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Study of Parameters and Theory of Sucrose Dust Explosion

Juju Jiang [1], Xiaoquan Li [1,2,*], Siting Liang [1], Yuankun Zhong [1], Lei Yang [1], Peng Hao [1] and Jeffrey Soar [2,*]

1 School of Resources, Environment and Materials, Guangxi University, Nanning 530004, China; jujujiang@st.gxu.edu.cn (J.J.); 2015392038@st.gxu.edu.cn (S.L.); zyk@st.gxu.edu.cn (Y.Z.); ylettomf@st.gxu.edu.cn (L.Y.); 2015392012@st.gxu.edu.cn (P.H.)
2 School of Business, University of Southern Queensland, Toowoomba 4350, Australia
* Correspondence: lxq0927@gxu.edu.cn (X.L.); jeffrey.soar@usq.edu.au (J.S.)

Abstract: To investigate the parameters of sucrose dust explosion, the minimum ignition energy (MIE) and minimum ignition temperature (MIT) were evaluated. The experiments tested the MIE of sucrose dust under different conditions of dust quantity, ignition delay time (IDT), and powder injection pressure (PIP). The experiments tested the MIT of different particle sizes. The results demonstrate that the MIE of sucrose powder under three conditions was an open-up quadratic polynomial. When the dust quantity, the IDT, and PIP were 0.5 g (417 g/m^3), 90 ms, and 150 kPa, respectively, the MIE was 58.9 mJ, 62.6 mJ, and 52.4 mJ. The MIT was positively correlated with the particle size of sucrose dust, and the MIT was 340 °C. At the molecular level, the "O–H" bonds of the sucrose molecule hydroxyl groups were broken by the discharge of electrodes or high temperature to generate H_2. The combustion of H_2 caused the explosion to spread to the surrounding sucrose dust and made the deposited dust rise, forming an interlocking explosion. The explosion would not stop until the dust concentration dropped below the lowest explosion limit. The results of this study can provide guidance for sucrose enterprises to prevent dust explosion accidents.

Keywords: sucrose dust explosion; minimum ignition energy; minimum ignition temperature; particle size; electrode discharge

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1. Introduction

Sucrose is one of the four national strategic materials in China; it is as important as grain, cotton, and oil. Dust explosions can cause damage to buildings and severe losses [1]. According to a study of Yuan et al. [2–4], food dust is responsible for 40% of global explosions. For example, a series of sucrose dust explosions that occurred in the Imperial Sucrose Refinery in Port Wentworth, GA, US, [5] resulted in 14 deaths, dozens of injuries, and the destruction of buildings throughout the factory area [6]. Stahmer et al. studied the maximum explosion pressure and its raise rate of sucrose dust [7]. Hence, it is of prime importance to study sucrose powder explosion by the experimental and theoretical research.

The minimum ignition energy (MIE) and minimum ignition temperature (MIT) of dust cloud are basic parameters for studying dust explosion. Sepideh et al. used a new theoretical model to predict the MIE by studying the characteristics of dust [8,9]. Pranav et al. found that the MIE might be affected because some smaller particles can escape the Hartmann tube [10]. Devi et al. measured the MIE of coal dust, L-isoleucine powder, and polyethylene dust, respectively [11–13]. Bu et al. [14] measured the MIE and MIT of corn starch, wood dust, and polymethyl methacrylate, respectively. Cao et al. [15,16] studied the MIE of zirconium powder for a hybrid system consisting of Pittsburgh Pulverized Coal, methane, and air. Lidor et al. studied affected factors of the zirconium dust explosion in a 20 L cylindrical explosion device [17]. Shu et al. processed by the fitting method, and the degree of influence of three factors on the explosion intensity parameter of micron-sized zinc powder was as follows: dust concentration, ignition delay time (IDT), and powder injection pressure (PIP) [18]. Sanchirico et al. proposed the volatilization point as a key parameter to evaluate flammability and studied its influence in single and mixed dusts [19–21]. Mixed explosions can occur even when the explosive concentration of both dust and gas is below its minimum explosive concentration [22]. Di Sarli et al. developed a theoretical model to predict the MIT for polyethylene dust at different concentrations, based on the assumption that pyrolysis or devolatilization is fast. In addition, a statistical approach has been proposed to study the autoignition temperature of powder clouds [23,24]. The MIT of mixtures has been found to be lower than that of a single substance [25]. Fu et al. used CFD to simulate the magnesium dust dispersion and explosion of a 20 L apparatus [26]. Rybak et al. investigated the ignition phenomenon of eight coals of different coal ranks, petrographic compositions, and places of origin using TGA/DSC, DTIF, EFR, and a 20 L cylindrical explosion device [27].

