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Influence of Molasses on the Explosion and Decomposition Properties of the Coal Dust Deposited in Underground Mines

Jianguo Liu [1,2,3,*], Minglei Lin [4,*], Longzhe Jin [1,2], Gang Li [3], Shengnan Ou [4], Yapeng Wang [5], Tianyang Wang [4], Mulati Jueraiti [4], Yunqi Tian [4] and Jiahui Wang [4]

1 NHC Key Laboratory for Engineering Control of Dust Hazard, University of Science and Technology Beijing, Beijing 100083, China
2 Research Institute of Macro-Safety Science, University of Science and Technology Beijing, Beijing 100083, China
3 State Key Laboratory of Safety and Health for Metal Mine, Maanshan 243000, China
4 School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China
5 College of Environment and Safety Engineering, Qingdao University of Science and Technology, Qingdao 266042, China
* Correspondence: liujg@ustb.edu.cn (J.L.); s20200122@xs.ustb.edu.cn (M.L.)

Abstract: Coal dust endangers the health and safety of workers in underground coal mines. Therefore, developing coal dust suppressants with dust prevention and explosion-proof properties is critical. The influence of molasses on the explosion and decomposition of the coal dust deposited in underground mines was investigated using 20 L explosion experiments and thermogravimetric and differential thermal analysis (TG-DTA). Findings reveal that, first, molasses can weakly promote the explosion of coal dust at low coal dust concentrations (<400 g/m^3) but has no significant effect on the explosion at high coal dust concentrations (≥400 g/m^3). Second, the decomposition process of the coal dust mixed with molasses has three stages: the moisture evaporation stage (0–150 °C), the molasses decomposition stage (150–300 °C), and the coal dust decomposition stage (300–500 °C). Molasses oxidation consumes oxygen and releases heat; at low coal dust concentrations, the released heat can promote coal dust decomposition to produce combustible gas, enhancing the coal dust explosion; at high coal dust concentrations, under the co-influence of the heat generation and oxygen consumption, molasses has no effect on the coal dust explosion. This is the mechanism of which molasses influences coal dust explosions.

Keywords: coal dust; molasses; coal dust explosion; suppression performance; TG-DTA

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1. Introduction

Coal is still the primary energy source in the world, and it is widely used in the chemical industry, electric power, metallurgy, and other industries [1–4]. In underground coal mining, a large amount of coal dust is produced [5–7]. Coal dust is harmful to the health of coal miners and contains explosives [8,9], which endangers the safety of workers [10–13]. Coal dust explosions are highly destructive and can cause massive casualties and heavy property losses; for example, a coal dust explosion accident caused the deaths of 21 people in Yulin, Shaanxi Province, China, on 12 January 2019 [14]. Therefore, it is critical to study the technology for suppressing coal dust explosions in underground coal mines to ensure the safety of coal miners.

Numerous studies have been conducted on the technology for suppressing coal dust explosions in underground mines. Da et al. [15] found that talc powder could significantly reduce the explosion intensity of coal dust. Song et al. [16] investigated the inert effect of rock dust on the explosion of coal dust and methane and discovered that small rock dust has a remarkable suppression effect on the coal dust explosion flame. Wang et al. [17]

prepared a composite using carbamide and fly ash cenosphere with a noticeable suppression effect on coal dust explosions and found that the thermal decomposition products of carbamide at high temperatures can effectively absorb the active group produced in the coal dust explosion process, thus inhibiting the propagation of the explosion and finally achieving the suppression performance on coal dust explosions. According to Yu et al. [18], the suppression performance of fly ash cenosphere in coal dust explosions is better than that of calcium carbonate ($CaCO_3$), which the authors attribute to the large specific heat capacity of the fly ash cenosphere. Du et al. [19] compared the suppression characteristics of water, $CaCO_3$, and ammonium dihydric phosphate on the severity of coal dust explosions using a 20 L spherical explosion device, and the results showed that water has the most potent suppression effect on coal dust explosions. Yuan et al. [20] reached similar conclusions when exploring the impact of humidity on the explosive characteristics of coal dust. Gan et al. [21] suggested that water mist can inhibit dust explosions by diluting the oxygen concentration and absorbing heat through evaporation. Du et al. [12] proposed that increasing the humidity of the deposited coal dust is the most desirable method to suppress coal dust explosions in underground coal mines due to its low cost, simple operation, and environmental friendliness. However, this method still faces two challenges: (1) the coal dust is mainly hydrophobic and cannot be efficiently wetted by pure water [22,23], and (2) the evaporation rate of water is high because of the high temperature in underground mines [24]. Therefore, optimizing and improving the method of using water spray to suppress coal dust explosions in underground coal mines is critical.

Adding chemicals to water to improve the suppression effect of water on coal dust explosions is a common and effective method. Molasses, a byproduct of sugar production [25,26], is low in cost, has strong bonding, and is environmentally friendly [27–29]. Therefore, many studies have revealed that molasses is an effective and environmentally friendly dust suppressant. For example, Gotosa et al. [30] discovered that molasses has good prevention performance on grave road dust, with molasses solutions decreasing dust deposition by 77–83% compared to pure water; similar findings were reported in the studies performed by Parsakhoo et al. [31] and Omane et al. [32]. In our previous study [33], the suppression performance of molasses solutions on coal dust was investigated using various experimental methods, and the results showed that it is highly possible to prepare coal dust suppressants using molasses because of the high agglutination and anti-evaporation effects of molasses on coal dust. However, molasses is a kind of organic combustible material, and coal dust is explosive. Thus, the influence of molasses on coal dust explosions must be studied before using molasses as a coal dust suppressant. In addition, Myrna et al. [34] discovered a high concentration of phenols and aldehydes in molasses, which have strong reduction properties and can consume oxygen in the air at low temperatures, potentially suppressing coal dust explosions. However, the influence of molasses on coal dust explosions has not yet been studied to the best of our knowledge. Therefore, it is critical to investigate the influence of molasses on coal dust explosions to develop molasses-based coal dust suppressants.

To this end, the main objective of this study was to investigate the influence of molasses on the explosion and decomposition of the coal dust deposited in underground coal mines. The explosion characteristics of the coal dust, sampled from underground coal mines and mixed with molasses solutions at various concentrations, were tested using a 20 L spherical explosive device. The decomposition process of the coal dust samples was investigated using thermogravimetric and differential thermal analysis (TG-DTA). Finally, the influence mechanism of the molasses solution on the coal dust explosion was discussed based on the explosion experiments and TG-DTA results.

