

Experimental study of the effects of coal dust particle size on laminar burning velocity in a mixture of coal dust and methane

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Abstract

This study investigates the effect of variations of coal dust particles size on the rate of burning of coal dust particles in a 2-liter closed chamber. Coal dust was selected from three different mines with different sizes (149 μm , 125 μm , 105 μm , 74 μm , 63 μm , 53 μm , 44 μm , 37 μm) for explosion testing in a closed chamber of 2-liters. In this analysis, the concentration of coal dust was considered constant (10000 g/m³), all tests were carried out at a pressure of 1.5 bar and the initial temperature was 25 °C. To calculate the burning rate, the explosion severity parameters of each sample, such as the maximum explosion pressure, the maximum rate of increase in pressure, and the explosion index must be determined during various tests. The results of the experiments show that by varying the size of the coal dust particles, the burning rate of the particles also changes and there is an inverse relationship between them. Coal dust particles with dimensions of 44 μm and 37 μm have a higher burning velocity than other dimensions. Thus, with a reduction in the size of coal dust particles, the burning velocity of coal dust increases. The outcomes acquired in this examination are not just valuable in developing information on coal dust explosion processes, but also improve the measures needed to prevent coal dust explosions in coal mines.

Keywords

coal dust explosion, burning rate, closed chamber, explosion intensity, particle size

1. Introduction

Nowadays with advances in technology and the increasing application of powder in various industries, dust explosion is one of the most substantial hazards in the production industry. (Chao and Dorofeev, 2015). When gas and dust are dispersed simultaneously in the air, a complex physical-chemical process occurs that causes severe risk and damage (Kundu et al., 2017). One of the most significant and sensitive industries that is susceptible to gas and dust explosions is underground coal mines, where methane and coal dust coexist (Kundu et al., 2017). As shown in Figure 1, when the combustion wave is generated in a mixture of coal and methane, a series of physical and chemical processes arise. (Xie et al., 2012). According to this figure, the primary methane explosion disperses coal dust particles from the floor and then clouds of coal dust are formed.

The complex phenomenon of coal dust and gas explosion is still not well known due to the combination of the factors affecting the explosion process (Addai et al.

2016). However, research and studies in this regard have reduced the potential for dust explosion in coal mines in underground coal mines. However, there is still a danger, and explosions can occur. Therefore, efforts around the world continue to prevent the risk of gas and coal dust explosion. In order to assess and prevent the explosion of coal dust, explosive parameters have been investigated as the basis for assessing the explosion risk and mainly include maximum explosion pressure (P_{max}), maximum pressure increase rate $(dp/dt)_{\text{max}}$, explosion index (K_{ST}) and burning velocity (S_L) (Li et al., 2018).

In order to study the parameters of coal dust explosion severity, many experiments have been carried out and the results of these investigations have been used to increase production safety in the industry (Garcia-Torrent et al., 2016; Ajrash et al., 2015). However, the determination of coal dust particle burning velocity is one of the most important parameters in evaluating the explosion risk of methane and coal mixtures. Therefore, in order to prevent the explosion of methane and coal dust mixtures, adequate studies and investigations should be carried out on the mechanism of the burning velocity of coal dust particles (Ranganathan et al., 2018). The burning velocity of coal dust depends on various param-

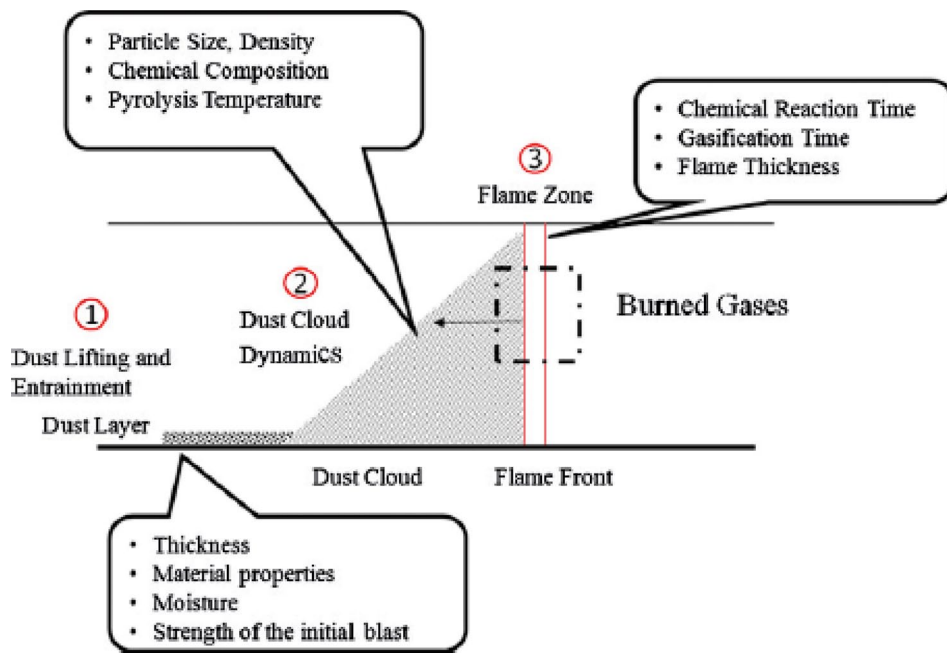


Figure 1: A schematic diagram of the gas and coal dust explosion process (Xie et al., 2012)