Grain dust differs greatly from coal dust, metal dust, and wood dust in its molecular structure. Coal and wood dust are made up of a mixture of macromolecule dust, and their structure is complex; their MIE and MIT are relatively high. The molecular structure of metal dust is relatively simple, and it can oxidize with oxygen directly, but the MIE and MIT are greatly affected by the metal activity. The complexity of the grain dust molecule is between the three, and there is the existence of a hydroxyl group in sucrose molecules, which has its unique characteristics, such as low melting point, hydrophilicity, decomposition, etc. Therefore, this paper intends to test the MIE and the MIT of sucrose dust and discuss the theory of sucrose dust explosion from the perspective of its molecular structure. The research results provide an experimental and theoretical basis for sucrose enterprises to prevent sucrose powder explosion accidents.

2. Experimental Devices and Sample

2.1. Experimental Device of MIE of Dust Cloud

The experimental apparatus for studying the MIE of sucrose powder explosions consisted of a 1.2 L Hartmann tube (HY16428A, Hongyuan Scientific Instrument Co., LTD, Jilin, China), an air compressor, and a high-speed camera, as shown in Figure 1. The Hartmann tube is mainly composed of a quartz glass tube, an ignition electrode, and a powder spraying system. The device can provide ignition energy ranging from 0.1 to 999.9 mJ. In order to observe the flame development, a high-speed camera (MEMRECAM GX-8, nac Image Technology, Inc., Tokyo, Japan.) was used to catch flame images of the experimental process. During the experiment, a certain quantity of sucrose powder was dispersed on the umbrella diffuser at the bottom of the Hartmann apparatus; simultaneously, the air compressor, high-speed camera, and discharge ignition of the electrode was triggered, and the computer automatically recorded whether the dust was ignited. The conditions were adjusted, and the steps were repeated until all the conditions of the experiment were completed.

A flame height of 60 mm was considered the criterion for determining whether the dust had been ignited. The MIE is defined between the highest energy E_2 that successively ignites the dust 20 times and the lowest energy E_1 that fails to ignite the dust, namely: $E_1 < E_{min} < E_2$. Although the MIE is a range rather than a single value, in order to obtain the MIE of sucrose powder clearly, it usually is estimated by Equation (1):

$$\mathrm{MIE} = 10^{\log E_2 - \frac{I\,[E_2] \times (\log E_2 - \log E_1)}{(NI+I)\,[E_2]+1}} \tag{1}$$

where E_2 is the energy level at which ignition occurs and E_1 is the energy level below E_2 where no ignition was observed after 20 tests. $I\,[E_2]$ is the number of runs with ignition at E_2 and $(NI + I)\,[E_2]$ represents the total number of tests at E_2. For MIE testing, $(NI + I)\,[E_2]$ should be greater than or equal to 5 tests, based on BS EN 13821-2002 [28].

