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The Influence of the Sample Preparation on the Result of Coal Propensity to Spontaneous Combustion in the High-temperature Adiabatic Method

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Abstract. The liability of coal to spontaneous combustion is the principal cause of mine fires. Spontaneous combustion is one of the main threats in Polish and Vietnamese coal mines. The article presents an analysis of the spontaneous combustion of coal in mines of both countries. It is related to the natural prone of coal to spontaneous heating and consequently to its self-ignition. Despite the relevant recognition of the methods of preventing this threat, in mines, spontaneous combustion occurs during the exploitation of coal seams with low and very high self-ignition tendency. Apart from the technical factors related to the design of coal seam mining, the properties of coal have a significant impact on the occurrence of spontaneous combustion. Their correct recognition is essential to the precautions against spontaneous combustion for minimalizing the risk of a mine fire. Therefore, it is necessary to study the factors influencing the propensity of coal to spontaneous heating. A review of the methods used to determine the propensity of coal to spontaneous combustion is presented in the article. Based on the high-temperature method of determining the propensity of coals to spontaneous combustion, the influence of selected factors related to samples' preparation for testing on the determination result was investigated. The influence of the fractional decomposition and the moisture content in the prepared samples on the determination result was demonstrated. The presented research results may improve research procedures for determining the propensity of coal to spontaneous combustion.

Keywords: Spontaneous combustion of coal, Propensity to spontaneous combustion, High-temperature method

1. Introduction

Coal is still an essential source of energy for human life. However, people are exposed to many dangerous threats during the coal mining process. One of such threats is the spontaneous combustion of coal. The occurring spontaneous fires cause damage to the health and life of people working in mines and mainly cause significant economic losses. However, spontaneous fire prevention is a complex problem even in countries with world-leading modern mining industries due to coal's natural tendency to self-heating and self-ignition. Generally, there is a view that spontaneous combustion propensity is related to the rank of coal, i.e., the lower the coal rank, the more liability to spontaneous combustion. However, many factors make this propensity ambiguous. Apart from geological and mining factors, other factors affect the spontaneous combustion process related to coal properties. These include, for example, the heat of wetting, the temperature of the coal particles, the oxygen content of coal and coal particles. These factors are investigated while measuring the coal seam's liability to spontaneous combustion in a laboratory. Knowledge of the influence of these factors on the phenomenon's course can improve laboratory tests methods.

One such factor is the size of the coal particles, which is essential in many measurement techniques. There are known studies that use thermal analysis techniques to investigate the relationship between the thermal and fire properties of coal and particle size. On the base of coal samples with grain sizes < 20 µm, 50 µm, 100 µm, and 125 µm Morgan has indicated that the particle size decreases when the coal combustion reaction increases [1].

Yu et al. [2] showed, on samples of Chinese bituminous coal with particle sizes < 63 µm, 63-100 µm, 100-200 µm, and 200-400 µm, that when the particle size decreases, the petrographic composition of the coal sample changes, i.e. primarily vitrinite, the amount of volatile substances, the content of carbon and inert gas is reduced. Samples with smaller particle sizes have better oxygen absorption due to the increase in the sample particles' surface area. The combustion rate of samples is faster for a small particle size than that of samples with a larger particle size [2].

Prepared for laboratory testing samples with pulverised coal have different water absorption capacities.

If pellets (tablets) are prepared from dust samples, a fixed water content, called process water, is used. The samples might have higher external moisture content than raw coal. The influence of coal moisture on the heating and combustion of coal was demonstrated in Beamish's research using the Australian method [3, 4]. It is also an adiabatic method that determines the degree of coal self-ignition on the basis of the heating rate R70. The test results showed that coal samples with lower moisture content had a shorter temperature increase than coal samples with higher moisture content [4]. Coal samples from the same coal seam with different moisture content give different R70 results. It also means that the humidity changes the test results [4, 5].

Therefore, when preparing coal samples using the Olpiński method, in addition to ensuring the correct mixing ratio of water and coal in the amount of 0.4 ml per 2 g of coal, coal samples should be stored in a desiccator during the test to prevent the effect of water evaporation from the sample.

Zhai et al. [6] indicated the susceptibility of water soaked-dried coal samples on spontaneous heating and self-combustion process based on the difference in samples' thermal properties before and after the soaking process. Authors proved that water soaked-dried bituminous coal is more prone to self-heating, resulting in an increase in the rate of coal-oxygen compound reactions and a significantly increased risk of spontaneous combustion. In fact, this thesis is the implication for further research in self-heating of water soaked-dried coal samples [6].

The size of coal particles is a crucial factor that affects real spontaneous combustion behaviour and thus is a primary factor in the assessment of mine fire.

Even though particle size's influence on the course of the coal spontaneous combustion process has been proven, there is little data on the justification of selecting the fractional range of particles in the research procedures. The following part of the article discusses various methods to measure the coal seam's liability to spontaneous combustion against the background of spontaneous fires in Polish and Vietnamese coal mines. For the method used in Polish and Vietnamese coal mining, the influence of particle size on the course of spontaneous combustion was presented using the results of coal tests from three different coking coal seams.

2. Spontaneous fires in Polish and Vietnamese Mines

Poland is one of the countries with a long mining history, especially with the leading technology of mining sciences globally. Polish hard coal deposits belong to the Carboniferous EuroAmerican coal province. They occur in three basins, but coal exploitation continues in the Upper Silesian Coal Basin (USCB) and the Lublin Coal Basin (LCB). Based on the International Classification of Coal, the type of coal in Polish coal basins is bituminous coal. According to International Energy Agency (IEA), there are types of coal in the USCB, steam coal, coking coal and sometimes anthracite. In the LCB, mainly steam coal and coking coal occur.