eters, including environmental circumstances and the inherent characteristics of coal dust (Wu et al., 2018). Particle size is one of the most important factors in dust and gas explosion studies (Mishra and Azam., 2018). Recently, research on the effect of particle size on coal dust explosions has become more important. (Ajrash et al., 2017) investigated the effect of the concentration and particle size of coal dust on the combustion temperature of coal dust. The results of this study showed that the characteristics of coal dust such as chemical properties (H/C), concentration, particle size (D_{50}) and content of moisture affect the minimum combustion temperature. For concentrations less than 1000 gr/m^3 , with increasing concentrations of coal dust, the minimum combustion temperature decreased. Also, for concentrations less than 100 g/m^3 , the minimum combustion temperature is more closely related to the amount of coal dust particles. (Zhang and Yu., 2017) investigated the effect of the distribution of particle size of polymethyl methacrylate (PMMA) on flame propagation behavior. The results of high-speed camera photography showed that the combustion behavior of PMMA dust particles vary in dimensions of 100 nm , $5 \text{ }\mu\text{m}$ and $30 \text{ }\mu\text{m}$, and the burning velocity of flame is higher in smaller particles. (Zlochower et al., 2018) studied the effect of the size of coal dust particles on the amount of inert materials, such as rock dust to prevent coal dust explosion. According to the results of their studies, by decreasing the size of coal dust particles, the volume of used rock dust particles increases. (Tascon, 2018) examined the effect of the skewness of particle size distribution on the explosion potential of dust. (Mishra and Azam., 2018; Azam and Mishra, 2019) studied the effect of particle size, concentration and dispersion of dust on the minimum igni-

tion temperature and determination of the amount of lime powder used to contain coal dust explosions during the combustion process. In this study, coal dust particles were tested in a range of $38 \text{ }\mu\text{m}$ to $212 \text{ }\mu\text{m}$. The results of this study showed that an increase in the size of coal dust particles would increase the minimum combustion temperature, but with an increase in the dust concentration of coal, the minimum combustion temperature would increase. Also the proportion of rock powder to prevent the explosion of coal dust increases with a decrease in the particle size of coal dust.

According to these studies, the size of coal dust is one of the most important elements in the evaluation of gas and coal dust mixture explosions (Zhang et al., 2017). Therefore, the study of particle size changes is important in determining the burning rate of coal particles. In the present study, the effect of the particle size of coal dust has been investigated on the burning velocity of particles in the mixture of gas and coal dust.

1.2. Explosive parameters to describe the danger of coal dust explosion

Explosive parameters in gas and coal dust mixture explosions include maximum explosion pressure, maximum pressure rise rate and explosion index. These parameters are measured using a burst test in a closed chamber. The higher the values of these parameters, the more damage is done to the environment. (Ogle, 2017). The explosion pressure is the final pressure obtained in a test vessel (Skjold, 2014).

Figure 2 shows the types of pressure in a coal dust explosion. Explosion Pressure (P_{max}) is the maximum pressure obtained during the explosion test and is related

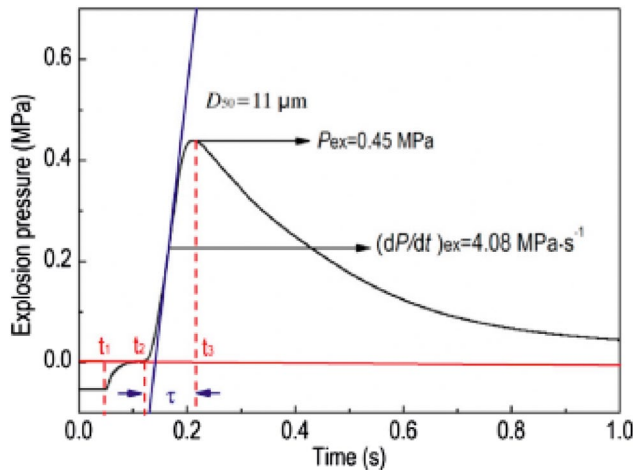


Figure 2: Pressure curve obtained in an explosion test in a closed chamber (Liu et al., 2018)

to the amount of heat released from the explosion. $(dp/dt)_{max}$ is the maximum rate of increase in pressure that rises during the explosion test and indicates the amount of heat released from the explosion.

The explosion index is determined by an explosion sphere apparatus based on the maximum rate of pressure rise and the volume of the explosion chamber (Dahoe et al., 1996) given by the cube root law in Equation 1:

$$K_{St} = \left(\frac{dp}{dt} \right)_{max} \times V_0^{1/3} \quad (1)$$

where:

- V_0 – volume of the explosion sphere (m^3),
- $(dp/dt)_{max}$ – maximum rate of pressure rise (bar/s),
- K_{St} – explosion index (bar.m/s).

