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The Relationship Between Spontaneous Combustion Duration And Temperature Rise Of Coal in Stockpile 1, Air Laya Mine, PT Bukit Asam Tbk

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Spontaneous combustion in coal stockpiles is a critical hazard in the mining industry. This study investigates the relationship between combustion duration and the increase in coal temperature at Stockpile 1 of the Air Laya Mine operated by PT Bukit Asam Tbk. Experimental simulations were conducted on four types of coal with calorific values of approximately 4,200; 4,900; 5,300; and 7,100 kcal/kg. Each coal type underwent a 6-hour heating process, with temperature data collected at 30-minute intervals using an infrared thermometer. The results reveal a strong linear correlation during the first 90 minutes of combustion. The coal with the lowest calorific value showed the highest and fastest temperature increase, peaking at 725°C, while coal with the highest calorific value peaked at only 544°C. The study concludes that low-rank coal is significantly more reactive and prone to spontaneous ignition, underscoring the importance of tailored management strategies.

Keywords: coal, spontaneous combustion, temperature rise, calorific value, oxidation, PT Bukit Asam

INTRODUCTION

Spontaneous combustion is a self-ignition phenomenon in coal stockpiles caused by exothermic oxidation reactions between coal and atmospheric oxygen. This thermal process progresses gradually, increasing in intensity as the heat accumulates, particularly under poor ventilation. The risk becomes acute when coal's volatile content and moisture are high, common in low-rank coals. Air Laya Mine, operated by PT Bukit Asam Tbk, has reported recurrent incidents of spontaneous combustion in Stockpile 1, motivating the need for deeper analysis.

Coal is a fossil fuel that contains various organic components which are highly reactive to oxidation when stored in bulk. As oxidation continues, it generates heat. When this heat cannot dissipate effectively due to inadequate ventilation or environmental conditions, the coal's temperature increases. If unchecked, this self-heating can escalate into spontaneous ignition, posing threats to operational safety, asset integrity, and the environment. The phenomenon is not only influenced by chemical properties like volatile matter, fixed carbon, and moisture, but also by physical storage conditions such as particle size, stockpile shape, and external temperature and humidity.

Globally, spontaneous combustion accounts for a significant portion of coal-related losses. The associated financial implications include loss of material, increased costs for fire suppression, production downtime, and potential regulatory fines. Understanding the dynamics of temperature evolution during combustion can offer crucial insights for preventive interventions.

This paper aims to explore the relationship between combustion duration and the rate of temperature increase in various coal grades. This understanding is crucial for developing risk mitigation strategies tailored to the thermal behavior of specific coal types.

METHOD

Experimental simulations were conducted using four coal types with different calorific values (±4,200; ±4,900; ±5,300; and ±7,100 kcal/kg). Each coal type was prepared in five 10 kg samples. The coal samples were first homogenized and screened using a 1-inch mesh sieve to ensure particle size consistency. Before initiating the spontaneous combustion process, the samples were weighed and placed into standardized steel drums that were open to atmospheric air but sheltered from wind and precipitation to simulate realistic stockpile conditions.

Kerosene (1 liter) was applied evenly to the surface of each coal sample to act as a combustion catalyst. The steel drums used in the test were customized to provide minimal but consistent ventilation from the bottom to mimic the limited oxygen flow typically observed in large coal piles. Combustion was initiated simultaneously across all samples to ensure uniform timing.

The experimental environment was monitored and maintained at consistent ambient conditions to minimize external variability. Throughout the 6-hour combustion process, temperature readings were taken at 30-minute intervals using the Benetech GM900 infrared thermometer. This thermometer was calibrated prior to testing to ensure accuracy, and readings were taken from multiple points on the coal surface to average out hot spots.

Data on temperature progression was then analyzed using Microsoft Excel and SPSS software. The focus of the analysis was the first 90 minutes of combustion, during which the temperature rise was most pronounced. A linear regression model was applied to quantify the relationship between time and temperature for each coal type. In addition to temperature, qualitative observations such as smoke emission, color change, and material degradation were also recorded to support the quantitative findings.