In Vietnam, coal comes in many types, such as Lignite, Subbituminous, Bituminous, and Anthracite, found in 2 major coal basins, namely Quang Ninh and Song Hong. Anthracite is close to the surface in Vietnam, and Lignite, Subbituminous, and Bituminous are less than 2.5 km from the surface, so now anthracite is mined, mainly in mountainous and hilly areas in the Quang Ninh region. This coal's ash content is 9.73-23.64%, and sulfur 0.29-0.36% [7]. Coal is under extraction using opencast and underground methods. Before 2010, opencast coal mining accounted for 60-80% of Vietnam's total coal production. However, over time, coal mining began to be carried out from greater depths, and the opencast method ceased to be effective. Opencast mines gradually cease to operate and switch to underground mining. Since then, more attention has been paid to underground coal mining. For this reason, spontaneous combustion of coal is increasingly occurring in Vietnam's underground coal mines.

The fire index (W), representing the number of fires per 1 million tons of coal extracted annually, will be provided to illustrate the impact of the intensity of mining activities on mine fire frequency. In the 1950s, in the Polish mining industry, it was within the range of W=3.74-5.72 [8]. More and more research projects, new or improving detection methods of spontaneous combustion of coal and fire prevention, were conducted and tested in connection with science and technology development. As a result, the number of coal fires was significantly reduced, and from the second half of the 1990s, the number of coal fires did not exceed 10 per year, and the index W did not exceed the value of 0.07. In the last decade, however, there was an increase in coal fires (see Tab. 1). However, the fire index reached the value of 0.013 in the years 2018-2019, which indicates an increase in the risk in Polish coal mines. The improvement in fire safety should be noted in 2020 as the fire index fell to 0.04.

Tab. 1. Number of coal fires and fire index in Polish and Vietnamese underground coal mines in the years 2004-2020, according to [7, 9, 10].

State of fires	Year																
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Poland																	
Number of coal fire due to spontaneous combustion	5	8	2	4	5	10	9	6	3	5	1	5	7	9	8	11	2
Fire Index W, 1/mln tones	0.05	0.087	0.02	0.05	0.06	0.13	0.12	0.08	0.04	0.07	0.01	0.07	0.1	0.14	0.13	0.13	0.04
Vietnam																	
Number of coal fire due to spontaneous combustion	1	2	0	2	2	1	0	2	2	1	0	0	0	6	0	3	-
Fire Index W, 1/mln tones	0.11	0.09	0	0.09	0,09	0.014	0	0.09	0.1	0.05	0	0	0	0.27	0	0.13	-

Recording fires in Vietnam did not start until 2004, as there had been a few fires before, but they were considered open fires in mine excavations as it was believed that anthracite was a hard or incapable coal to ignite. From 2004 to date, the total number of fires due to coal's spontaneous combustion is 21 occurred in 7 of 14th underground mines; of which: "Hong Thai" coal mine: 5 cases, "Coal Enterprise 91": 4 cases; "Khanh Hoa Mine": 6 cases, "Mao Khe Mine" 1 fire, "Ha Lam Mine" 2 cases, "Uong Bi": 2 cases; "Thong Nhat": 1 case. The number of fires per year, and the fire index are presented in Table 1.

It is necessary to know the propensity of various types of coal to spontaneous combustion to improve safety and develop the most effective prevention of coal fires. In the following part, the methods of testing the propensity of coals to spontaneous combustion and the conditions of factors influencing the results of one of the methods will be presented.

3. Materials and Methods

Many factors influence the process of coal self-ignition. These are mainly mining and geological factors related to the method of selecting the deposit. Above all, however, the propensity of coal to self-ignition should be emphasized. This tendency depends on the properties of coal, such as the coal metamorphism, the petrographic composition of the coal, moisture and gas content adsorbed on the carbon surface, and the particle size of the coal.

The classic division of the spontaneous combustion process is related to the three stages: the incubation stage, the self-heating stage, and the combustion stage. However, many authors of the investigation on spontaneous combustion suggest that this process should be divided into more stages [11, 12, 13]. Regardless of that, each stage is characterized, among other things, by variations in temperature and exhaust gas concentrations.

In the first stage of spontaneous coal combustion, the physical absorption between oxygen and coal takes place, releasing a small amount of heat and unstable oxides or oxygen-containing free radicals. Reactive sites, which adsorb oxygen, are responsible for this behavior. Subsequent chemical adsorption increases and heat release is higher than heat dissipation. There is an accumulation of heat and a slow increase in the coal temperature to the moment of rapid water evaporation. The external water of coal evaporates faster as the temperature rises, while the internal water does not evaporate yet. The water vapor can be carried away with the heat, but it can be partially absorbed by the coal pores, which trap heat, as shown by Beamish and Hamilton [4]. However, heat is still removed by the evaporation of moisture, and the self-heating of the coal is significantly delayed. However, more pore channels or fissures are created, thereby increasing the inner surface area for contact with oxygen.

As the coal's outer water is evaporated, the oxidation activation medium on the coal surface increases and the reaction becomes more intense. The internal water starts to evaporate, and the coal temperature stagnates to some extent due to trapping some of the heat for water evaporation. The heat demand associated with the evaporation of internal moisture is much greater than that of external moisture. This state depends on the moisture of the coal. Yoruk and Arisoy [14] developed and validated the new mathematical model based on data from incubation testing of raw coal and moisture removal rate data.