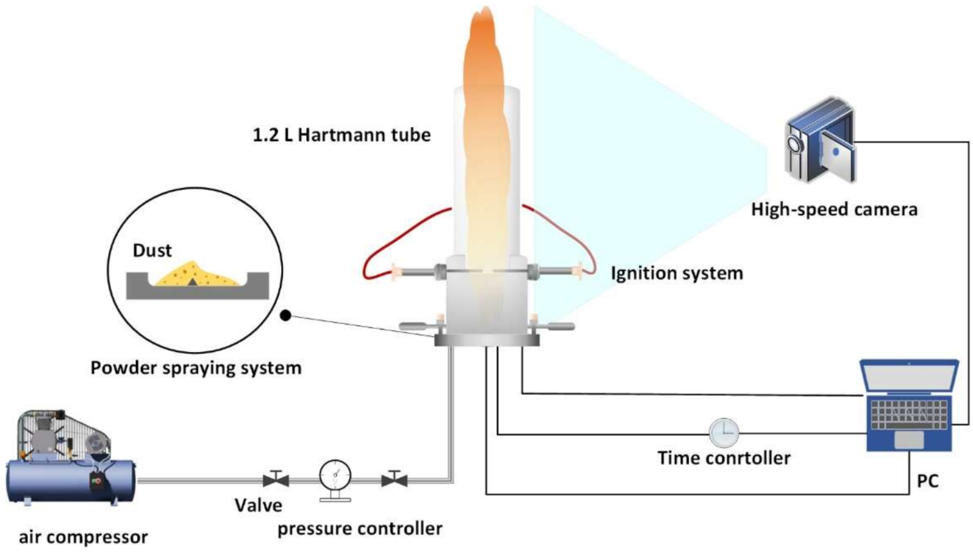

Figure 1. Experimental device of MIE of dust cloud.

2.2. Experimental Device of MIT of Powder Cloud

The dust MIT of sucrose powder was tested in a Godbert–Greenwald furnace (HY16429, Hongyuan Scientific Instrument Co., LTD, Jilin, China), as shown in Figure 2. The test apparatus included a heating furnace, control system, gas storage tank, solenoid valve, dust storage chamber, air compressor, high-speed camera, and observation room. The device can provide temperature ranging from 25 to 1000 °C. In order to observe the flame development, a high-speed camera (MEMRECAM GX-8, nac Image Technology, Inc., Tokyo, Japan) was used to catch flame images. The methods involved weighing a certain quantity of sucrose dust into the dust chamber and tightening the lid, setting the temperature of the heating furnace and the delay time of powder injection, and initiating the simultaneous start-up of the air compressor and the high-speed camera. The computer automatically records the dust cloud and whether it was ignited. The setting conditions were adjusted and the steps were repeated until all conditions of the experiment were completed.

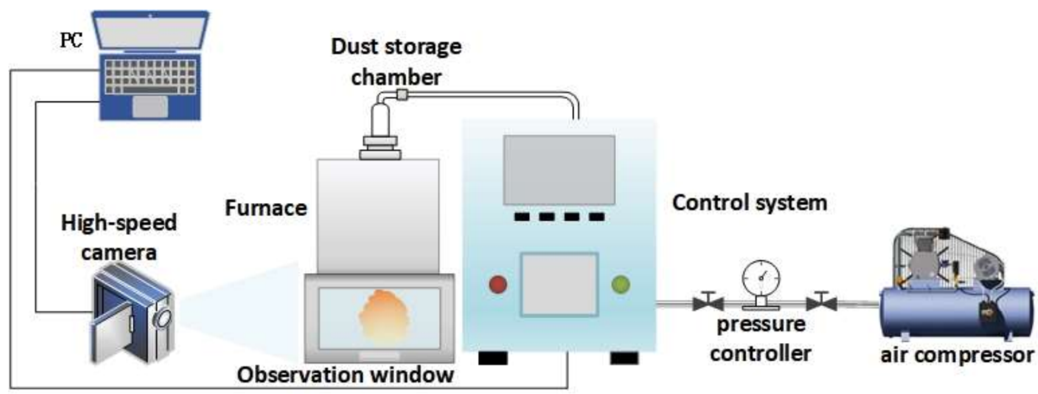

Figure 2. Experimental device of MIT of dust cloud.