Table 1, Table 2, Table 3, and Table 4 provides the proximate and ultimate analysis for the four coal types used in the study.

Table 1. Proximate and ultimate analysis of coal with a calorific value of ±4,200 kcal/kg

Sample	TM (%Ar)	IM (%Adb)	Ash (%Adb)	Ash (%Ar)	VM (%Adb)	VM (%Ar)	FC (%Adb)	FC (%Ar)	TS (%Adb)	TS (%Ar)	GCV (%Adb)	GCV (%Ar)
1	36,40	15,10	3,80	2,85	40,50	30,34	40,70	30,49	0,10	0,07	5.624	4.213
2	36,70	15,20	3,60	2,69	41,20	30,75	40,00	29,86	0,10	0,07	5.612	4.189
3	35,80	13,30	4,40	3,26	42,40	31,40	39,90	29,55	0,13	0,10	5.702	4.222
4	37,60	15,40	3,80	2,80	41,90	30,90	38,90	28,69	0,10	0,07	5.551	4.094
5	36,70	16,60	1,70	1,29	41,90	31,80	39,80	30,21	0,15	0,11	5.614	4.261
x̄	**36,64**	**15,12**	**3,46**	**2,58**	**41,58**	**31,04**	**39,86**	**29,76**	**0,12**	**0,09**	**5.621**	**4.196**

Table 2. Proximate and ultimate analysis of coal with a calorific value of ±4,900 kcal/kg

Sample	TM (%Ar)	IM (%Adb)	Ash (%Adb)	Ash (%Ar)	VM (%Adb)	VM (%Ar)	FC (%Adb)	FC (%Ar)	TS (%Adb)	TS (%Ar)	GCV (%Adb)	GCV (%Ar)
1	28,70	15,20	3,00	2,52	40,40	33,97	41,40	34,81	0,27	0,23	5.791	4.869
2	29,10	15,20	2,10	1,76	40,60	33,95	42,10	35,20	0,13	0,11	5.822	4.868
3	31,00	16,70	1,00	0,83	39,70	32,88	42,60	35,29	0,10	0,08	5.876	4.867
4	28,90	15,00	1,60	1,34	40,30	33,71	43,10	36,05	0,11	0,09	5.892	4.928
5	29,50	14,60	7,70	6,36	41,60	34,34	42,10	34,75	0,13	0,11	5.963	4.923
x̄	**29,44**	**15,34**	**3,08**	**2,56**	**40,52**	**33,77**	**42,26**	**35,22**	**0,15**	**0,12**	**5.869**	**4.891**

Table 3. Proximate and ultimate analysis of coal with a calorific value of ±5,300 kcal/kg

Sample	TM (%Ar)	IM (%Adb)	Ash (%Adb)	Ash (%Ar)	VM (%Adb)	VM (%Ar)	FC (%Adb)	FC (%Ar)	TS (%Adb)	TS (%Ar)	GCV (%Adb)	GCV (%Ar)
1	25,40	9,90	1,40	1,16	42,30	35,02	46,40	38,42	0,23	0,19	6.342	5.251
2	25,50	10,40	1,50	1,25	42,10	35,01	46,00	38,25	0,25	0,21	6.353	5.282
3	24,90	10,60	1,50	1,26	42,40	35,62	45,50	38,22	0,36	0,30	6.339	5.325
4	26,80	11,90	1,60	1,33	41,80	34,73	44,70	37,14	0,23	0,19	6.402	5.319
5	26,80	12,40	1,10	0,92	41,20	34,43	45,30	37,85	0,31	0,26	6.395	5.344
x̄	**25,88**	**11,04**	**1,42**	**1,18**	**41,96**	**34,96**	**45,58**	**37,98**	**0,28**	**0,23**	**6.366**	**5.304**

Table 4. Proximate and ultimate analysis of coal with a calorific value of ±7,100 kcal/kg