2. Material and Methods

2.1. Material Preparation

2.1.1. Sample Method for Coal Dust Deposited in Underground Coal Mines

This study sampled coal dust using the gravity deposition method from an underground coal mine in Datong City, Shanxi Province, China. The sampling method is described in our previous study [22]. First, during the work of the shearer, a sample plate was suspended at a height of 1.5 m (the average Chinese respiration height) in the return airway about 10 m from an upper corner. The suspension time was 8 h per time; the sampled coal dust in the plate was then collected and sieved using a 200 mesh (74.4 µm) to remove the large particles dropped off the roof, and the coal dust was packed into vacuum sample bags to be used in subsequent experiments. According to International Standard ISO 17247:2013 and GB/T 212-2008, the ultimate and proximate analyses of the coal dust were conducted, respectively, and the results are shown in Table 1.

Table 1. Ultimate and proximate contents of the coal dust.

Location	Ultimate Contents (%)					Proximate Contents (%)			
	C	H	O	N	S	M_{ad}	V_{daf}	A_{ad}	FC_{ad}
Datong City	59.04	3.83	35.32	0.91	0.91	1.16	26.01	25.79	47.04

M_{ad} = moisture under air-dried basis; V_{daf} = volatile matter under dried ash-free basis; A_{ad} = ash under air-dried basis; FC_{ad} = fixed carbon under air-dried basis.

2.1.2. Preparation of Explosion Coal Dust

In the explosion experiments, the coal dust was mixed with and dried in a molasses solution. The molasses used in this study was sugarcane molasses purchased from Jinqianwan Molasses Co., Ltd. (Liuzhou, China). Molasses is a byproduct of sugar production, and the components and contents of molasses produced in different regions differ slightly due to the differences in sugar production processes and conditions. Table 2 lists the main components and approximate contents [27,35].

Table 2. The main components and their content in sugarcane molasses.

Number	Components	Contents (wt.)
1	Sugar (sucrose)	~45%
2	Moisture	~10%
3	Crude protein	~10%
4	Ash (K, Ca, etc.)	~10%
5	Others (Other carbohydrates such as gums, starch, etc.)	~25%

First, in preparation for the explosion of coal dust, the molasses solutions were prepared with mass concentrations of 0% (pure water), 10%, 20%, 30%, 40%, and 50%, and the coal dust was mixed and slightly stirred with the molasses solution at a mass ratio of 2:1, after which the mixed wet coal dust was placed in a drying device at 100 °C until its quality no longer changed, and then removed and placed at room temperature (about 25 ± 1 °C) for cooling. Finally, after cooling, the mixed dried coal dust was placed in a crucible, ground into a powder, and screened with 200 mesh. The coal dust that passed through the sieve was an explosion of coal dust. The particle sizes of the coal dust samples were measured in a laser particle size analyzer (Winner 2000) with anhydrous ethanol as the dispersion liquid; the particle size distributions of the samples are shown in Figure 1a. It can be seen that the average particle sizes (D50) of the six samples are a little different, ranging between 10 and 20 µm. This provides the possibility of exploring the influence of molasses on the explosive characteristics of coal dust.

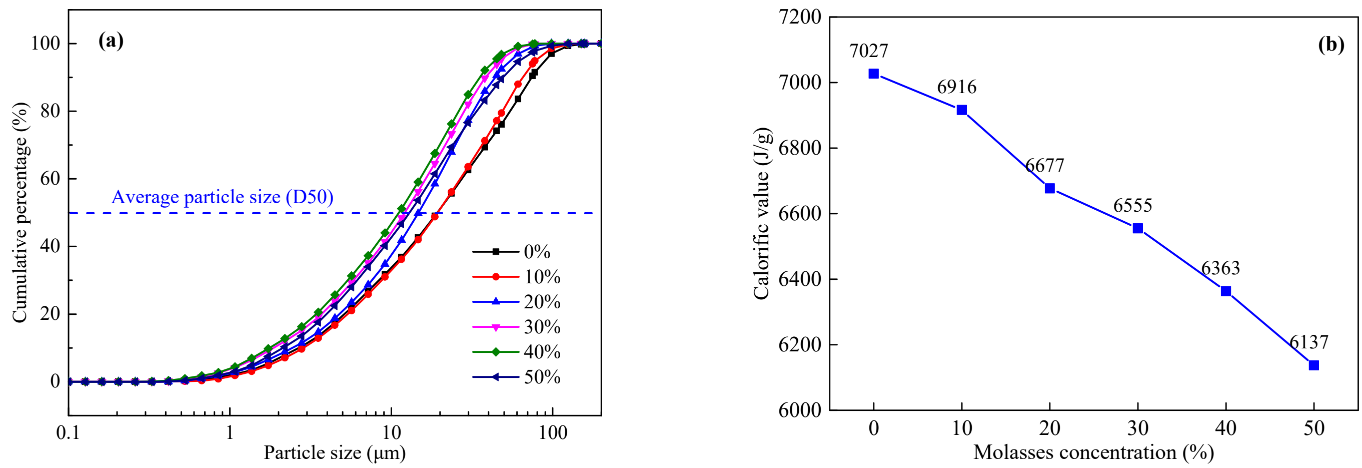

Figure 1. The particle size distributions (**a**) and the calorific values (**b**) of the explosion coal dust samples.

In addition, the calorific values of the explosion coal dust samples were also measured in an automatic calorimeter (HY-A9, China) according to GB/T213-2008. The measurement results are shown in Figure 1b. It can be seen that the calorific value of the coal dust decreased linearly with the increase in molasses concentration. The result indicates that molasses has less calorific value than coal dust. Therefore, adding molasses to the coal dust can reduce the calorific value of the coal dust.

2.2. Experiments

2.2.1. Coal Dust Explosion Experiment

The coal dust explosion experiment was conducted using a 20 L spherical explosive device. The device consists primarily of a gas source, a gas distribution system, a control system, and a 20 L spherical explosion chamber (Figure 2). The explosion chamber was equipped with a pressure sensor to monitor the pressure in the chamber at a frequency of 5000 Hz. Therefore, the explosion parameters, including the maximum explosion pressure ($P_{\max}$), explosion time (t_e), and maximum rate of pressure rise ($(dP/dt)_{\max}$), can be obtained by analyzing the pressure vs. time curve after the explosion [17,36]. In this study, the explosion parameters of the coal dust mixed with molasses were tested at concentrations ranging from 100 to 700 g/m^3 with intervals of 100 g/m^3 in an air atmosphere (oxygen concentration of 21%), and a fireworks ignition head was used with an ignition energy of 10 kJ. In detail, during the experiment, first, the coal dust was put into a cylindrical closed storage tank under the spherical explosion chamber; then, the 20 L spherical explosion chamber was pumped, and its inner air pressure was reduced to –0.05 MPa; finally, the coal dust was sprayed into the explosion chamber by inert gas; at the same time, the ignition head was electrified, and the explosion test experiment was completed. The pressure sensor could collect the pressure in the 20 L spherical explosion chamber within 5000 ms before and after the explosion.

