.1651	6.237	68.595	0.000	1.244	7,312

Table 4: Summary of fire index values for the mechanized longwall face 7-3.1, Seam 7

No.	Temperature	WP1	WP2	WP3	WP4	Graham
1	50	380.3806	0.0105	0.0857	0.0695	0.0062
2	75	774.0567	0.0170	0.0493	0.0176	0.0088
3	100	1364.3860	0.0147	0.1739	0.0716	0.0154
4	125	2806.4852	0.0099	0.3314	0.1271	0.0267
5	150	4566.4496	0.0193	0.6054	0.1779	0.0336
6	175	5254.9574	0.0082	0.8661	0.2235	0.0400
7	200	4362.4406	0.0027	0.7637	0.1943	0.0519
8	225	4177.9512	0.0015	0.6660	0.1490	0.0543
9	250	3447.8073	0.0000	0.5461	0.1180	0.0654
10	275	2909.7032	0.0000	0.2949	0.0594	0.0720
11	300	2826.9215	0.0000	0.4566	0.0820	0.0857
12	325	1950.0286	0.0000	0.5410	0.1079	0.1136
13	350	379.3706	0.0100	0.0866	0.002	0.1085

4.4. Significance of fire indices in assessing endogenous fire risks

The research results demonstrate that the fire indices WP₁, WP₂, WP₃, and the Graham index are all closely correlated with the coal heating temperature. As temperature rises,

oxidation and thermal decomposition reactions within the coal intensify, leading to an increased evolution of indicator gases such as CO, H₂, and light hydrocarbons. Under actual mining conditions, monitoring the variations of these gases in the mine atmosphere can facilitate the early detection of

the coal self-heating process. In particular, the WP₁ and Graham indices are considered critical criteria for assessing endogenous fire risks and implementing timely preventive measures. Thus, the study's findings not only provide insights into the gas emission characteristics during coal oxidation but also contribute to establishing a scientific basis for monitoring and warning of endogenous fires in coal mines. Furthermore, the results highlight that developing standard characteristic curves for indicator gases and fire indices is of paramount importance for the surveillance and early detection of endogenous fires. By comparing gas samples collected in the field with the standard characteristic curves established in the laboratory, the development stage of the self-heating process can be identified, and the internal temperature of the coal mass can be estimated. Implementing this method, combined with periodic gas monitoring systems at the longwall faces, allows for the early detection of abnormal signs. Consequently, preventive measures such as enhancing ventilation, injecting inert gases, or isolating hazardous areas can be deployed promptly. This approach significantly enhances the level of safety in underground mining operations at the Ha Lam mine.

5. Conclusion

This study evaluated the spontaneous combustion susceptibility of coal in Seams 7, 10, and 11 at Ha Lam Coal Joint Stock Company - Vinacomin by analyzing the self-ignition index, activation energy, gas emission characteristics during coal oxidation, and fire state assessment indices. The analysis of the self-ignition index (Sza) and activation energy (Ea) indicates that the coal samples from the investigated seams belong to Group II - Low susceptibility, according to the PN-90/G-04558 standard. Temperature-programmed oxidation experiments revealed that the concentrations of CO, CO₂, CH₄, and particularly ethylene (C₂H₄) progressively increased with temperature, reflecting an escalation in the intensity of coal oxidation and thermal decomposition. Fire indices, including Graham's ratio and WP indices, exhibited a sharp upward trend within the 200-300 °C range, signifying an increased risk of endogenous fire development during the high-temperature stage. These research findings provide a scientific basis for utilizing indicator gases and fire indices within mine gas monitoring systems to facilitate the early detection of endogenous fire risks. This is of significant importance for mine fire prevention and control, contributing to the enhancement of safety standards in underground coal mining at the Ha Lam mine. Future work should focus on more detailed investigations into the oxidation reaction kinetics of coal under actual mine ventilation conditions, as well as the integration of gas monitoring methods with predictive models for endogenous fire risk to improve the effectiveness of early warning systems in underground mining.

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