It has been shown that the explosion index changes as the size of coal dust changes (Eckhoff, 2003) This makes the investigation of a dust flame rather difficult and also complicates the hazard classification. Figure 3 shows an illustrative sketch of an expanding flame front at four different times inside of a typical explosion sphere. The graph shown in Figure 3 shows the turbulent intensity at different time intervals. Since the flame front is nonstationary, and accelerates as the flame grows in size, the turbulent intensity will also correspondingly increase as shown in Figure 3 Location, t_1 indicates when the flame is initiating (usually using a chemical igniter or a spark). t_2 indicates the laminar flame propagating outward away from the ignition point. t_3 denotes the onset of turbulence which wrinkles the flame. At t_4 the turbulent intensity (u'_{rms}) further increases as shown in the inset to Figure 3 (Rockwell, 2012).

If it is assumed that the dust particles are sufficiently small and well mixed to behave as premixed flames, the laminar burning velocity SL or the velocity at which the flame front propagates itself and relative to the flow into the unburnt mixture is very important, according to Equation 2. The deflagration index has also been used

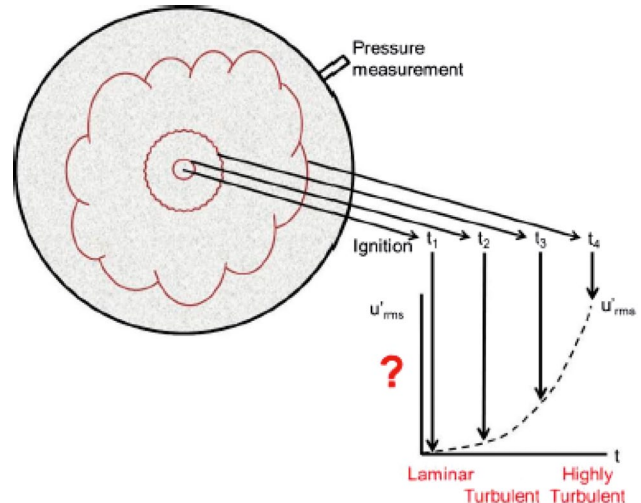


Figure 3: Diagram of explosion sphere with increasing turbulence as the flame propagates (Rockwell, 2012)

to estimate the laminar burning velocity for a given dust concentration (Cashdollar, 2000)

$$S_L = \frac{K_{St}}{4.84 \times \left(\frac{P_{max}}{P_0} - 1 \right) \times P_{max}} \quad (2)$$

where:

- P_{max} – the maximum pressure (bar),
- P_0 – is the initial pressure (bar),
- S_L – laminar burning velocity (m/s).

2. Materials and methods

2.1. Samples preparation

In this research, coal samples were collected from three different mines in Iran and crushed in the laboratory and then sieved into coal dust samples of different size ranges (up to 149 μm , 125 μm , 105 μm , 74 μm , 63 μm , 53 μm , 44 μm , 37 μm) using a standard wire mesh sieve as per (ASTM D388–05; ASTM E 11:87). Figure 4 shows the samples of prepared coal dust in order of size from small to large. Table 1 shows the results of the analysis of the inherent characteristics of these three coal samples.

2.2. Experimental apparatus

In this study, coal dust explosion tests were performed at a constant volume in a 2-liter chamber. The designed compartment is cylindrical and has a fuselage body and two heads of steel. The inside diameter and cylinder body height are 135 mm and the wall thickness is 40 mm. The two sides of the body are covered with quartz glass with a thickness of 80 and a diameter of 160 mm. Despite this glass, the chamber is capable of bearing pressures up to 100 times higher of initial. The purpose