Water evaporation completion is determined by the minimum self-heating start temperature and is called the critical temperature or minimum self-heating or SHT temperature. Depending on the type and grade of coal, SHT ranges from 40°C to 140°C, as reported by Smith and Lazzara [15]. For Polish coals, it ranges from 70°C to 90°C.

Due to the complete evaporation of both the internal and external moisture, the further reaction between the carbon and the oxygen begins actively because the heat generated in this reaction is no longer used for evaporation moisture. Dried coal is more reactive than the original moist coal due to increasing the coal's pore area. During oxygen consumption, heat is released, and qualitative and quantitative changes in discharged gases are visible.

The temperature of the coal rises rapidly up to the critical temperature of coal ignition. If the oxygen supply is sufficient, flame combustion and smoke production occur. However, if the supply of oxygen is insufficient, smoldering will be formed in the coal sample. Generally, as the temperature increases, the coal's activated molecules will appear in higher numbers, and more oxygen will be needed. If the oxygen supply is insufficient, the coal sample will develop smoldering smoke without a flame. In general, when the activated molecules in the coal seam increase with increasing temperature, more oxygen will be required [11]. This process step is highly dependent on the quality of the coal.

When the coal temperature does not reach the critical temperature or after it is reached, changes in external conditions favoring heat dissipation occur, then the self-heating slowly turns into a cooling period, and further air supply to the heated coal causes it to smouldering. A similar phenomenon is observed in the case of oxidation of coals, which are not prone to spontaneous combustion, which quickly turns into a state of weathering. Weathered coal does not ignite spontaneously [16, 17, 18].

4. Methods for determining the liability of spontaneous coal combustion

Many techniques for predicting the spontaneous combustion of coal have been developed all over the world. In methods that have been developed to predict spontaneous combustion, different experimental procedures, both laboratory and field, are used.

In the Russian mining industry U index has been using. In this method, the amount of oxygen absorbed by individual coal samples over 24 hours is measured. The gases obtained in experimental conditions are quantified by evaluating the gas composition. Onifade and Genc [19] reported that the oxygen absorbed during testing is directly proportional to coal's spontaneous combustion liability.

The crossing point temperature methods (CPT) are used to categorize the spontaneous combustion liability of coal in Indian, Polish, Vietnamese, Turkish, and South African mines. These methods are often referred to as the ignobility method [3]. The propensity of coal towards spontaneous combustion is determined with respect to their ignition temperature. The temperature at which the increasing coal temperature is equal to the increasing to steady ambient temperature in the oven or chamber is called the crossing point temperature [3, 20, 21]. An example of one of the CPT-based methods is the method known as XPT [19].

In differential scanning calorimetry (DSC) the changes in energy inputs provided to a sample and a reference material with respect to temperature when these materials are kept at a constant temperature are determined [19]. In thermogravimetric analysis (TGA) the loss in weight of coal samples at variable temperatures due to self-heating is estimated. In this method, the mass of a sample is measured over time as the temperature changes. The TG curve is referred to as the differential thermogravimetric (DTG) curve and is the difference between the coal curve and the inert material curve.

In Australia, New Zealand, South Africa, UK and USA adiabatic calorimetric method are usually used. In this method, the rate of temperature increase, ignition temperature and the kinetic constant of coal are used to determine the liability of coal for spontaneous combustion [22].

In China, coal's propensity to spontaneous combustion is determined based on measurements of the amount of oxygen absorbed per unit mass of the coal sample, including the type of coal and sulphur content [23]. Coal propensity tests are also performed using the crossing point temperature method using the Temperature-Programmed System (TPS) [24]. The method is often referred to as the ignobility method [3]. The coal's propensity to spontaneous combustion (ISCP) was classified based on the R70 index, calculated based on the temperature rise time from 40 to 70°C in the Australian mining industry. The R70 index is proportional to the coal's spontaneous combustion capacity, which means that the higher the R70, the higher the coal's propensity to self-ignition. The R70 procedure involves drying a 150 g sample of crushed coal at 110°C under nitrogen for approximately 16 hours and served below 212 μm [25].

There are other methods for predicting the spontaneous combustion liability of coal, mentioned by Onifade and Genc [19, 26], such as average heating rate (AHR), Feng, Chakravorty and Cochrane (FCC) liability index, differential scanning calorimetry (DSC), differential thermal analysis (DTA), flammability temperature (FT), wet oxidation potential (WOP), X-ray diffractometer (XRD) used by [27], Wits-Ehac tests used to forecast the propensity of coal and coal-shale by [26, 28, 29, 30, 31, 32] and Wits-CT tests developed by Onifade et al. [26].

Both in Poland and Vietnam, the method known as the Olpiński index is widely used. The Science and Technology Institute in Vietnam launched on October 28, 2016 a laboratory for testing the propensity of spontaneous coal combustion. This method is known as the high-temperature method and is a variation of CPT methods. The propensity of coal to ignite is determined from the self-ignition index Sz^a and activation energy A. For this purpose, coal samples in the furnace are performed for two air temperatures maintained by non-linear heating by fixing the thermostat at a particular point near the coal sample.

The sample is mounted on a thermocouple recording the coal temperature changes over time with an interval of 1 s. Temperature changes are measured for two cycles of air temperatures, 190°C and 237°C, respectively. The sample temperature and air temperature changes with an accuracy of 0.1°C around the sample are recorded by thermocouples connected to a computer.