2.2.2. Thermal Decomposition of Coal Dust

To investigate the influence mechanism of molasses on coal dust explosion, TG-DTA of the explosion coal dust mixed with molasses solution at mass concentrations of 0% (pure water), 10%, 20%, 30%, and 40% was conducted in a STA7000 device (Hitachi, Japan). In the TG-DTA experiment, 5 ± 0.5 mg of coal dust was heated from 30 °C to 600 °C at a heating rate of 10 °C/min in an air atmosphere.

Figure 2. The 20 L spherical explosive device.

2.3. Data Analysis Methods

2.3.1. The Extraction Method for Explosion Characteristics of Coal Dust

To quantify the influence of molasses solutions on the coal dust explosion, three explosion properties were extracted from the pressure vs. time curves, including the maximum explosion pressure (P_{max}), maximum rate of explosion pressure rise ($(dP/dt)_{max}$), and explosion time (t_e), as shown in Figure 3a. Specifically, P_{max} is the maximum pressure in the chamber after a coal dust explosion, and ($(dP/dt)_{max}$) is the maximum value obtained from the first-order derivative of the explosion pressure vs. time [37], as shown in Figure 3b. t_e is the time from ignition to the maximum pressure, and the smaller t_e, the faster and more intense the explosion [38].

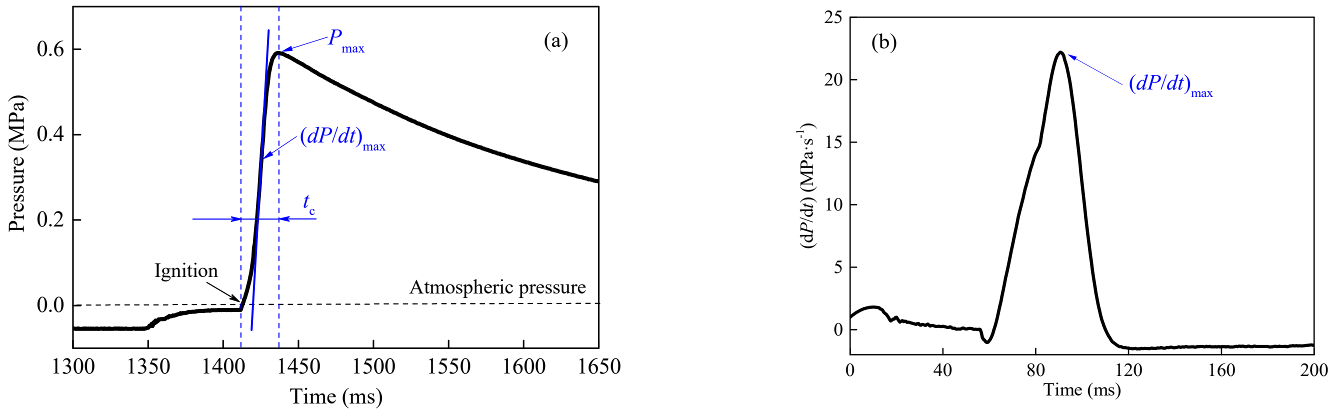

Figure 3. The explosion pressure (**a**) and the first-order derivative of the explosion pressure (**b**).

The deflagration index (K_{st}) is a parameter for comprehensively estimating the explosion intensity of coal dust [39], as shown in Equation (1) [40]. In this study, the explosion intensity of coal dust was compared using K_{st}:

$$K_{st} = \left[\frac{dP}{dt}\right]_{max} \sqrt[3]{V} \tag{1}$$

where K_{st} is the deflagration index (MPa·m/s), V is the volume of the explosion chamber (m^3), and $(dP/dt)_{max}$ is the maximum rate of the explosion pressure rise (MPa/s).

2.3.2. Calculation of the Decomposition Characteristics of Coal Dust

The mass variation (TG) and loss rate (DTG) are essential parameters for analyzing the coal dust decomposition process. The calculations are shown in Equations (2) and (3), respectively; Equation (3) shows that the DTG is the inverse of the first-order derivative of mass variation vs. time:

$$\mathrm{TG} = \frac{m_t}{m_0} \times 100\% \tag{2}$$

$$\mathrm{DTG} = -\frac{d(m_t - m_0)}{dt} \tag{3}$$

where TG denotes the mass fraction of coal dust at time t (%); m_0 and m_t denote the masses of coal dust at time 0 and t, respectively (μg); and DTG denotes the mass loss rate (μg/min).

To compare the effects of molasses on the coal dust decomposition process, as shown in Figure 4a, the maximum DTG ($\mathrm{DTG_{max}}$) was selected as an evaluation parameter for the coal dust decomposition rate, and the corresponding temperature (T_d) of $\mathrm{DTG_{max}}$ was used as the coal dust decomposition temperature. Therefore, the effect of molasses on coal dust decomposition was analyzed by comparing $\mathrm{DTG_{max}}$ and T_d. Additionally, the DTA value is the temperature difference between the experimental coal dust and the reference material (aluminum oxide), as shown in Figure 4b. A DTA value less than 0 indicates that the test sample experienced an endothermic reaction, while a DTA value greater than 0 indicates that the test sample experienced an exothermic reaction [41].

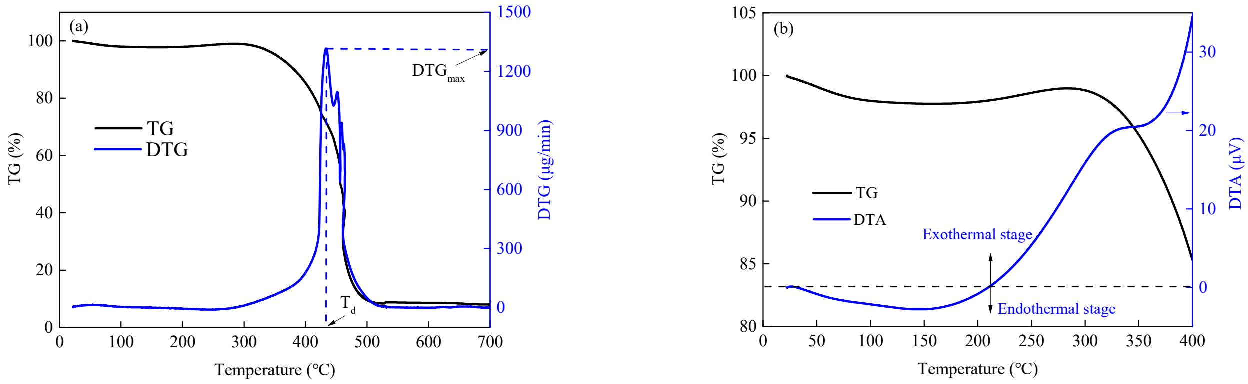

Figure 4. The typical thermogravimetric and derivative thermogravimetric (TG-DTG) curve (**a**) and the differential thermal value (DTA) curve (**b**) of the decomposition of coal dust.