In the experiment, when the flames are ejected from the lower end of the heating furnace, it can be considered that the dust has been ignited; otherwise, it has not been ignited. The MIT lies between the highest temperature T_2 that ignites 10 times successively and the lowest temperature T_1 that fails to ignite the dust, namely, $T_1 < T_{min} < T_2$.

2.3. Experimental Materials

The sucrose powders were collected in the drying workshops, screening workshops, and packing workshops of four sucrose refineries, Mingyang, Dongjiang, Lingli, and Xiangshan, of Nanning Sucrose Industry Co., Ltd. (Nanning, China), a listed company.

Scanning electron microscope (SEM) imaging of sucrose powder was undertaken using the Hitachi S-3400N (Hitachi (China) LTD, Beijing, China), which depicts the particle microscopic morphology. Figure 3 shows the images of sucrose dusts with different particle sizes. It shows that most sucrose particles have irregular shapes, and there are many smaller sucrose particles attached to the relatively smooth surface of larger particles.

(**a**) 25–37 μm (**b**) 38–47 μm (**c**) 48–75 μm

Figure 3. Electron microscopy scanning images of sucrose dusts with different particle sizes.

The samples were less than 75 μm to comply with the EN13821 [28] standard for MIE testing. After being ground by a mechanical crusher, the standard sample sieved was used to screen out three groups different particle sizes (25–37 μm, 38–47 μm, and 48–74 μm). In order to eliminate the effect of moisture, all samples were dried in a room temperature activated carbon oven for 12 h before tests and then stored in a dry bottle.

3. Results and Discussion

3.1. Effect of Parameters on MIE of Sucrose Dust Cloud

3.1.1. Effect of Quantity of Dust on MIE

In the experiments, the MIE of sucrose dust with quantities of 0.3, 0.4, 0.5, 0.6, and 0.7 g, were tested by setting the PIP of 60 kPa and the IDT of 90 ms. Repeated experiments were conducted to obtain the MIE, which is shown in Figure 4. This shows that the relationship between dust quantity and MIE is an open-up quadratic polynomial. When the quantity of sucrose dust is 0.5 g, the MIE is 58.9 mJ, which shows that this concentration of dust is the most sensitive. The ignition sensitivity grade is between medium sensitivity to medium to high sensitivity in Table 1. The concentration of sucrose dust near the electrode is the greatest, the spacing of particles is the most appropriate, and the minimum energy is required.

Table 1. Level of ignition sensitivity based on MIE [1].

MIE (mJ)	Level of Ignition Sensitivity	Precautions
500	Low sensitivity	Earth plant when ignition energy is at or below this level.
100	Medium sensitivity	Consider earthing personnel when ignition energy is at or below this level.
25	Medium to high sensitivity	The hazard from electrostatic discharges from dust clouds should be considered, although the majority of ignition is below this level.
10	High sensitivity	Take above precautions and consider restrictions on the use of high-resistivity materials (plastics). Electrostatic hazard from bulk powders of high resistivity should be considered.
1	Extreme sensitivity	Precautions should be as for flammable liquids and gases when ignition energy is at or below this level.

[1] BS 5958-1-1991, Code of practice for control of undesirable static electricity—General considerations, 1991 [29].