Two time-temperature curves for samples of the same coal are recorded to determine coal's spontaneous combustion liability. The curves are recorded in two ranges (Zhang, 2002):

1) for CPT of 190°C, the temperature of the coal sample is recorded in the temperature range of 200÷260°C;

2) for CPT of 237°C, the coal sample's temperature is recorded in the temperature range of 165-215°C.

The tangents to curves at the point of 237°C for the temperature range of 200-260°C and at the point of 190°C for the temperature range of 165-215°C are plotted, respectively.

Based on the tangent to the time-temperature curve at a point of 237°C, coal self-igniting index Sz^a (°C/min) is calculated according to the formula:

$$Sz^a = \frac{t_2 - t_1}{\tau_2 - \tau_1} \tag{1}$$

For the tangent to the time-temperature curve in ranges 165-215°C, the self-igniting index of coal $Sz^{a'}$ (°C/min) is calculated according to formula:

$$Sz^{a'} = \frac{t'_2 - t'_1}{\tau'_2 - \tau'_1} \tag{2}$$

where (τ_1, t_1), (τ_2, t_2) are the coordinates of any two sufficiently distant points lying on the tangent line to time-temperature curve in the range 200-260°C and (τ'_1, t'_1), (τ'_2, t'_2) are the coordinates of any two sufficiently distant points lying on the tangent line to time-temperature curve in the range 165-215°C.

The activation energy A, J/mol is determined from the dependence:

$$A = \frac{R \cdot (\ln Sz^{a} - \ln Sz^{a\prime})}{\frac{1}{T'} - \frac{1}{T}} \qquad (3)$$

where R is universal gas constant, T', T are absolute temperatures, 463.15 K and 510.15 K, respectively.

Depending on the Sz^a index's value and the activation energy A, the coal seam's liability to spontaneous combustion is divided into five groups, and, in principle, the higher the Sz^a index, the higher the liability is. Table 2 presents the criteria for the division into spontaneous combustion groups.

Tab. 2. Labiality of seam coal's spontaneous combustion in EPolish mines [33].

Sz^a index, °C/min	Activation Energy A, kJ/mol	Group of liability	Rank of liability to Spontaneous Combustion
Up to 80	Below 67	I	Very low liability to spontaneous combustion
	From 46 to 67	II	Low liability to spontaneous combustion
	Below 46	III	Medium liability to spontaneous combustion
Above 80 to 100	Above 42		
	Below or equal to 42	IV	High liability to spontaneous combustion
Above 100 to 120	Above 34		
	Below or equal to 34	V	Very high liability to spontaneous combustion
Above 120	Beyond the standardization		

According to this method, the sample is made of coal particles with a size in the range of 0.063-0.075 mm. However, very often, the results obtained from samples of the same coal are inconsistent. Therefore, it was decided to check how the spontaneous combustion process looks for other ranges of size particle fractions.

5. Experimental investigation

5.1 Coal samples preparation

Coal samples were collected from three different coal seams in Mine B, Uppers Silesian Coal Basin, Poland. After core samples being sealed and stored on-site, they were transported to the laboratory. After peeling off the surface oxide layer, the raw coal samples were crushed and ground to screen out coal powders. Part of the sample masses was transferred to proximate analysis in air-dry condition. Outcomes proximate analyses are presented in Table 3.

Tab. 3. Proximate analysis of tested coal samples.

Coal Seam No.	Symbol of samples	Proximate analysis, mass %				Density, kg/m^3	Gross calorific value, Q_{daf}, kJ/kg
		W_{ad}	V_{daf}	A_{ad}	S_{ad}		
401	P2	0.58	29.2	11.6	0.65	1.37	29856
364/2	P5	0.71	32.4	11.8	0.78	1.33	29494
405/1	P7	0.61	28.6	5.6	0.90	1.16	18450

The remaining sample weight was sieved into five particle size fractions, 0.075-0.125 mm, 0.063-

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0.075 mm, and below 0.063 mm, respectively. Then, each of the samples is separately mixed with demineralised water in the proportion of 0.4 ml of water per 2 g of coal. The sample is made at an ambient temperature of 20°C and relative humidity of 50%. The sample mixed in this way is formed in a cylinder-shaped die. The sample in the matrix is compacted with a press with a force of 2.28 kN. Finally, a compacted sample of cylinder shape with a diameter of 7.5 µm, a height of 9 µm, and a centre hole is obtained. Sample and furnace views are shown in Figures 1-2. For each particle size range, three samples were made and placed immediately in the desiccator. Then all samples were weighed on an analytical balance with an accuracy of 10^{-3} g. The results of the sample mass measurements are presented in Table 4.

Fig. 1. View of prepared coal sample mounted on a thermocouple prior to insertion into the furnace.

Fig. 2. View of furnace for Olpiński method.

Tab. 4. Results of the sample mass measurements.