Sample	TM (%Ar)	IM (%Adb)	Ash (%Adb)	Ash (%Ar)	VM (%Adb)	VM (%Ar)	FC (%Adb)	FC (%Ar)	TS (%Adb)	TS (%Ar)	GCV (%Adb)	GCV (%Ar)
1	6,90	4,20	5,20	5,05	40,40	39,26	50,20	48,79	0,65	0,63	7.371	7.163
2	6,10	0,80	8,30	7,86	32,30	30,57	58,60	55,47	0,51	0,48	7.556	7.152
3	8,40	2,10	4,50	4,21	38,50	36,02	54,90	51,37	1,12	1,05	7.639	7.147
4	6,40	1,40	6,30	5,98	36,90	35,03	55,40	52,59	1,49	1,41	7.534	7.152
5	6,20	1,40	6,90	6,56	36,70	34,91	55,00	52,32	1,48	1,41	7.533	7.166
x̄	**6,80**	**1,98**	**6,24**	**5,93**	**36,96**	**35,16**	**54,82**	**52,11**	**1,05**	**1,00**	**7.527**	**7.156**

RESULTS AND DISCUSSION

The average temperature data for each coal type showed a consistent trend of rapid increase during the first 90 minutes. The coal with 4,200 kcal/kg calorific value reached an average maximum temperature of 684.1°C at 90 minutes, peaking at 725°C. In contrast, the 7,100 kcal/kg coal peaked at just 544°C. This temperature difference reflects the intrinsic thermal behavior and reactivity of each coal grade.

To analyze the rate of temperature increase, the temperature-time relationship was modeled using linear regression for each coal type. The general form of the regression model is in Equation (1):

$$T(t) = a \times t + b \quad (1)$$

where: T(t) – the temperature (°C) at time t (minutes), a – is the slope of the regression line, representing the rate of temperature increase (°C/min), b – the y-intercept, representing the initial temperature.

The regression models for each coal type are as follows:

a. For 4,200 kcal/kg coal: $T(t) = 7.52 \cdot t + 30$
b. For 4,900 kcal/kg coal: $T(t) = 7.22 \cdot t + 29$
c. For 5,300 kcal/kg coal: $T(t) = 7.10 \cdot t + 70.04$
d. For 7,100 kcal/kg coal: $T(t) = 5.85 \cdot t + 29$

These models indicate that the 4,200 kcal/kg coal has the highest rate of temperature increase (7.52 °C/min), confirming its higher susceptibility to spontaneous combustion due to higher volatile content and reactivity. Meanwhile, the 7,100 kcal/kg coal has the lowest rate (5.85 °C/min), reflecting its higher thermal stability.

The coefficient of determination (R^2) values for these models exceeded 0.98 in all cases, demonstrating a very strong linear fit and confirming that temperature rise during the early stages of combustion is predominantly a function of time.

The detailed average temperature values at each 30-minute interval for all four coal types are presented in Table 5, Table 6, Table 7, and Table 8. These values provide a clear overview of the heating patterns and combustion behavior.

Table 5. The relationship between temperature and spontaneous combustion duration of coal with a calorific value of ±4,200 kcal/kg

Spontaneous Combustion Duration (minutes)	Temperature (°C)					
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
0	30,4	30,2	29,8	29,5	30,1	30,0
30	334,3	339,7	305,4	299,4	363,3	328,4
60	569,3	644,5	630,0	643,3	629,2	623,3
90	655,3	658,9	725,3	687,7	693,2	684,1
120	585,8	569,9	608,3	569,0	554,9	577,6
150	497,3	460,6	466,3	486,7	521,1	486,4
180	451,4	484,2	427,3	419,2	449,1	446,2
210	398,1	427,9	440,4	460,6	453,2	436,0
240	351,9	332,1	394,9	395,0	416,8	378,1
270	321,4	284,6	348,1	293,0	316,8	312,8
300	298,6	293,4	263,1	354,5	285,9	299,1
330	265,9	325,8	268,2	282,2	286,8	285,8
360	244,4	221,1	287,3	246,0	266,7	253,1

Table 6. The relationship between temperature and spontaneous combustion duration of coal with a calorific value of ±4,900 kcal/kg