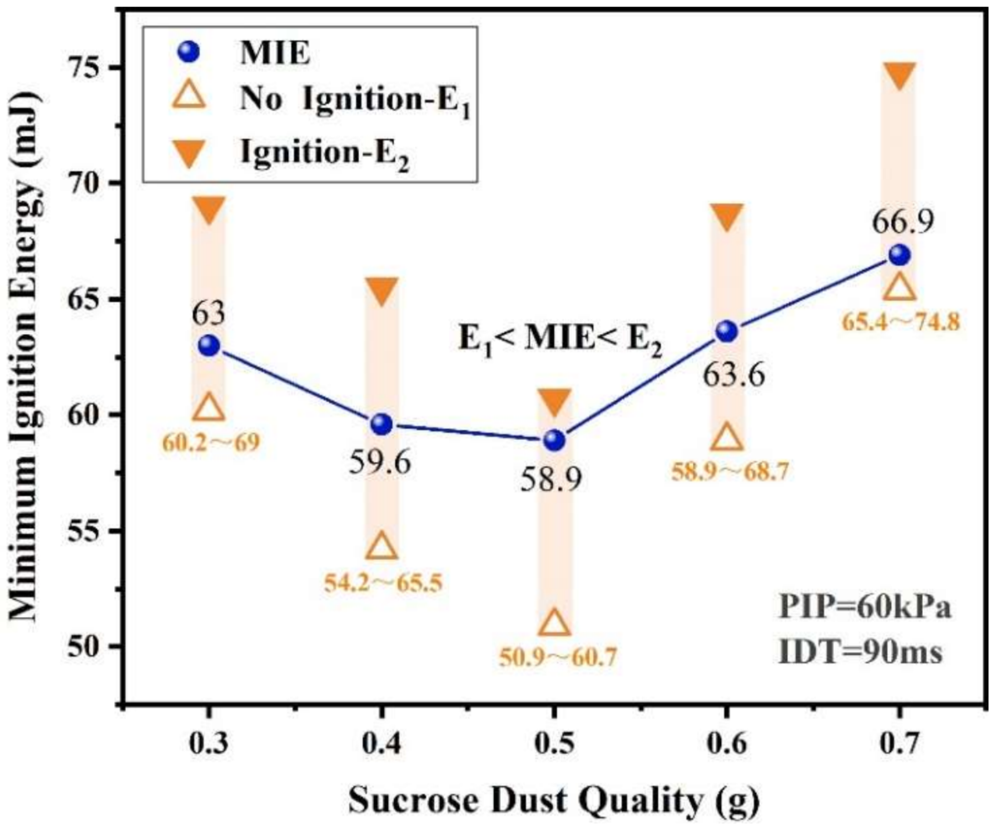

Figure 4. Effect of the sucrose dust quantity on the MIE.

As the sucrose dust concentration increased, the distance between the sucrose dust particles gradually decreased. Meanwhile, the MIE slowly reduced, since some ignited particles transferred energy to unignite them [17]. When the most sensitive concentration of sucrose dust explosion is 417 g/m^3, the corresponding MIE is 58.9 mJ. When the sucrose dust concentration is greater than 417 g/m^3, because the energy required for the combustion of a single particle of dust is certain, the dust concentration increased, and more dust particles per unit volume existed near the ignition electrode, so the MIE required became larger.

Figure 5 shows the propagation timing images of the deflagration flame of sucrose powder at the concentration of 417 g/m^3 and the PIP of 60 kPa. It can be seen that the IDT and duration were short. Meanwhile, low ignition energy and fast flame propagation velocity were found. After 95 ms ignition, a bright yellow flame appeared above the tube, which indicates that the deflagration intensity increases gradually. Since 185 ms, an intense burning flame spray pressure and dust cloud were taken to the upper tube, while the bottom cloud of the dust mass concentration greatly decreases. This can be seen in the figure: the top still has a dust cloud burning flame, but in the middle and bottom, the sucrose dust is burnt and there is no flame. With the mass concentration of the sucrose dust cloud on the upper side, the combustion decreases further, and the combustion gradually weakens until it goes out. The flame will not extinguish until all the raised dust burns completely.