3. Results

3.1. Effect of Molasses Solution on the Explosion Characteristics of the Coal Dust

The explosion characteristics of the coal dust samples were investigated to explore the influence of molasses on coal dust explosions. Figure 5 depicts the series pressure curves of the pure coal dust (mixed with 0% molasses) in the explosion concentrations of 100 to 700 g/$\mathrm{m^3}$ with a 100 interval. The same experiments were conducted for the other six explosion coal dust samples.

To investigate the influence of molasses on the explosion characteristics of coal dust, the explosion parameters of the coal dust samples were compared, and the parameters included the P_max, $(dP/dt)_\mathrm{max}$, t_e, and K_st. The results are shown in Figure 6.

As shown in Figure 6a, first, with the increase in coal dust concentration, the P_max of the coal dust samples increased, then decreased, and reached the maximum value between 300 and 400 g/$\mathrm{m^3}$. After adding molasses to the coal dust, the maximum of the P_max of the coal dust in series concentration had no significant change, and all varied at around 0.60–0.61 MPa. Second, at low coal dust concentrations (less than 300 mg/$\mathrm{m^3}$), the P_max of the coal dust mixed with molasses increased obviously; for example, the P_max of the coal dust mixed with 10% molasses solution increased by 16.3% than that of the pure coal dust (mixed with 0% molasses solution) at 100 g/$\mathrm{m^3}$; when the coal dust concentration was larger than 400 g/m^3, the P_{max} of the coal dust samples mixed with molasses was weakly higher than that of the pure coal dust, indicating molasses had a limited improvement effect on the coal dust explosion at high coal dust concentration.

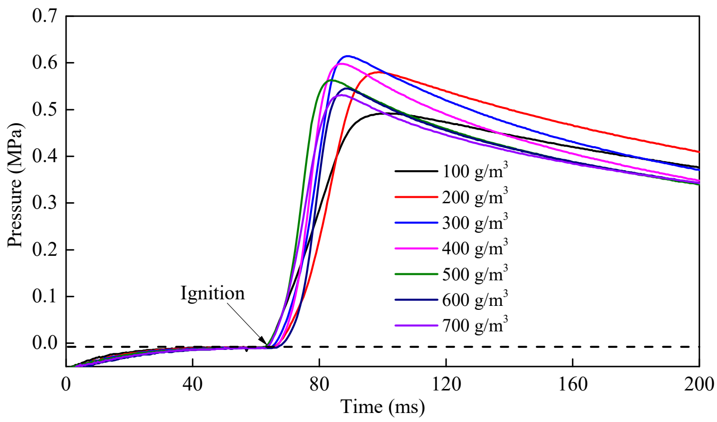

Figure 5. The explosion pressures of the coal dust mixed with a 0% molasses solution at various explosion concentrations.

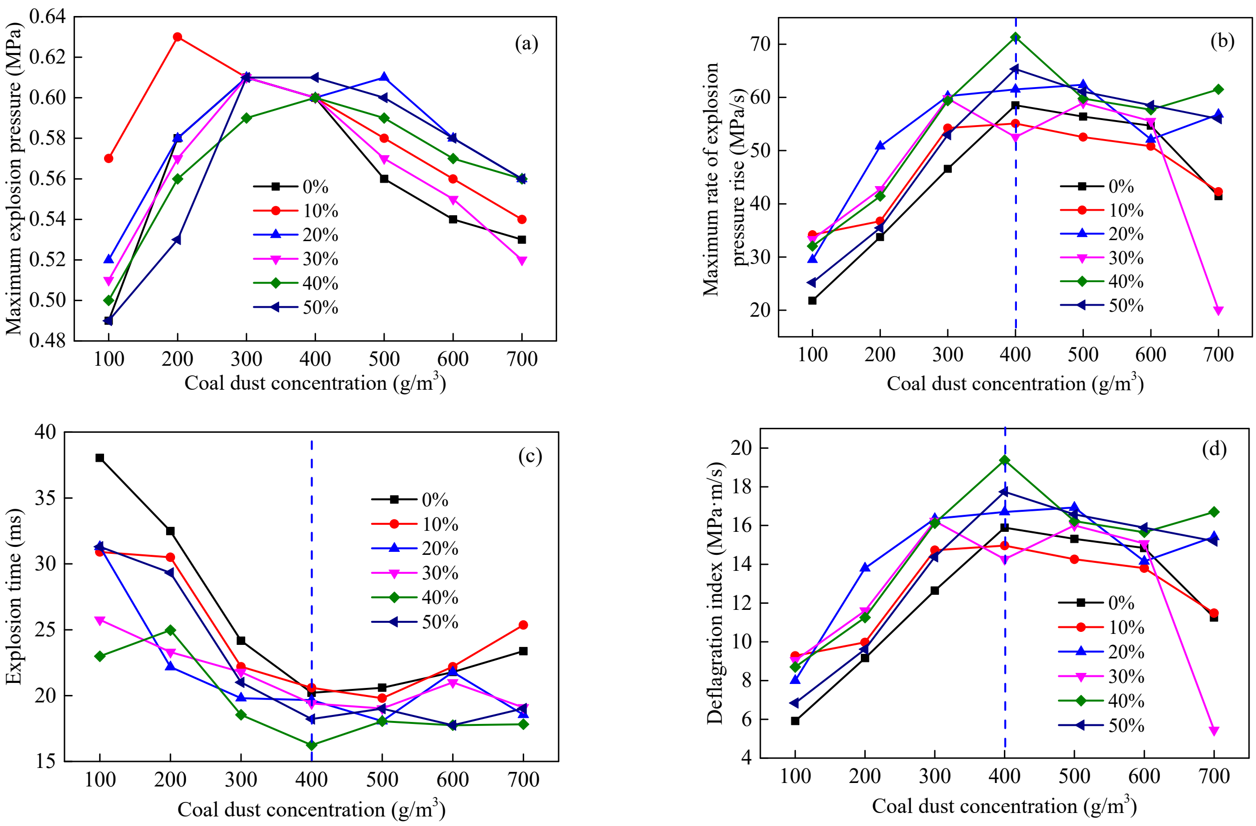

Figure 6. The maximum pressure (**a**), the maximum rate of the explosion pressure rise (**b**), the explosion time (**c**), and the deflagration index (**d**) of the explosion coal dust samples at a series of explosion concentrations.