Symbol of coal	Coal particle size ranges					
	< 0.063 mm		0.063-0.075 mm		0.075-0.125 mm	
	Symbol of particle fraction	Mass of coal sample, g	Symbol of particle fraction	Mass of coal sample, g	Symbol of particle fraction	Mass of coal sample, g
P3	A1	0.3085	B1	0.2630	C1	0.2622
	A2	0.2905	B2	0.3572	C2	0.2430
	A3	0.2659	B3	0.3538	C3	0.2366
	A4	0.3228	B4	0.3485	C4	0.2397
P5	A1	0.2583	B1	0.2856	C1	0.2718
	A2	0.2599	B2	0.3324	C2	0.2835
	A3	0.2571	B3	0.3110	C3	0.2878
	A4	0.2784	B4	0.3243	C4	0.2504
P7	A1	0.3217	B1	0.3554	C1	0.3062
	A2	0.2784	B2	0.3296	C2	0.3424
	A3	0.3202	B3	0.3834	C3	0.3410
	A4	0.3941	B4	0.3695	C4	0.3318

5.2 Methodology

To determine the effect of particle size distribution on the change of the sample temperature increase rate, the Olpiński method, which is used in Poland and Vietnam, was used. The two weighed samples were sequentially inserted into continuous mass airflow furnaces, matching the first crossing point temperatures 190°C and 237°C. For each sample, the course of the time-temperature curve was recorded. Next, both indices Sz^{a} and $Sz^{a'}$, as well as activation energy, were determined.In small surveying projects, rotary-wing UAVs such as DJI Phantom 3, or 4 professional are often utilized widely. In this work, the study sites are small so we use a phantom 4 professional to capture images. The Phantom 4 professional is a quadcopter drone with four powerful rotors (Fig. 2). Its airframe carries the GPS/IMU that enables it to have posture control, stop flight, and automatically take off and land with high stability [6]. The drone is capable of both manual flight mode using the controller and automatic flight mode using the Android or IOS smartphone applications. If you use the automatic mode, you can set the flight path, flight speed, flight altitude, shooting range and overlapping of the photographs, so you can take more aerial photographs. The drone is equipped with a 20 megapixel RGB camera with a focal length of 8.8 mm and sensor a size of 13.2 x 8.8 mm that allows high-resolution aerial photography [7].

6. Results and discussion

Figures 3-5 show the time-temperature curves of the investigated coals. The recording of the coal samples' temperature ended when the critical temperature of ignition of the sample was reached above each set crossing point temperature.

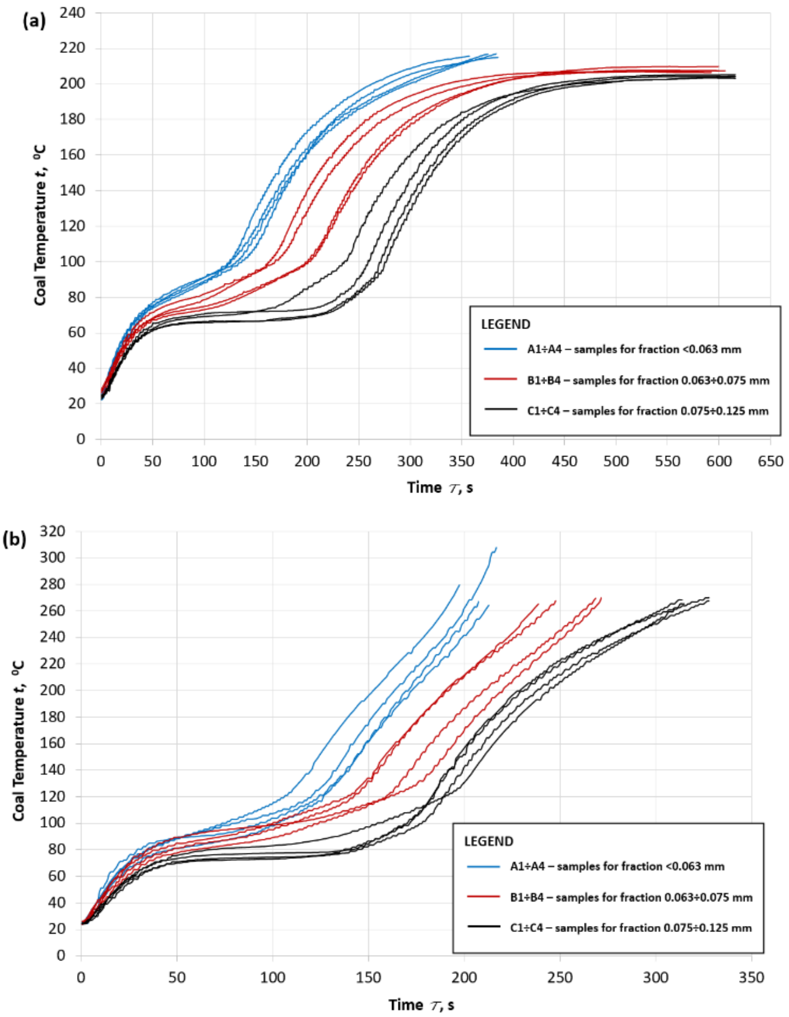

Fig. 3. Thermal curves of temperatures of coal samples P3 for different coal particle fractions, (a) for t_{CPT} = 190°C, (b) for t_{CPT} = 237°C.