Spontaneous Combustion Duration (minutes)	Temperature (°C)					
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
0	29,3	30,4	29,5	30,1	29,4	29,7
30	247,3	250,6	262,7	207,9	252,3	244,2
60	596,4	556,4	610,2	648,5	567,9	595,9
90	611,1	677,4	588,8	676,2	611,3	633,0
120	590,8	609,8	589,4	606,4	585,0	596,3
150	485,7	451,1	449,7	557,4	530,3	494,8
180	422,4	399,5	501,4	473,0	406,3	440,5
210	386,3	346,3	421,2	375,0	348,1	375,4
240	357,1	357,7	353,8	341,6	413,2	364,7
270	334,9	334,3	315,5	388,8	384,5	351,6
300	311,2	329,9	391,0	366,9	272,4	334,3
330	281,2	291,5	278,6	281,1	330,6	292,6
360	271,6	330,8	351,6	320,6	347,9	324,5

Table 7. The relationship between temperature and spontaneous combustion duration of coal with a calorific value of ±5,300 kcal/kg

Spontaneous Combustion Duration (minutes)	Temperature (°C)					
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
0	30,4	30,1	29,1	29,7	29,9	29,8
30	105,1	161,5	155,9	101,7	100,2	124,9
60	427,9	400,9	407,2	459,3	438,6	426,8
90	595,8	569,8	592,4	611,8	612,9	596,5
120	635,5	700,2	649,5	684,6	657,1	665,4
150	598,2	586,0	583,0	584,2	606,3	591,5
180	491,5	454,4	471,7	543,0	510,5	494,2

210	390,5	434,8	407,3	407,3	434,9	415,0
240	360,1	322,6	407,8	406,5	433,4	386,1
270	333,7	322,5	323,1	326,8	320,2	325,3
300	310,4	368,5	309,7	386,1	383,3	351,6
330	297,5	309,5	348,9	343,7	363,3	332,6
360	281,1	285,3	305,5	352,1	252,1	295,2

Table 8. The relationship between temperature and spontaneous combustion duration of coal with a calorific value of ±7,100 kcal/kg

Spontaneous Combustion Duration (minutes)	Temperature (°C)					
	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Average**
0	29,5	30,1	30,4	30,1	29,5	29,9
30	275,3	335,1	268,3	340,0	240,0	291,7
60	492,6	497,4	547,6	509,6	494,7	508,4
90	477,5	456,5	441,2	444,1	532,1	470,3
120	438,8	454,6	400,6	417,9	404,5	423,3
150	433,3	453,9	427,0	445,0	412,6	434,4
180	466,4	435,4	436,6	459,5	476,1	454,8
210	487,7	477,7	447,8	486,8	542,4	488,5
240	512,2	490,3	542,7	476,4	531,6	510,6
270	469,3	503,5	437,3	449,7	544,2	480,8
300	433,2	474,0	505,4	477,1	430,8	464,1
330	347,8	413,4	378,3	363,2	400,7	380,7
360	204,4	167,9	260,2	279,5	219,2	226,2

The graphical representation of these linear regressions is provided in Figure 1, Figure 2, Figure 3, and Figure 4, plotting temperature vs. time.