Figure 6b presents the variation of the $(dP/dt)_{max}$. It can be seen that the $(dP/dt)_{max}$ of the coal dust samples increased first and then decreased with the increase of coal dust concentration, which is the same as the variation of the P_{max} (Figure 6a), with the maximum of the $(dP/dt)_{max}$ achieved at around 400 g/m^3. In addition, when coal dust concentration is less than 400 g/m^3, the $(dP/dt)_{max}$ of the coal dust samples mixed with molasses were all slightly larger than that of the pure coal dust, indicating that molasses could have a limited improvement effect on coal dust explosion at low coal dust concentrations. In contrast, when coal dust concentration is higher than 400 g/m^3, there is no obvious change in the $(dP/dt)_{max}$, showing molasses has no significant influence on the explosion properties of coal dust at high coal dust concentration.

Figure 6c depicts the variation of the t_e with coal dust concentration. It can be found that, first, in contrast with the variations of the P_{max} and $(dP/dt)_{max}$, the t_e decreased first and then increased with the increase in coal dust concentration, and the minimums were also obtained at around 400 g/m^3. Second, consistent with the result of $(dP/dt)_{max}$, the explosion intensity of the coal dust mixed with molasses obviously decreased at low coal dust concentrations (less than 400 g/m^3), and the explosion intensity did not change significantly at high coal dust concentrations (greater than 400 g/m^3). Figure 6d shows the variation of the K_{st}. The K_{st} of the coal dust samples increased first and then decreased with the increase in coal dust concentration. At low coal dust concentrations, the K_{st} of the coal dust samples mixed with molasses was all slightly larger than that of the pure coal dust sample. This result also indicated that molasses had a weak improvement effect on the explosion intensity of coal dust at low concentrations. However, at high coal dust concentrations, there is no significant effect of molasses on the explosion of coal dust.

To sum up, according to Figure 6, it was known that all the coal dust samples reached the maximum explosion intensity at around 400 g/m^3. Therefore, to further analyze the influence of molasses on the explosion of coal dust, the explosion parameters of the coal dust samples at 400 g/m^3 were compared with each other. The results are shown in Figure 7.

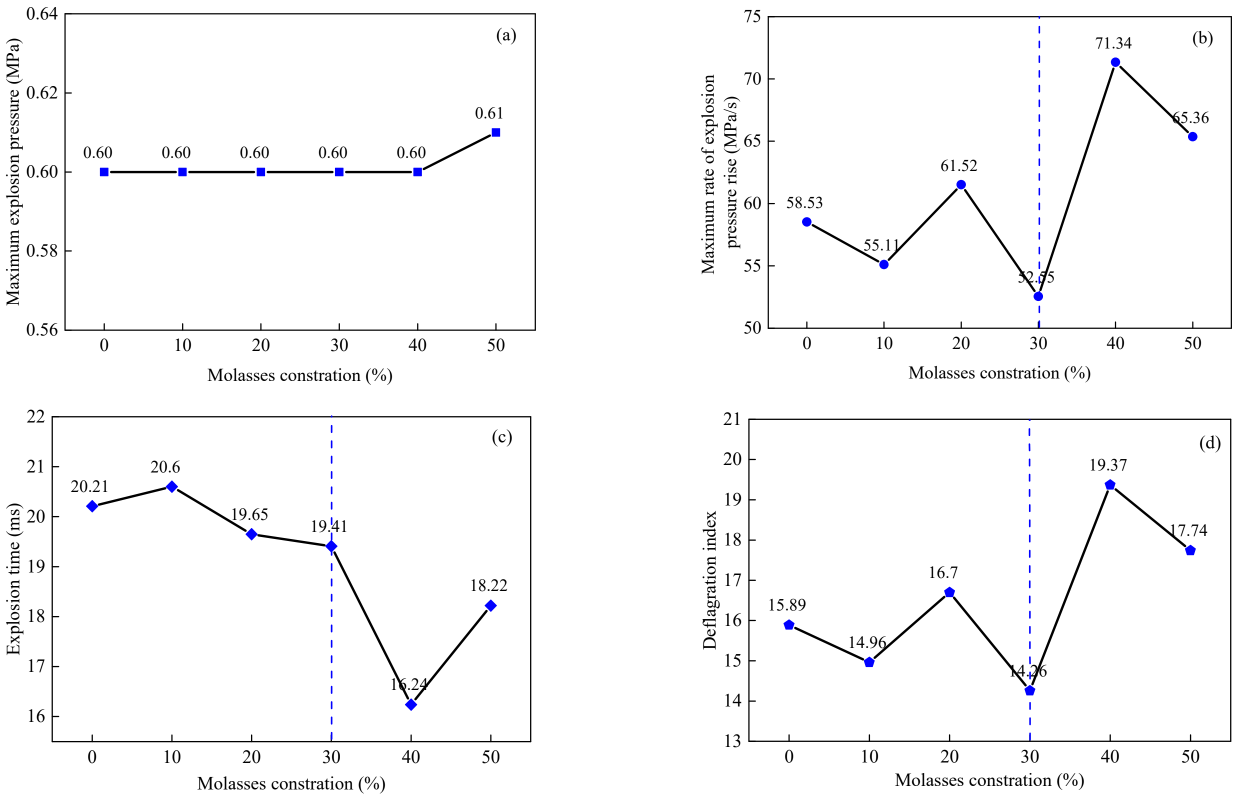

Figure 7. The maximum pressure (**a**), the maximum rate of the explosion pressure rise (**b**), the explosion time (**c**), and the deflagration index (**d**) of the explosion coal dust samples at a 400 g/m^3 explosion concentration.

As shown in Figure 7a, at the coal dust concentration of 400 g/m^3, molasses almost had no effect on the P_{max} of the coal dust. Except for the coal dust sample mixed with 50% molasses solution, the P_{max} of the other five coal dust samples were all 0.60 MPa. In addition, the other three explosion parameters all showed a similar change rule. Specifically, when molasses concentration is less than 30%, the molasses has no significant influence on the explosive characteristics of the coal dust; when molasses concentration is greater than 30%, the explosive intensity of the coal dust samples increases significantly. The results show that the molasses concentration is better ≤30% when using molasses as a coal dust suppressant.