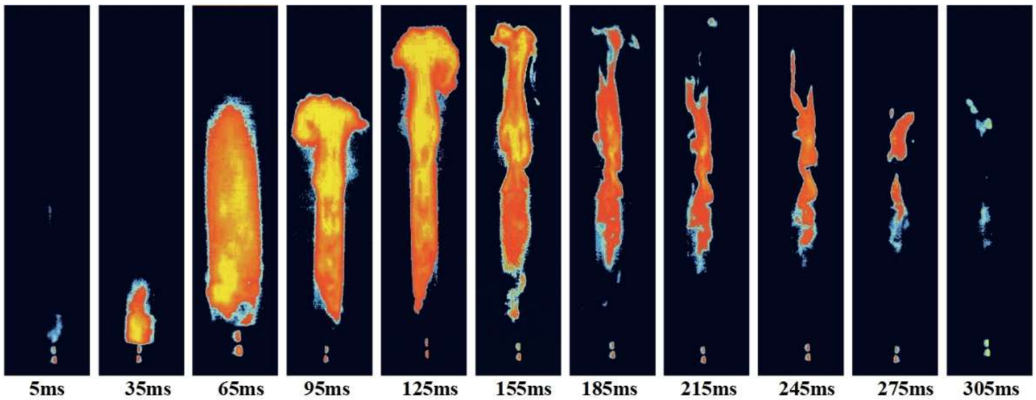

Figure 5. Image of explosion development of sucrose dust in Hartmann apparatus.

3.1.2. The Relationship between IDT and MIE of Sucrose Dust

IDT refers to the time interval between PIP and electrode ignition. When other experimental conditions are unchanged and the IDT is different, the dispersion and settlement behavior of dust in the Hartmann tube are different. The MIE of sucrose dust was tested when the IDT was 15, 30, 60, 90, 120, 150, and 180 ms, respectively. The MIE under corresponding conditions was found through repeated experiments. The experimental data are as shown in Figure 6. It shows that the relationship between dust quantity and MIE is an open-up quadratic polynomial.

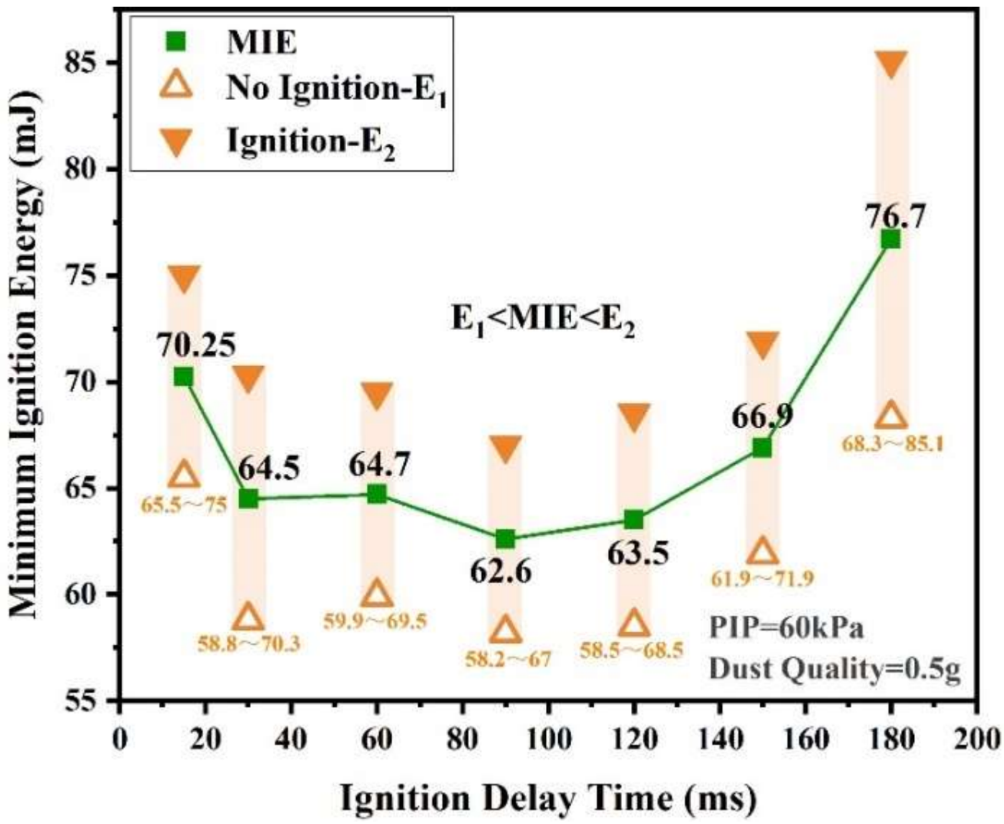

Figure 6. The relationship of IDT and MIE.