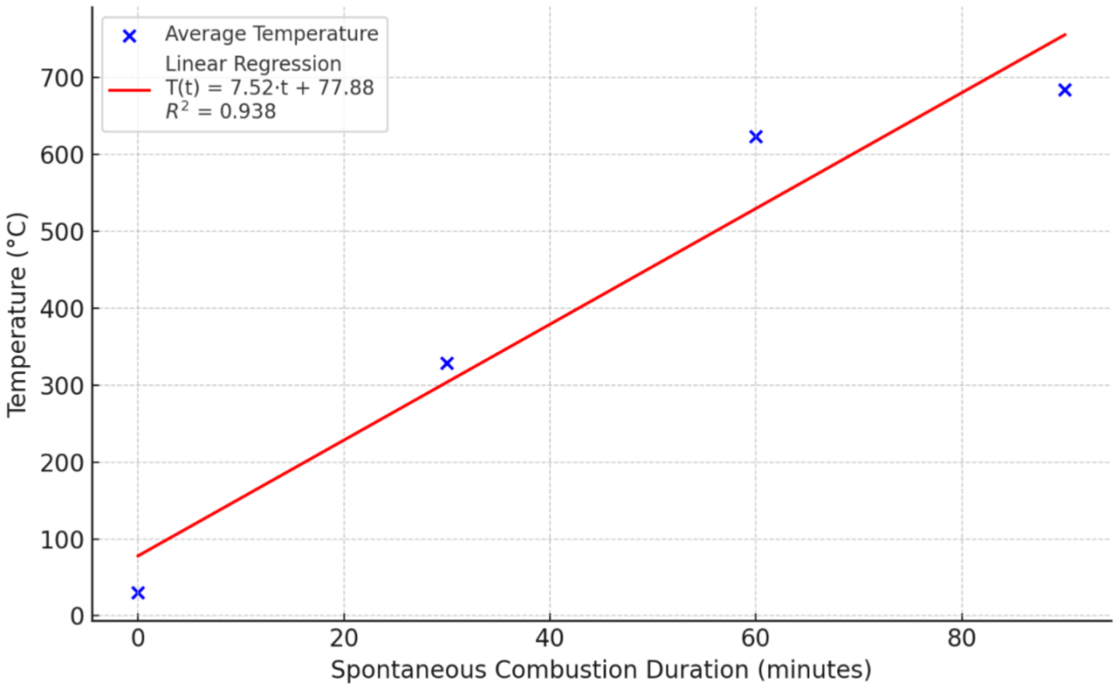

Figure 1. Linear model of temperature and spontaneous combustion duration of coal with a calorific value of ±4,200 kcal/kg

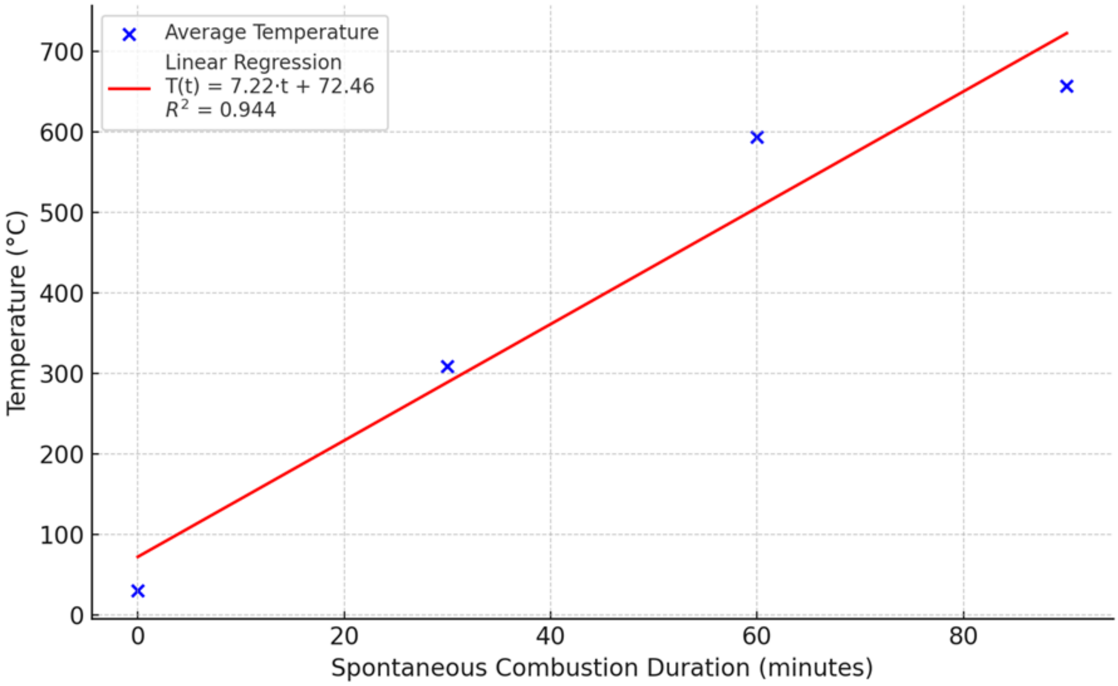

Figure 2. Linear model of temperature and spontaneous combustion duration of coal with a calorific value of ±4,900 kcal/kg