Note that molasses has a significant bonding function on particulates [28,29,32]; therefore, after spraying molasses solution, coal dust particles could bond with each other and form small coal particles into large coal particles, which would reduce the explosion intensity of the coal dust. Simultaneously, after spraying the molasses solution at the bottom of the underground roadway, the coal dust deposited on the surface of the roadway formed a hard bonding shell, which could significantly decrease the concentration of secondary flying coal dust caused by underground pressure bumping, fall of ground, and spalling rib, thus decreasing the explosion intensity. Therefore, due to the analysis above, the actual suppression performance of the molasses solution on underground deposited coal dust explosion will be greater than the results obtained in this study.

3.2. Effect of Molasses Solution on the Decomposition Characteristics of the Coal Dust

3.2.1. TG-DTG Analysis

The decomposition characteristics of coal dust mixed with various molasses concentrations were investigated to better understand the influence mechanism of molasses solutions in coal dust explosions. Figure 8 depicts the mass variation of coal dust during the decomposition process. As shown in Figure 8a, the decomposition of coal dust mixed with pure water (0% molasses) includes the following three stages: (1) in stage 1, the mass of coal dust is reduced owing to moisture evaporation at temperatures less than 150 °C; (2) in stage 2, the temperature ranges between 150 °C and 300 °C, and the mass of coal dust increases slightly because of the oxygen adsorption of coal dust; a similar result was obtained in our previous study [42]; and (3) in stage 3, at temperatures above 300 °C, the mass of coal dust rapidly decreases due to the thermal decomposition of coal dust; in this stage, massive combustible gases are generated, such as CH_4, H_2, CO, and others [15,37]. The mass of the coal dust no longer changed at around 500 °C, indicating that the decomposition of coal dust had completed at this temperature. The decomposition process of the coal dust varied significantly after adding molasses, and the variation was mainly present in stage 2, i.e., 150–300 °C, as shown in Figure 8b. The mass of coal dust rapidly decreased after 150 °C; the mass increase caused by oxygen adsorption was dispersed, and the mass loss increased as molasses concentration increased.

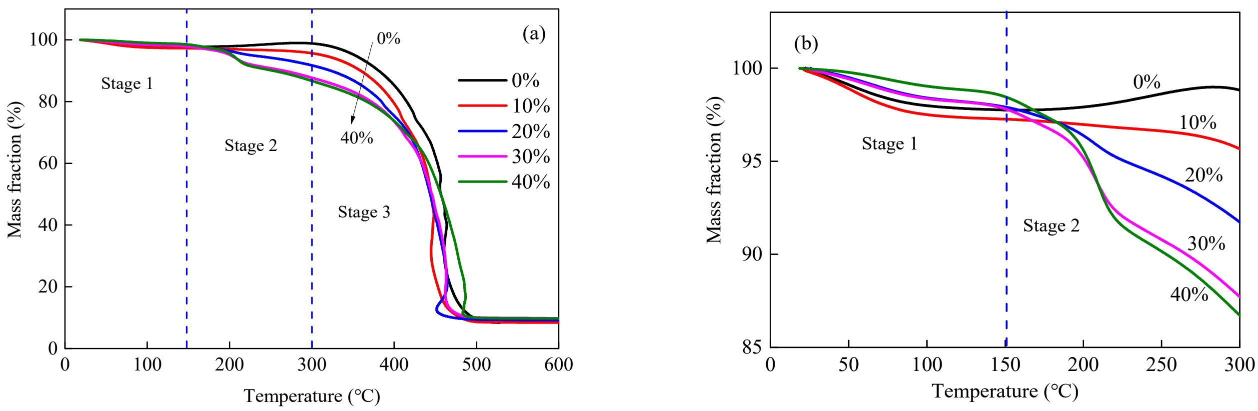

Figure 8. The mass fraction of the coal dust at 0–600 °C (**a**) and 0–300 °C (**b**).

To further investigate the effect of molasses on the decomposition of coal dust, the DTG curves of the coal dust samples were analyzed, as shown in Figure 9. As shown in Figure 9a, the three decomposition stages of coal dust decomposition are also clearly observed; the coal dust decomposition process varies significantly in stages 2 and 3 with increasing molasses concentration. At 150–300 °C, the DTG_{max} of coal dust mixed with pure water (0% molasses) was less than zero, as shown in Figure 9b. The results showed that the mass of coal dust increased at this stage. This was caused by the oxygen adsorption of coal dust [43]. When 10% molasses was added to the coal dust, the DTG value did not change significantly and remained at approximately 0 µg/min, indicating that the mass of coal dust did not change during this stage. This is because molasses on the surface of the coal dust can be pyrolyzed at this temperature. When the mass loss of molasses equals the oxygen absorption of coal dust, the total mass of coal dust remains constant; thus, the value of DTG remains at 0 µg/min. The decomposition rate then increased with molasses concentration, as shown in Figure 10a. DTG_{max} increased linearly with an R^2 = 0.84, indicating that molasses may speed up the decomposition rate of coal dust.

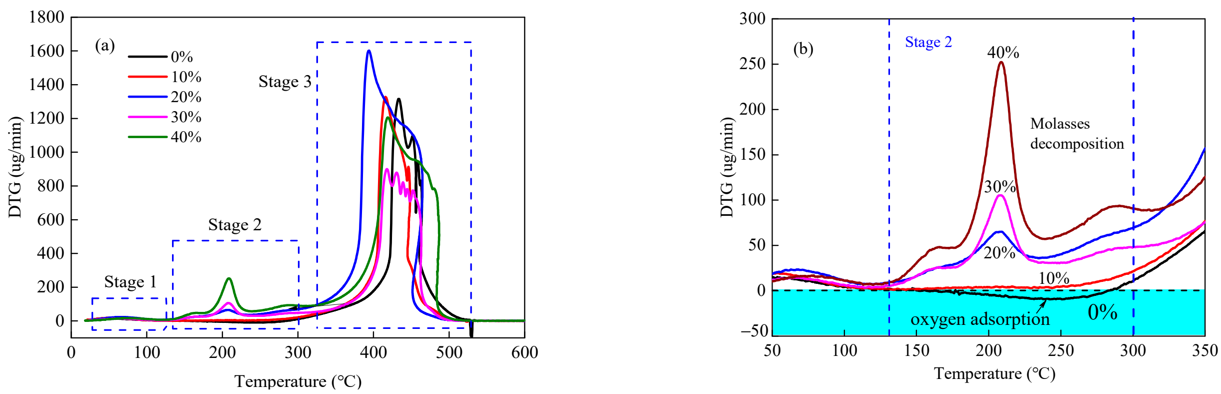

Figure 9. The DTG curve of the coal dust mixed with molasses at 0–600 °C (**a**) and 0–300 °C (**b**).