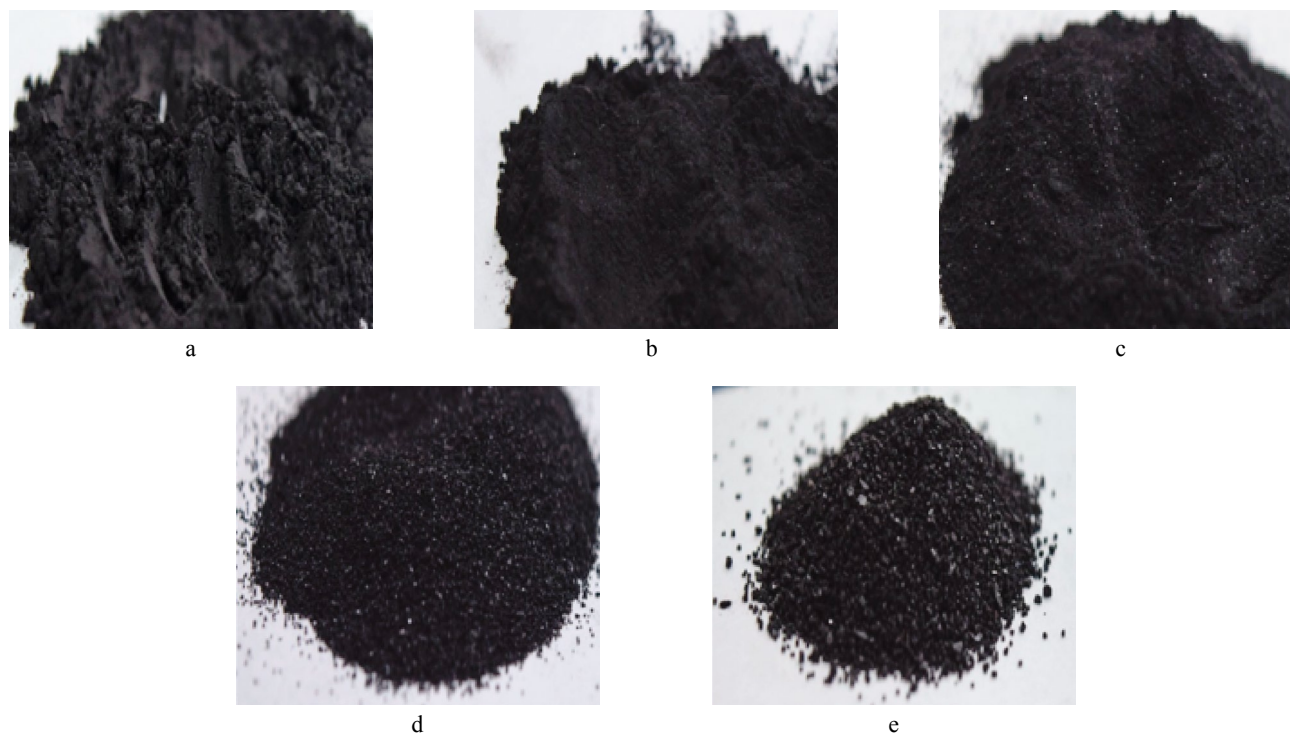


Figure 4: Prepared samples coal dust in various sizes: (a) 44 μm , (b) 63 μm , (c) 74 μm , (d) 125 μm and (e) 149 μm

Table 1: characteristics inherent in coal dust samples tested

Sample number	Sampling site	Primary analysis (%)			
		moisture content	Volatile substances	Ash	Fixed carbon
1	Gheshlagh Mine, Layer 123	10	29	7.6	53.4
2	Tazare mine, layer K25	1.2	51.6	1.2	46
3	Parade mine 4, layer C ₁	1.27	44.5	2.4	51.87

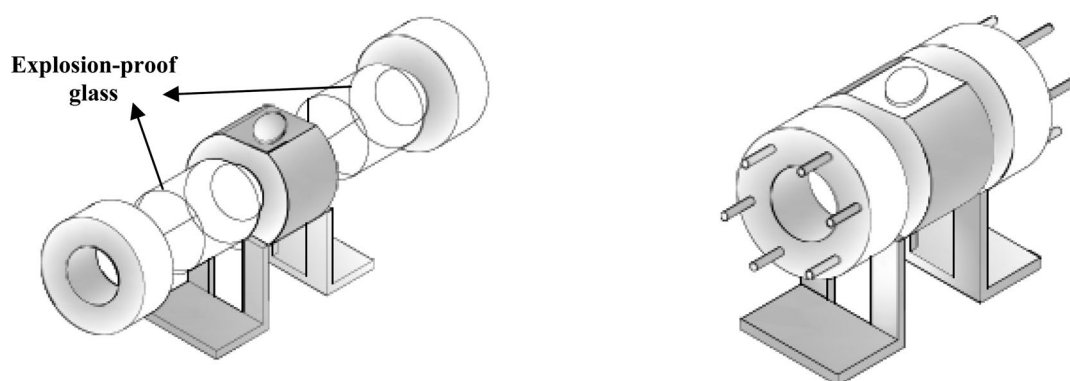


Figure 5: Fixed volume combustion chamber

of placing this glass is to view the inside of the enclosure in order to investigate phenomena such as spraying and combustion. Two silicon seals are placed on both ends of the cylindrical body and two ends of the enclosure to prevent leakage of the gases inside the enclosure and prevent the entry of air outside during the vacuum creation. The explosion-proof and aligned view of this compartment is shown in **Figure 5**.

Figure 6 shows the layout designed to test the coal dust explosion. Two spray nozzles, a coal dust collector tank, two spark plug steel electrodes, a coil, a dynamic pressure sensor (PZ), four band heater and a thermometer are installed on it. The light from the light source (Halogen Lamp) is directed to the first spherical mirror on the right and collides with the second spherical mirror to the left after passing through the combustion chamber.