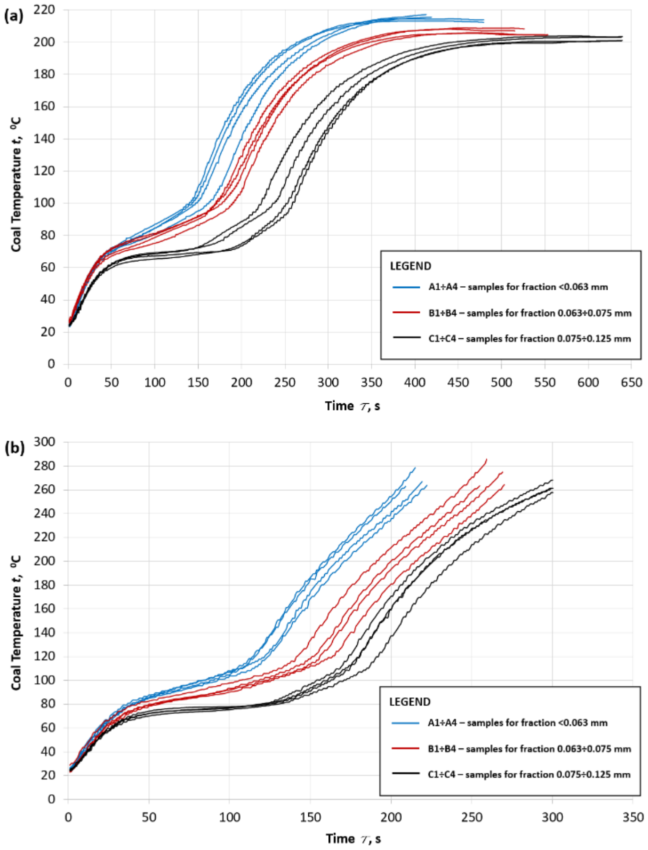

Fig. 4. Thermal curves of temperatures of coal samples P5
for different coal particle fractions, (a) for t_{CPT} = 190ºC, (b) for t_{CPT} = 237ºC.

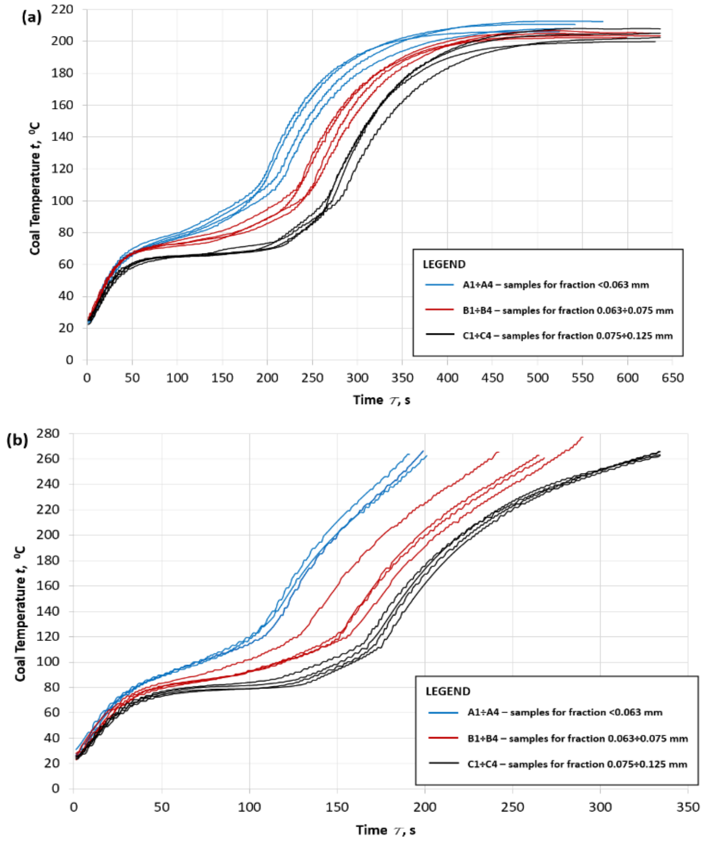

Fig. 5. Thermal curves of temperatures of coal samples P7
for different coal particle fractions, (a) for t_{CPT} = 190ºC, (b) for t_{CPT} = 237ºC.

The figures show that the minimum self-heating temperature (SHT) of the starting process for all tested samples is 90°C at a crossing point temperature (t_{CPT}) of 190°C. All samples reached SHT at the same time. The incubation period is strictly dependent on the type of coal and particle size in the sample agglomerate.

Under isothermal conditions of 237°C, the SHT value is no longer as unambiguous as in the case of t_{CPT} = 190°C. For samples with particle size 0.075-0.125 mm, it is clearly visible that SHT is 90°C, but with smaller particle sizes, the temperature increase is higher. The SHT ranges from 90°C to 120°C.

Table 5 shows the incubation period's average times to illustrate the effect of particle size distribution on water evaporation.

Tab. 5. Incubation period of tested coal samples.

Coal No.	Particle size range	Time of incubation period, s	
		For t_{CPT} = 190°C	For t_{CPT} = 237°C
P3	<0.063 mm	80	80
	0.063-0.075 mm	140	105
	0.075-0.125 mm	230	150
P5	<0.063 mm	100	80
	0.063-0.075 mm	140	105
	0.075-0.125 mm	260	150
P7	<0.063 mm	170	80
	0.063-0.075 mm	220	105
	0.075-0.125 mm	270	135

The evaporation period is much more visible at the crossing point temperature of 190°C than at 237°C. Figures 3a-5a show a more extended period of temperature stabilization for coal samples with larger particles (0.075-0.125 mm) than for samples with particles below 0.063 mm. For particles smaller than 0.063 mm, the incubation period is the shortest, and for particle size range 0.075-0.125 mm, the longest. It is natural that at 237°C, this time is shorter than at 190°C. It is the period of evaporation of moisture and steady temperature, which is visible at the temperature of 190°C. At 237°C, the temperature rise rate is already faster, but the rise is also linear (Figs. 3b-3c).