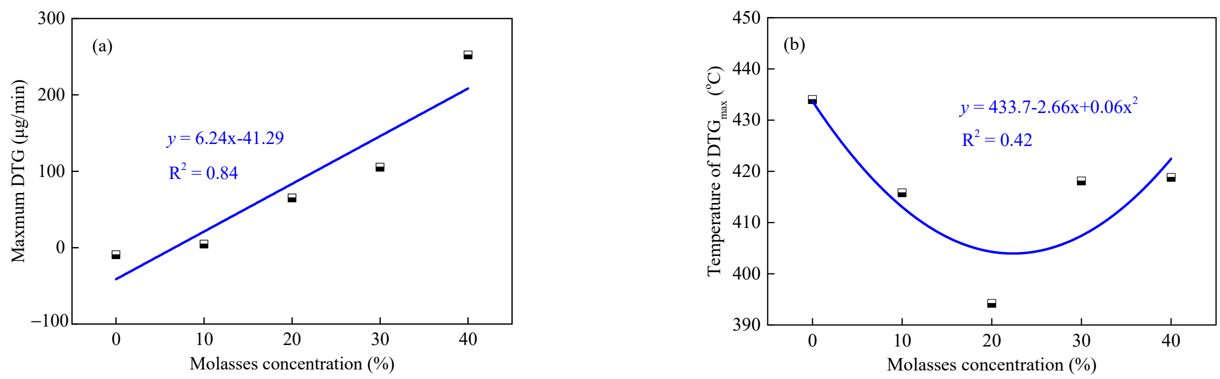

Figure 10. The maximum of the DTG (DTG_{max}) at 150–300 °C (**a**) and the temperature corresponds to the DTG_{max} at >300 °C (**b**).

The maximum value of the DTG was obtained at 400–450 °C in stage 3, as shown in Figure 9a, indicating that the coal dust underwent rapid decomposition at these temperatures. As shown in Figure 10b, the temperature corresponding to DTG_{max} (T_D) decreased first and then increased with a quadratic function with an R^2 = 0.42. This means that molasses can lower the decomposition temperature of coal dust to an appropriate concentration.

3.2.2. DTA Analysis

Figure 11 depicts the variation in the DTA of coal dust with temperature. In Figure 11a, three stages were observed, consistent with the results shown in Figure 9a. When the temperature was between 0 °C and 150 °C (Stage 1), the DTA value was less than 0 µV, indicating that an endothermic reaction occurred in this stage. Combined with the DTG curves (Figure 9), it is clear that the moisture evaporation in the coal dust caused the endothermic reaction. When the temperature is between 150 °C and 300 °C (Stage 2), as shown in Figure 11b, the DTA value begins to rise from 150 °C and exceeds 0 μV at approximately 200 °C. Subsequently, it rapidly increased with temperature and reached the maximum at approximately 300 °C; the result verified that the exothermic reaction of molasses decomposition occurred in this stage. When the temperature exceeds 300 °C (Stage 3), the DTA rapidly increased again and reached a maximum at approximately 450 °C. The decomposition of coal dust occurs, a massive oxidation reaction occurs, and a large amount of heat is generated; thus, the DTA rapidly increases and maintains a large value in this stage. When the temperature exceeds 500 °C, the DTA returned to 0 μV, indicating that the coal dust decomposition process is over. The results showed that the molasses decomposition process has a significant exothermic effect, starting at a decomposition temperature lower than that of coal dust.

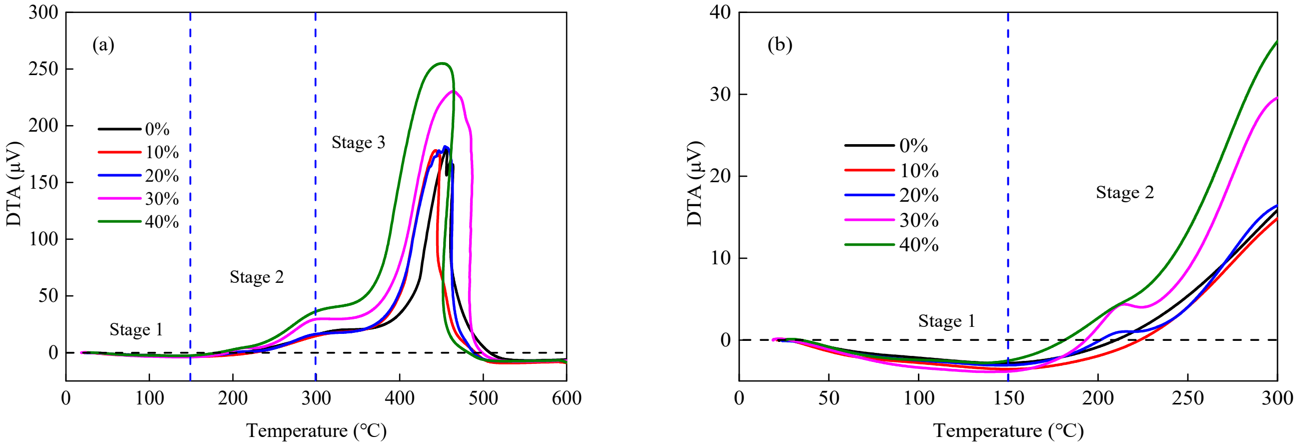

Figure 11. The DTA of the coal dust at 0–600 °C (**a**) and 0–350 °C (**b**).

4. Discussion

The explosion parameters of the coal dust samples mixed with molasses solutions were tested using a 20 L spherical explosion device in this study to investigate the influence of molasses solutions on the explosion of coal dust deposited in underground coal mines. The findings revealed that molasses could weakly promote coal dust explosions at low coal dust concentrations but had no significant effect at high coal dust concentrations. Subsequently, TG-DTA experiments were performed on coal dust samples mixed with molasses solution to determine how molasses works with the explosion of coal dust.

It is widely accepted that the coal dust explosion process includes two stages [15,17,38,44]. In stage 1, coal dust decomposes and releases combustible gases such as methane, ethane, and hydrogen [15,37]. In stage 2, the combustible gases are mixed with air and violently burn when encountering a fire flame, resulting in an explosion [15]. Therefore, heat and oxygen are key factors affecting the first and second stages of a coal dust explosion, respectively. Molasses and coal dust decomposed at 200–300 °C and 350–500 °C, respectively, according to the results of the TG-DTA experiment (Figures 9 and 11). According to these findings, we know that the heat generated by the oxidation reaction of molasses can accelerate the decomposition of coal dust, increasing the intensity of coal dust explosions; however, the oxidation reaction of molasses could consume a lot of oxygen and produce large amounts of incombustible gases such as CO_2 simultaneously, which can suppress the combustion of the gases generated by coal dust decomposition, thus inhibiting coal dust explosions. Therefore, molasses could promote the explosion of coal dust at low coal dust concentrations, but it has no effect on the explosion of coal dust at high coal dust concentrations.