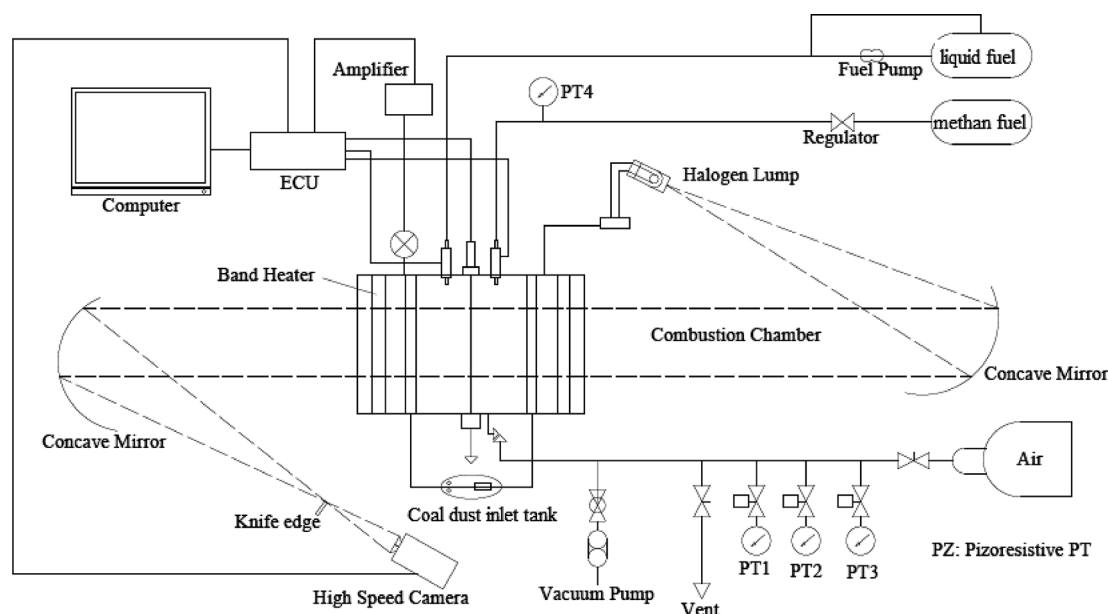


Figure 6: Schematic diagram of the test layout

The reflected light from this mirror enters the high-speed camera after passing through the knife edge. From the pipeline underneath the compartment, the air required for the enclosure is supplied and the smoke from the combustion goes out from the same direction. There are three pressure sensors (PT1, PT2, PT3) in this direction, and the pressure setting operation is performed with these sensors. The first pressure sensor (PT1) measures the vacuum pressure generated by the vacuum pump in the enclosure. Stimulation of the spray nozzles sparks the ignition electrodes, which starts the filming and recording of dynamic pressure with the electric management unit (ECU). Liquid fuel and methane gas tanks shown on the right side of the arrangement are embedded outside the test room.

2.3. Measurements of explosive parameters

Table 2 shows the steps to prepare and test the measurement of coal dust explosive parameters. The following sections explain these steps.

Table 2: Steps to measure coal dust explosive parameters

1	Creating a vacuum in the combustion chamber
2	Prepare a mixture by partial pressure
3	Record the combustion pressure
4	Fill and empty the chamber with air to sweep the remaining dust
5	Estimation of the explosion index according to the combustion pressures

2.3.1 Vacuum chamber

To ensure that the remaining dust is evacuated from the previous test, after filling and emptying the compartment with a pressure of 2 times, using the vacu-

um pump, the pressure inside the compartment is reduced to 1.5 kPa.

2.3.2 Preparation of fuel and air mixture using partial pressure method

For the preparation of fuel and air mixture in the specified equivalence ratio, the partial pressure method of gases is used in ideal conditions (ideal gas). In the mixture of a few gases in a closed box of **Equations 3 to 5**, based on the Dalton model, it governs:

$$V = V_1 = V_2 = \dots = V_n \quad (3)$$

$$P = P_1 + P_2 + \dots + P_n \quad (4)$$

$$P_i = x_i \times P \quad (5)$$

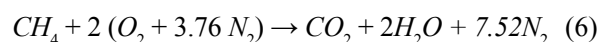
Where:

V – the volume,

P – pressure,

x_i is the molar fraction of i and 1 to n of the gases in the mixture.

Therefore, according to **Equation 5**, the pressure of each component will be obtained by multiplying the total pressure in the molar fraction (**Moran, 2010**). The mixture of gas for this test will be a mixture of methane and air, with its one-step reaction as follows:



Tests for the steady-state mixture (equivalence ratio) at an initial pressure of 1.4 bar and at 25°C will be performed. To prepare the mixture for the desired conditions, it can be assumed that the ideal gas (due to low pressure and temperature) has a partial pressure for the gas injection rate, which can be calculated by **Equations 7 and 8**:

Table 3: Results of partial pressures in the equivalence ratio of one

equivalence ratio	Primary total pressure (bar)	The partial pressure of methane (bar)	The partial pressure of air (bar)
1	1.492	0.142	1.35

$$P_{CH_4} = y_{CH_4} \times P \quad (7)$$

$$P_{air} = y_{air} \times P \quad (8)$$

y is the molar fraction of chemical compounds which, in a stoichiometric state for methane in the mixture, is as **Equation 9** and is equal to 9.5%:

$$y_{CH_4} = \frac{n_{CH_4}}{n_t} = \frac{1}{10.52} = 0.095 \quad (9)$$

Where:

n_t – The mole number of gases in **Equation 6**

At the initial pressure of the chamber, the partial pressure of air and methane will be as described in **Table 3**:

2.3.3 Spark generation and recording of the combustion pressures

An igniter is used to create a spark as shown in **Figure 7** at the center of the enclosure. These candles are connected to the spark coil. The spark coil used in the test, is made by the Bush company and is of type ZS-K 1×1.

The coil filling time was chosen at a maximum of 2.5 ms for most tests, and given that the input voltage to the coil is 12 volts, the supply current is approximately 6 amps and the supply energy for the spark will be about 30 mJ. It is also mounted on the wall of the pressure sensor chamber, which has a 10-bar pressure measurement range and the combustion pressure is recorded on the computer.

The ECU, which includes three inputs, outputs and communication ports, sends commands for spark generation and spray winding (methane gas spray). An intermediate software is used to enforce sparking and spark command between the computer and the electrical management unit. This software includes three parts of variables, constants and charts while adjusting factors such as spraying time, sparking winding time and also recording the pressure data on the computer with this software. The combustion chamber pressure increases after the start of combustion over a certain period to reach its maximum point and leads to a downward trend due to heat transfer through the wall. The explosion process of coal dust in a 2-lit vessel was recorded by high speed photographs during coal dust explosions as shown in **Figure 8**. The interval between each frame was 5 ms.