The changes in the temperature curve are due to the moisture removal rate. It may be due to the agglomeration of the dust particles in the cylindrical shape of the sample. The shape of the particle is a rational component of particle agglomeration. The tendency of coal dust to agglomerate increases with decreasing particle size.

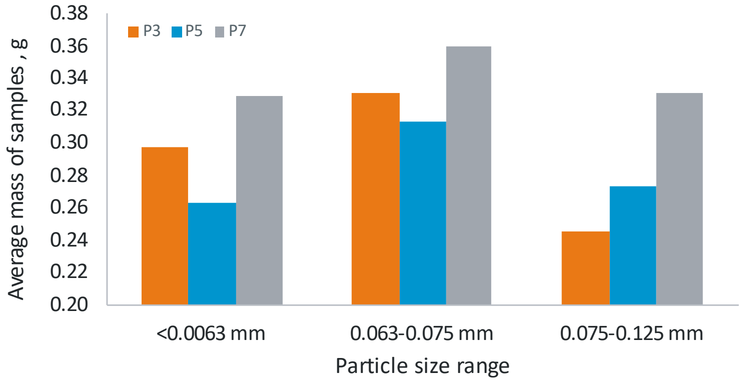

Fig. 6. Average mass of samples of coals P3, P5, P7 for the analysed particle size range.

It should be noted, however, that the samples were prepared with the same proportion of water. Also, the natural moisture content in all three coals was similar (Tab. 3). From Figure 6, it can be seen that the mass of the samples was variable. The highest mass could be expected with the largest particles, probably resulting from regularly shaped particles on the agglomeration, and yet the samples ranging from 0.063-0.075 mm had the highest mass. On the other hand, samples with sizes 0.075-0.125 mm had the lowest weight. Thus, it is not synonymous with increasing the regular particle size's size - the agglomeration causes more water absorption. Such studies should be repeated using other research methods.

The effect of the particle size distribution on the temperature increase rate Sz^a and the calculated activation temperature A was also checked, and the results are presented in Table 6.

Tab. 6. Incubation period of tested coal samples.

Coal Particles range	No.	τ_1, s	t_1„ °C	τ_2, s	t_2„ °C	Δt„ °C	$\Delta\tau$, s	Sz^a, °C/min	τ'_1, s	t'_1„ °C	τ'_2, s	t'_2„ °C	$\Delta t'$„ °C	$\Delta\tau'$, s	$Sz^{a'}$, °C/min	A, kJ/mol
P2 < 0,063 mm	1	164	200.3	199	257.2	56.9	35	98	190	166.6	349	215.0	48.4	159	18	70.4
	2	173	200.4	211	260.3	59.8	38	94	207	165.1	374	215.0	49.9	167	18	69.8
	3	170	200.0	204	259.4	59.2	34	105	203	165.9	364	214.7	48.8	161	18	73.5
	4	152	200.1	188	258.0	58.2	36	97	194	156.4	384	215.0	58.6	190	19	69.6
P2 0,063÷ 0,075 mm	1	221	201.5	266	259.3	57.3	45	76	261	157.4	479	207.0	49.6	219	14	72.6
	2	211	201.0	261	259.1	57.9	50	69	268	159.2	495	209.0	49.8	227	13	69.9
	3	193	200.9	242	259.7	58.5	49	72	230	155.6	431	205.1	49.4	201	15	66.4
	4	191	200.8	236	260.8	59.5	45	79	220	157.0	418	206.0	49.0	198	15	70.4
P2 0,075÷ 0,125 mm	1	230	201.2	306	260.1	58.4	76	46	310	155.3	557	205.0	49.7	247	12	56.3
	2	232	200.8	302	260.4	59.1	70	51	320	154.2	554	204.2	50.0	234	13	57.8
	3	239	201.0	314	259.1	58.1	75	46	327	154.7	562	203.0	48.3	235	12	55.8
	4	245	202.3	311	261.5	59.2	66	54	290	153.7	528	202.2	48.5	238	12	62.3
P5 < 0,063 mm	1	171	200.4	218	259.3	58.9	47	75	197	165.9	363	214.0	48.1	166	17	61.6
	2	161	200.8	205	257.3	56.5	44	77	199	163.2	380	213.0	49.8	181	16	64.8
	3	160	200.8	204	259.8	59.0	44	80	210	165.3	372	215.0	49.7	162	18	62.0
	4	166	200.1	214	259.6	59.5	48	74	225	166.6	398	215.0	48.4	173	17	62.6
P5 0,063÷ 0,075 mm	1	200	200.1	251	259.5	59.4	51	70	232	155.6	424	205.1	49.5	192	15	63.4
	2	206	201.1	258	259.7	58.6	52	68	245	156.6	455	205.8	49.2	210	14	66.0
	3	191	200.9	241	257.8	56.9	50	68	240	160.3	448	208.9	48.6	208	14	66.5
	4	215	200.3	266	258.7	58.4	51	69	228	158.9	419	208.1	49.2	191	15	62.7
P5 0,075÷ 0,125 mm	1	227	201.0	297	260.0	59.0	70	51	292	152.6	521	202.0	49.4	229	13	57.3
	2	221	201.6	288	259.6	58.0	67	52	277	153.2	513	203.0	49.8	236	13	59.3
	3	226	201.3	298	259.8	58.5	72	49	308	150.8	550	200.4	49.6	242	12	57.9
	4	239	200.8	302	259.2	58.4	63	56	302	149.9	537	199.4	49.5	235	13	62.3
P7 < 0,063 mm	1	150	200.1	194	258.8	58.7	44	80	243	161.4	415	209.0	47.6	172	17	66.2
	2	149	200.2	199	259.8	59.6	50	71	254	159.8	427	209.7	49.9	173	17	59.6
	3	143	200.4	187	257.9	57.5	44	78	231	155.4	409	205.1	49.7	178	17	64.9
	4	163	201.8	204	259.1	57.3	41	84	321	156.8	486	206.0	49.2	165	18	64.9
P7 0,063÷ 0,075 mm	1	197	200.5	261	259.0	58.5	64	55	286	151.7	494	201.6	49.9	208	14	56.2
	2	207	200.7	273	259.2	58.5	66	53	277	154.1	485	203.0	48.9	208	14	55.8
	3	200	200.1	267	259.4	59.3	67	53	281	155.5	498	205.0	49.5	217	14	57.0
	4	176	200.2	238	259.9	59.7	62	58	301	156.8	502	206.4	49.6	201	15	57.2
P7 0,075÷ 0,125 mm	1	220	200.0	323	259.8	59.8	103	35	333	152.4	599	202.0	49.6	266	11	47.8
	2	230	201.2	327	259.8	58.6	98	36	320	155.2	590	204.5	49.3	270	11	49.9
	3	226	201.9	320	259.2	57.3	94	37	312	150.1	576	199.8	49.7	263	11	49.2
	4	221	201.6	320	259.8	58.2	99	35	323	158.3	554	208.0	49.7	231	13	42.3