The results indicate that under the condition of constant concentration, dust particles were not fully mixed with air in a short time. A better dust cloud state failed to form in this case. So, the MIE required was bigger. In addition, a larger IDT resulted in occurring agglomeration phenomenon due to the dust self-gravity. Therefore, the explosion effect is suppressed, and the MIE increased gradually. Finally, when the IDT is 90 ms, the MIE is 62.6 mJ and approximate to the lowest point, which shows that the IDT is the greatest.

3.1.3. The Relationship of PIP and MIE of Sucrose Dust

When the IDT is 90 ms and the dust mass is 5 g, the MIE of sucrose dust is tested at 40, 60, 80, 100, 120, 150, and 180 kPa, respectively. The MIE under corresponding conditions was found through repeated experiments. The experimental data are as shown in Figure 7. It shows that the relationship between dust quantity and MIE is an open-up quadratic polynomial.

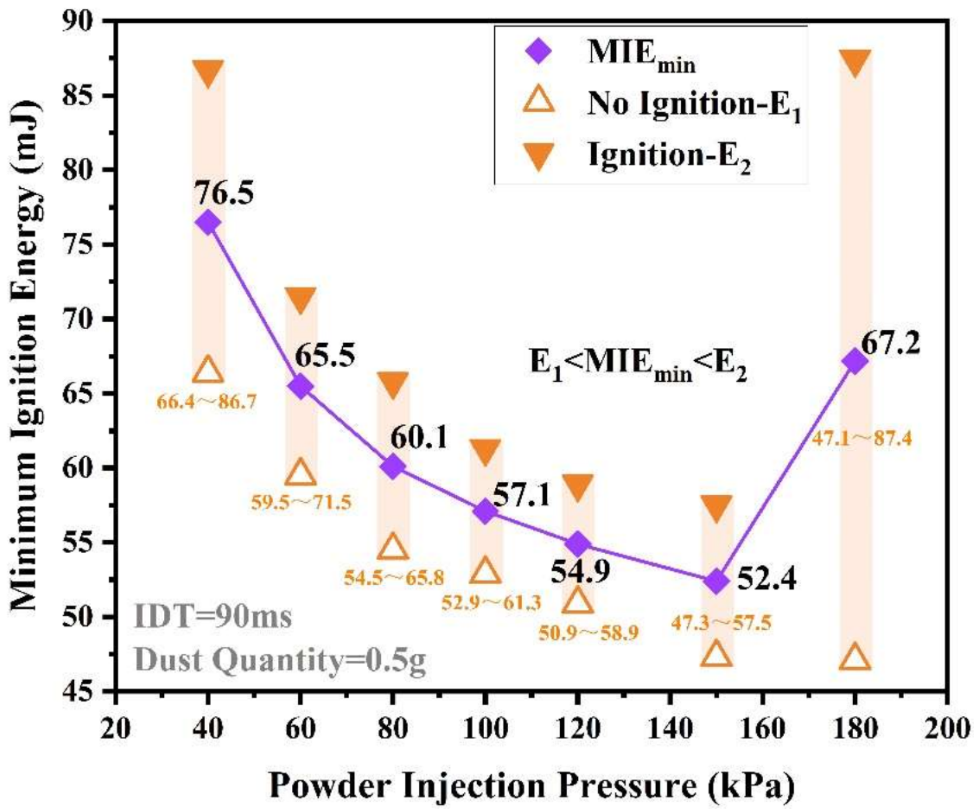

Figure 7. The relationship between PIP and MIE.