3. Results and discussion

To investigate the effect of coal dust on the explosive parameters, all experiments were carried out at a specific concentration (10000 g/m³). The variation of P_{max} , $(dp/dt)_{max}$, K_{ST} and S_L with particle size for all three coal dusts is shown in **Table 4**.

In **Figures 9**, as shown, by reducing the particle size of coal dust, the P_{max} and $(dp/dt)_{max}$ of the coal dust cloud increases. Also, in all three curves, sample 3 has a higher explosion pressure than the other two samples, which is related to the intrinsic properties (ash content, moisture content, volatile substances and fixed carbon) of the samples.

Now, having procured the deflagration index and through calculations with **Equation 2**, a burning veloc-

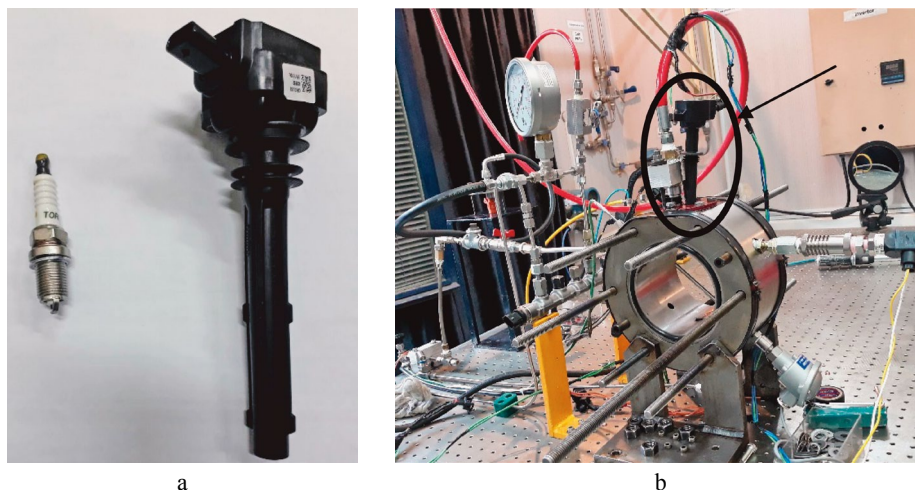


Figure 7: a) Spark Plugs and Plugs; b) Spark Plugs placed on the chamber

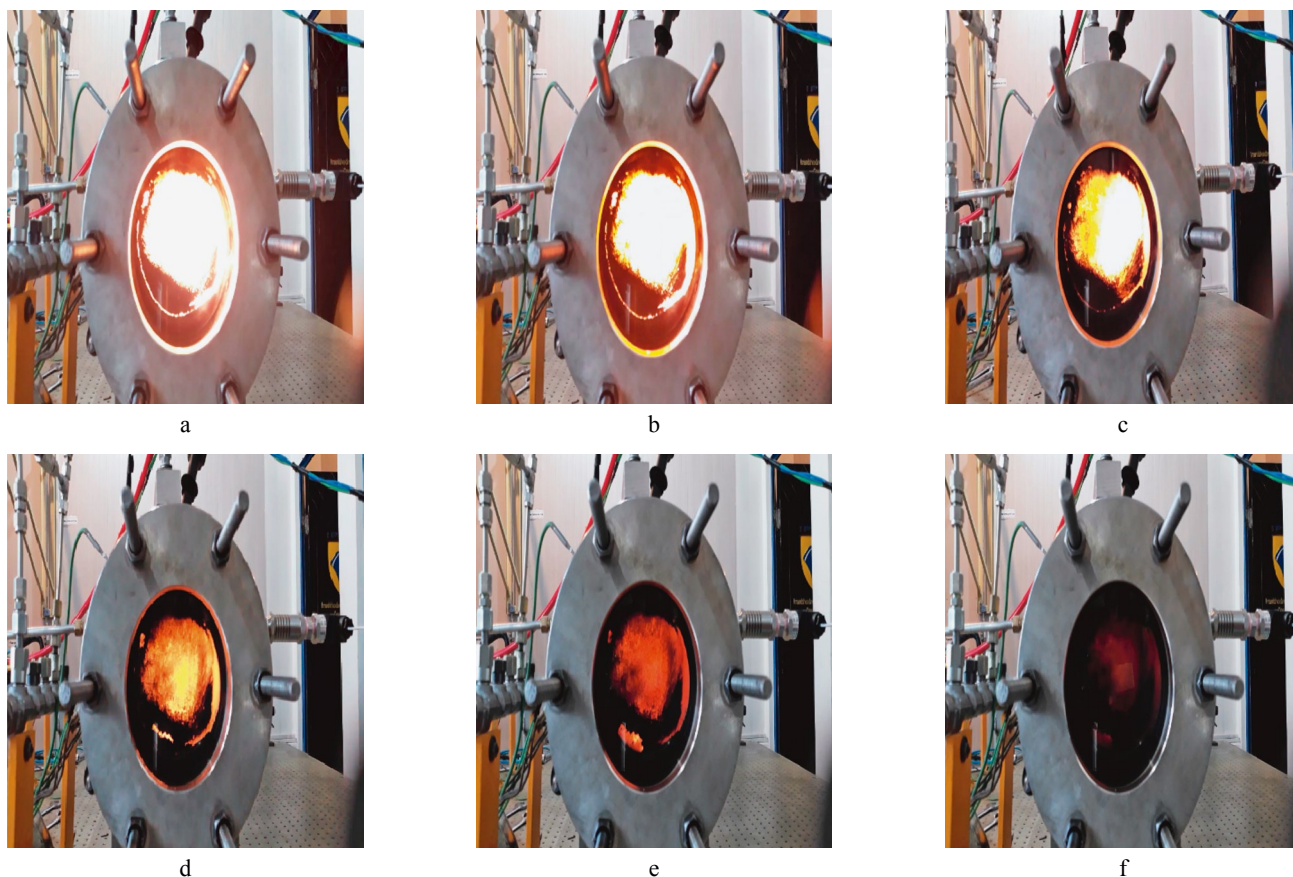


Figure 8: Combustion cycle of mixing coal dust and methane in a closed chamber

Table 4: The results of the combustion of a sample of coal dust tested

Sample number	Explosive parameters	Particle size (μm)							
		149	125	105	74	63	53	44	37
1	P_{max} (bar)	2.02	2.06	2.3	2.4	2.45	3.03	3.16	-
	$(dp/dt)_{max}$ (bar/s)	47	39.11	64.78	67.88	125.69	168.56	178.86	-
	K_{ST} (bar.m/s)	59.08	49.17	81.42	85.31	157.99	211.87	224.84	-