According to the coal dust explosion test (Figure 6), molasses can weakly strengthen the explosion intensity of coal dust when its concentration is less than 400 g/m^3 in a confined space with limited oxygen. In this stage, the suppression effect of molasses on the coal dust explosion caused by oxygen consumption is not significant; however, the heat released by molasses oxidation can improve the decomposition of coal dust and cause massive combustible gas generation, which could strengthen the coal dust explosion intensity. When the coal dust concentration is greater than 400 g/m^3, the molasses oxidation consumes the oxygen in the confined space (Figure 12) and also produces a large amount of heat, which could accelerate the decomposition of coal dust and the generation of combustible gas; however, the combustible gas cannot be ignited or fully burned because too much oxygen is consumed by the molasses oxidation. Therefore, under the co-influence of these two effects, molasses had no significant effect on the coal dust explosion.

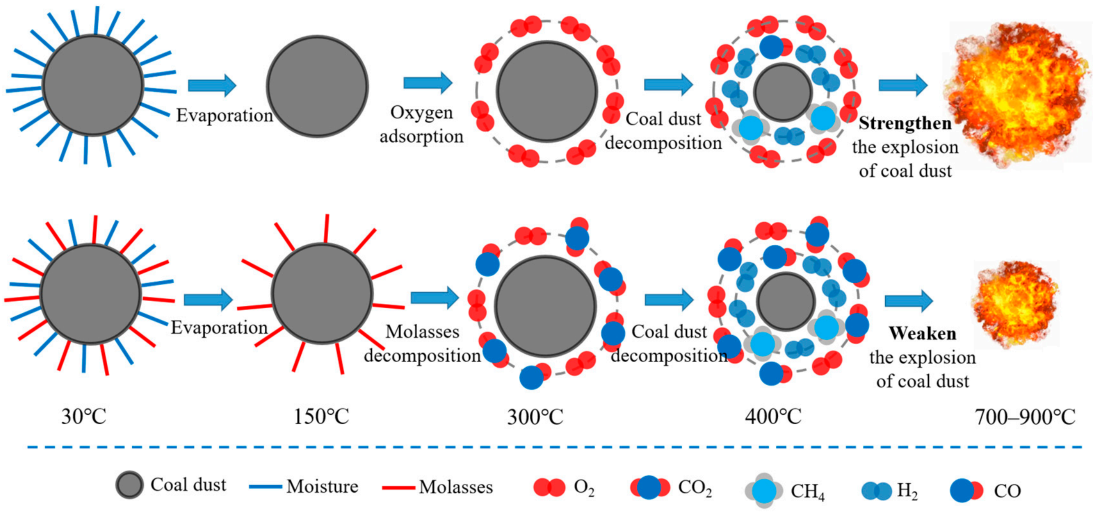

Figure 12. Schematic diagram of the influence of molasses on the coal dust explosion.

Furthermore, numerous studies have shown that molasses has a significant bonding effect on particulate matter [33]. Therefore, after spraying molasses solution on the roadway surface in underground coal mines, the coal dust deposited at the bottom of the roadway can be bonded into a shell that is difficult to raise under the action of a shock wave caused by a rock burst, a roof fall, or other disasters. The raised coal dust is also composed of large coal dust particles bonded by molasses, which reduces the explosion intensity of coal dust deposited in underground coal mines [36,43,45]. The analysis mentioned above is not reflected in the experimental results of this study due to the limitations of the experimental platform; therefore, the actual suppression efficiency of molasses on coal dust will be higher than that of the results of this study. To explore the exact suppression efficiency of molasses on the explosion characteristics of coal dust deposited in underground coal mines, it is of great significance to conduct explosion experiments using a large-scale platform.

In general, this paper studied the influence of molasses on coal dust explosions. The results show that, at low coal dust concentrations, molasses can weakly improve the coal dust explosion, but at high coal dust concentrations, molasses has no significant effect on the coal dust explosion. This indicates that the explosion of the coal dust should be considered when using molasses as coal dust suppressant.

5. Conclusions

The objective of the study is to investigate whether molasses has effects on the explosion of coal dust deposited in underground coal mines. To achieve the objective, the explosion tests and the TG-DTA experiments were conducted for the coal dust samples mixed with molasses solutions in various concentrations. The following conclusions were drawn from the study:

(1) With the increasing of coal dust concentration, the P_{max}, $(dP/dt)_{max}$, and K_{st} of the coal dust samples all increased first and decreased then; in contrast, the t_e of the coal dust samples decreased first and increased then, with the turning points located

around 400 g/m^3. According to the result, the molasses can weakly promote the explosion of coal dust at low coal dust concentrations (less than 400 g/m^3) but has no significant effect on the coal dust explosion at high coal dust concentrations (larger than 400 g/m^3).

(2) The maximum explosion intensity of the coal dust samples was achieved at around 400 g/m^3. At the coal dust concentration of 400 g/m^3, molasses has no significant effect on the coal dust explosion when its concentration is less than 30%, but molasses has a weak promotion effect on the coal dust explosion when its concentration is greater than 30%. Therefore, the molasses concentration is better $\leq$30% when using molasses as a coal dust suppressant.

(3) The coal dust decomposition process mixed with molasses included three stages: moisture evaporation (0–150 °C), molasses decomposition (150–300 °C), and coal dust decomposition (300–500 °C). The characteristic decomposition temperature (T_d) of coal dust first decreased and then increased as molasses concentration increased.

(4) Molasses has a lower decomposition temperature than coal dust. Molasses oxidation produces heat, consumes oxygen, and produces a non-combustible gas. At low coal dust concentrations, the heat produced by molasses oxidation promotes the decomposition of coal dust and accelerates combustible gas generation, thereby enhancing coal dust explosions. At high coal dust concentrations, molasses oxidation consumes massive amounts of oxygen, resulting in the combustible gas, decomposed by coal dust, cannot be fully burned; with the co-influence of the generation-heat and consumption-oxygen, molasses has no significant influence on the coal dust explosion.

In summary, in this study, the influence of molasses on the explosion of coal dust was investigated, and the influence mechanism was discussed. The study is significant for preparing environmentally friendly and low-cost coal dust suppressants using molasses. According to the study, the influence of molasses on coal dust explosions should be considered when preparing coal dust suppressants using molasses in underground mines.

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