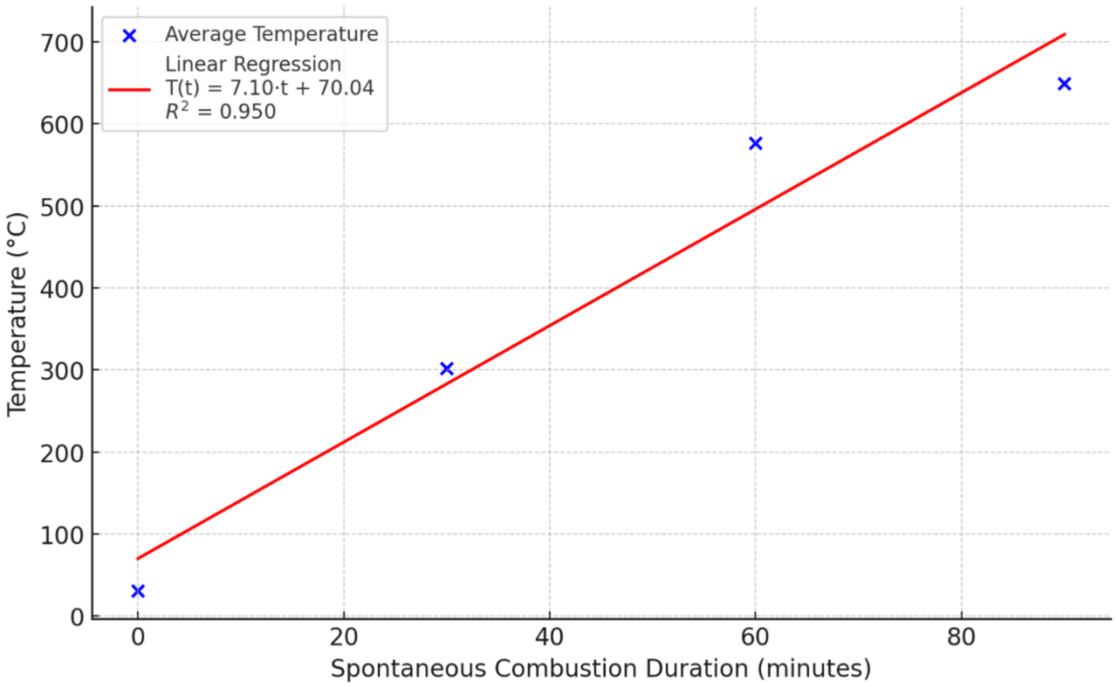

Figure 3. Linear model of temperature and spontaneous combustion duration of coal with a calorific value of ±5,300 kcal/kg