	S_L (m/s)	11.43	12.22	12.71	15.24	21.03	14.16	13.28	-
2	P_{max} (bar)	2.4	2.5	3.09	3.7	4	4.4	4.65	-
	$(dp/dt)_{max}$ (bar/s)	80.98	88.94	110.27	292.02	349.82	385.83	451.45	-
	K_{ST} (bar.m/s)	101.79	111.81	138.61	367.07	439.72	485	567.48	-
	S_L (m/s)	8.62	9.24	9.74	13.98	13.63	12.78	12.07	-
3	P_{max} (bar)	3.74	3.83	3.9	4.5	5.75	6.12	5.3	5.33
	$(dp/dt)_{max}$ (bar/s)	432.81	526.25	639.38	749.81	1347.18	1501.45	1850.93	1511.25
	K_{ST} (bar.m/s)	544.05	661.50	804.09	942.53	1693.43	1887.34	2326.65	1899.61
	S_L (m/s)	20.13	20.97	26.62	28.59	30.48	33.68	35.80	28.84

ity can be obtained, which can be seen in **Table 4** and **Figure 10**.

As shown in **Figure 10**, with a decrease in the particle size of coal dust, the index of explosion capability also

increases. Also, the highest burning velocity of sample 3 (Parvarde mine) is 44 μm in size.

Figure 11 shows the variations of the burning velocity of 3 samples of coal dust tested in different sizes.

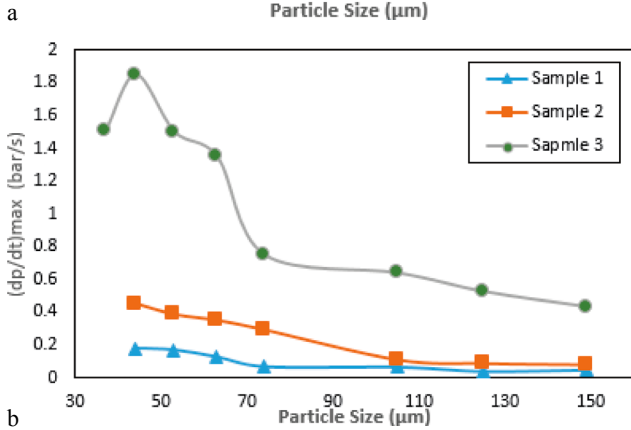
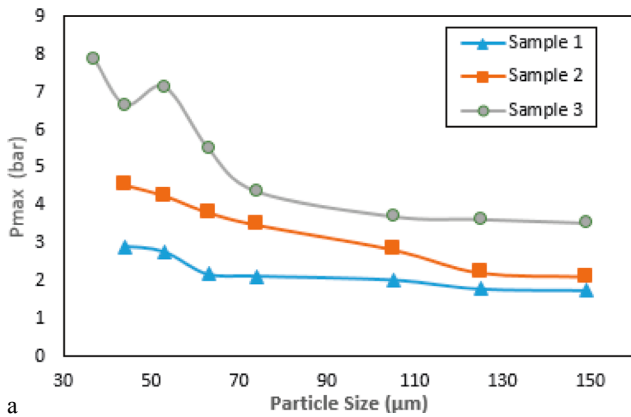


Figure 9: a) The relationship between P_{max} with particle size of coal dust, b) The relationship between $(dp/dt)_{max}$ with particle size of coal dust

According to this form, the maximum burning velocity of coal dust is mine sample 3 and the size is 44 μm .