The results show that as the particle size decreases, the self-ignition index Sz^{a} and $Sz^{a'}$ increases. The combustion time $\Delta\tau$ and $\Delta\tau'$ is shortened, which means that coal samples with a smaller particle size are more flammable than coal samples with a larger particle size range. The average values of the temperature increase rate and activation energy are presented in Figure 7.

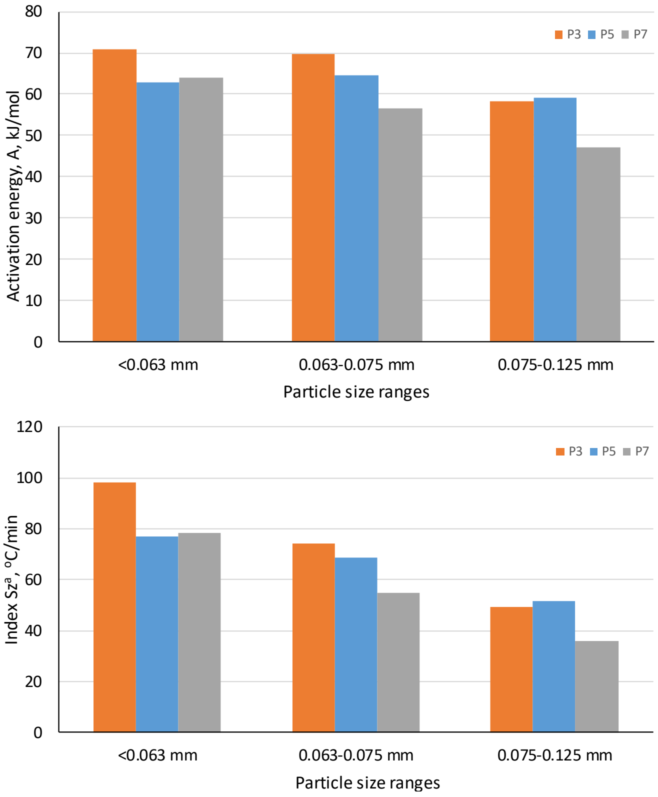

Fig. 7. Average values of index Sz^{a} and activation energy A for the analysed particle size range of coals P3, P5, P7.

The results show that the P2 coal can be included in the 3rd group of propensity to spontaneous combustion for the sample fraction <0.063 mm, the 1st group for the 0.063-0.075 mm fraction, and the 2nd group for the 0.063-0.075 mm fraction. For all fractions, the P5 and P7 carbons are included in group 2nd. Even though for the coals P5 and P7, the tendency to spontaneous combustion does not depend on the analyzed fractions of coal particles, the differences in the Sz^{a} index and activation energy A are visible. Further research should be undertaken to determine if the 0.063-0.075 mm fraction is appropriate for this test procedure. The particle size range 0.075-0.125 mm gives as good a course of the process rate curves as the fraction 0.063-0.075 mm. Indeed, too extensive a particle size range should not be used in research methods with prepared samples. The authors are aware of the small research scope in terms of the type and types of coal and the number of research trials. The obtained results may constitute the basis for further research on the improvement of the research method to contribute to the prevention of spontaneous combustion in coal mines.

7. Conclusions

Despite the scientific developments in the spontaneous combustion process, fires still occur during underground coal mining in various countries. The process of spontaneous coal combustion is complex, and its course is influenced by many factors, among which there are particle sizes and the moisture content of coal. There are various methods of testing the propensity of coal to ignite. In order to determine the effect of particle size distribution during the measurements of adiabatic oxidation, the high-temperature Olpiński method, which is used in Poland and Vietnam, was used. The tests performed for the three particle sizes will show differences in the temperature changes of the coal samples. The differences result from the different identification of the moisture evaporation and removal from agglomerated particles in the sample.

For the model course of the phenomenon, samples should be prepared with the smallest possible particle size range. Both the range of 0.063-0.075 mm and the range of 0.075-0.125 mm in the tested shape of the coal sample show the proper character in the course of temperature changes.

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