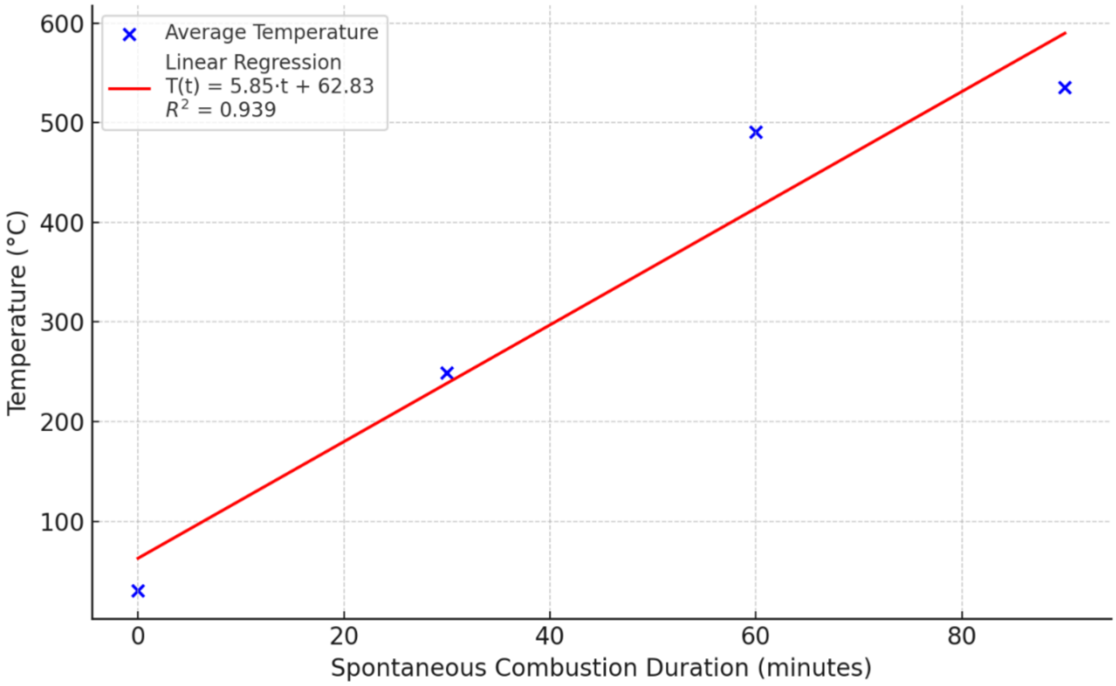

Figure 4. Linear model of temperature and spontaneous combustion duration of coal with a calorific value of ±7,100 kcal/kg

Qualitative observations during the combustion test supported the quantitative data. The 4,200 kcal/kg and 4,900 kcal/kg coals emitted thick smoke and showed early signs of glowing red-hot material, indicative of intense oxidation. Material color changed rapidly from black to gray-white ash. In contrast, the 7,100 kcal/kg coal exhibited delayed ignition, minimal smoke, and more stable thermal response.

In addition to linear trends, further analysis beyond the 90-minute mark showed a plateau in temperature for higher-rank coals. This suggests that the thermal equilibrium was reached faster in more stable coals, thereby lowering the overall combustion risk over time. On the contrary, low-rank coals continued to heat, peaking above 700°C and posing a greater hazard if left unmanaged.

These findings highlight the critical importance of proactive risk management. Storage of low-rank coal should be accompanied by continuous temperature monitoring systems and aeration control. Preventive steps like compacting, layering, and cover application may help reduce oxygen exposure. Conversely, high-rank coal can be stored with standard operational procedures due to its slower thermal response.

CONCLUSIONS

There is a strong linear relationship between combustion duration and temperature rise in coal stockpiles, particularly during the first 90 minutes of oxidation. This study demonstrates that lower-rank coals, due to their higher moisture and volatile matter content, are significantly more reactive and thus more susceptible to spontaneous combustion. These findings are not only consistent with previous studies but also reinforce the urgency for enhanced monitoring systems, especially when storing lower-grade coals in open stockpile environments.

The practical implications of this research are substantial. Mining operators, particularly in tropical climates like South Sumatra, must implement tailored risk mitigation strategies, including proper ventilation, periodic rotation of stockpile material, and possibly pre-treatment or blending of coals to stabilize thermal behavior. The regression models presented can also serve as predictive tools to anticipate combustion behavior, allowing for data-driven decisions in coal storage management.

Furthermore, this research highlights the value of integrating both quantitative (temperature data, regression analysis) and qualitative (visual combustion effects, smoke, ash color) indicators when assessing spontaneous combustion potential. It suggests that a multi-faceted monitoring system combining thermal sensors with visual inspections could offer a more comprehensive early-warning framework.

For future studies, longer combustion durations and additional coal properties—such as ash composition, porosity, and particle size distribution—should be considered to expand the understanding of thermal dynamics. Comparative studies between different stockpile designs or storage methods may also reveal structural factors that exacerbate or mitigate spontaneous combustion risks.

In conclusion, managing the spontaneous combustion of coal is not merely a matter of reactive suppression but of proactive prevention. The findings of this study emphasize the need for continuous thermal surveillance and customized handling protocols tailored to coal rank, ensuring both operational safety and economic efficiency.

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