4. Conclusions

In this study, the effect of particle size of coal dust on the burning velocity of particles was investigated. For this purpose, three samples of coal were collected from different mines in Iran and were prepared in the form of coal dust in different dimensions. The present investigation will advance the improvement of methodologies to manage coal dust explosions in underground coal mines. Based on the observations of the present study, the following conclusions are drawn:

1 – if dimensions of coal dust particles are decreased to a certain extent, the explosion intensity parameters such as the P_{max} and $(dp/dt)_{max}$, explosion index (K_{St}), and finally the burning velocity of particles increase.

2 – If the particle size of the coal dust is smaller than the specified limit, in this case, the particles will stick together and become larger particles, and will decrease the explosive parameters such as burning velocity and deflagration index.

3 – Among the samples of coal tested, sample number 3 (Parvarde mine) has the highest deflagration index and burning velocity (S_L). This factor is related to the intrinsic characteristics of sample number 3. The moisture and

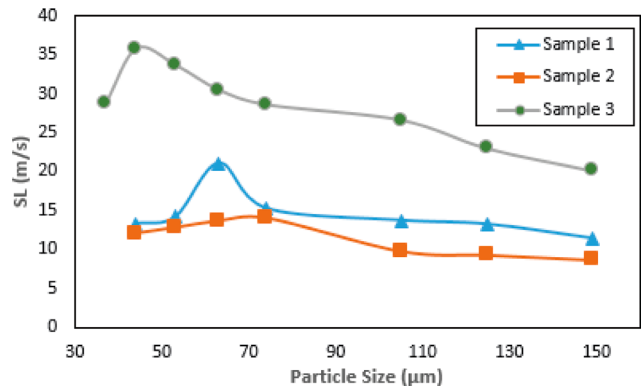


Figure 10: The relationship between the burning velocity of coal dust particles with size of particles

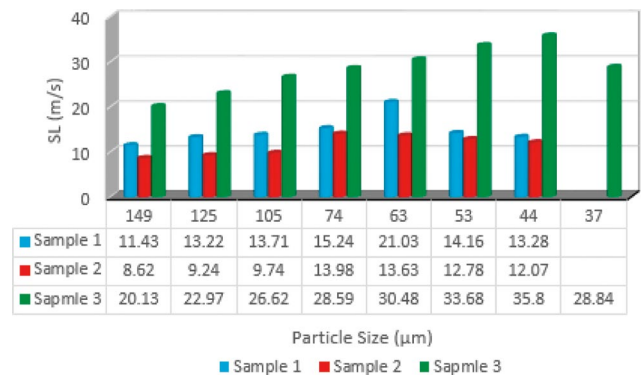


Figure 11: Variation in three coal dust samples burning velocity tested in different particle sizes

ash content of this sample are lower than the other samples, and the volatile matter and fixed carbon content are higher than those of the other two samples. Therefore, in addition to the amount of dust particles of coal, the inherent characteristics of coal dust are also factors in coal dust explosions.

4 – With a decrease in particle size from 74 μm to 44 μm , the S_L of coal dust for sample 3, increased from 28.5 (m/s) to 35.8 (m/s). In the particle size range of 63 μm to 44 μm , the burning rate of coal dust particles increased significantly. Therefore, the coal dust particles of dimension smaller than 70 μm , which are mostly produced during extraction, are more likely to explode.

5 – The particle size range where no significant change in the burning rate of coal occurred has been observed in the range of 1 μm to 2 μm .

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SAŽETAK

Eksperimentalno istraživanje utjecaja veličine čestica ugljene prašine na laminarnu brzinu izgaranja mješavine ugljene prašine i metana

U radu se istražuje utjecaj promjena u veličini čestica ugljene prašine na brzinu njihova izgaranja u zatvorenoj komori volumena 2 l. Prašina je uzorkovana u trima različitim rudnicima te je testirana eksplozivnost uzoraka različite veličine (149 μm , 125 μm , 105 μm , 74 μm , 63 μm , 53 μm , 44 μm , 37 μm). Koncentracija prašine bila je konstantna (10000 g/m³), testiranje je načinjeno pri tlaku od 1,5 bara te temperaturi od 25 °C. Višestrukim testiranjem određeni su izračun iznosa gorenja te varijable svakoga uzorka (najveći eksplozivni tlak, najveći iznos povećanja tlaka, indeks eksplozivnosti). Rezultati su pokazali kako promjene veličine čestica ugljene prašine utječu obrnuto proporcionalno na promjenu brzine njihova izgaranja. Čestice od 37 i 44 μm pokazale su najveću brzinu gorenja. Rezultati su primjenjivi u analizi eksplozivnih procesa prouzročenih ugljenom (prašinom), ali i u sprječavanju takvih pojava u rudnicima.

Ključne riječi:

eksplozija ugljene prašine, brzina gorenja, zatvorena komora, snaga eksplozije, veličina čestica

Authors contribution

Hadis Moradi (Ph.D. candidate): initialized the idea, completed literature review and participated in all work stages, such as providing coal samples, running experimental tests and data analysis. **Farhang Sereshki** (Full Professor): executed experimental tests, data analysis and test of its accuracy, and helped with field work. **Mohammad Ataei** (Full Professor): managed the whole process and supervised it from the beginning to the end. **Mohsen Nazari** (Associate Professor) Tested the device, finalized the device, and helped with field work.