The results show that when the PIP is lower than 150 kPa, it is difficult for the sucrose dust particles to overcome gravity, and the sedimentation phenomenon begins to occur after the whole tube has not been dispersed. At this time, the dust is mainly distributed in the lower half of the tube. When the PIP is at an optimum level of 150 kPa, the dust is evenly distributed throughout the sphere, and the dust concentration in the entire sphere is relatively uniform [18]. When the PIP exceeds 150 kPa, the dust will be driven by the powerful airflow and move rapidly in the tube, and the dust is unevenly distributed throughout the tube. Therefore, the MIE will be maximized only when the PIP is 150 kPa.

The results highlight that different concentrations of dusts, IDT, and PIP can significantly impact the MIE. These three factors should be taken into account when assessing the risk of sucrose dust explosion. With the help of the role of parameters on MIE, ignition prevention efforts could be guided in process industries.

3.2. *Effect of Parameters on MIT of Sucrose Powder Cloud*

This experiment is mainly about the relationship between dust particle sizes and the MIT of sucrose dust. In the experiment, the sucrose dust with particle sizes of 25–37 µm, 38–47 µm, and 48–74 µm was tested when the PIP was 50 kPa and sucrose dust quantity was 0.5 g. The MIT of sucrose dust under the corresponding conditions is shown in Table 2.

The MIT of sucrose dust decreases monotonously with the decrease in particle size, and the gradient decreased between 20 and 30 °C. The MIT of sucrose dust was linearly related to the particle size.

Table 2. The MIT under different dust particle sizes.

Dust Quantity (g)	PIP (kPa)	Particles Size (μm)	MIT (°C)
0.5	50	48–74	390
		38–47	370
		25–37	340

Figure 8 shows the pictures taken with a high-speed camera when the sucrose dust quantity is 0.5 g, the PIP is 50 kPa, and the furnace temperature is 340 °C. From left to right, we can see the whole process of the development of a yellow-white flame. The explosion intensity and speed of sucrose powder are very fast, and the flame is ejected from the bottom of the furnace at high speed. A shock wave will raise the unburned dust at the bottom of the observation room to participate in the combustion, and the flame will not extinguish until all the sucrose dust is completely burned.

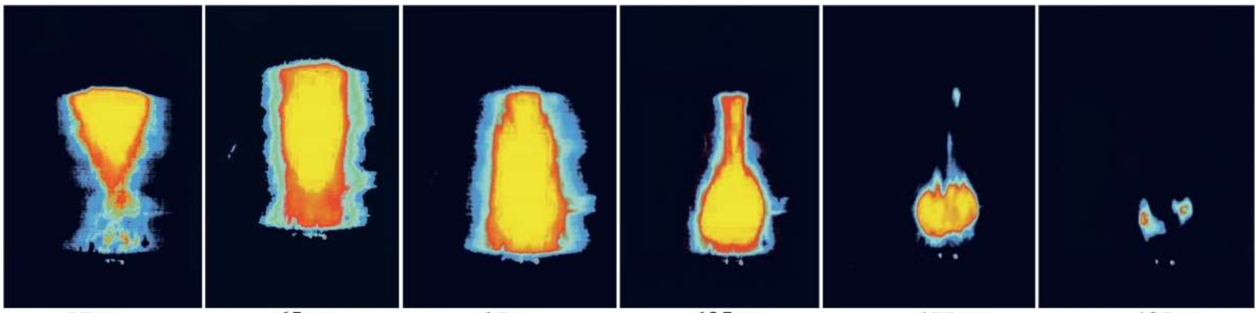

Figure 8. Image of explosion development of sucrose dust in Godbert–Greenwald furnace.

When the specific surface area of small particle size dust was larger, the contact with oxygen was greater when burning, the reaction speed was faster, the sucrose dust was more fully burned, and the dust cloud be ignited under lower temperature [30].

3.3. Theory of Broken Hydroxyl "O–H" Bonds in the Sucrose Dust Molecule

The existing theories of dust explosion mainly focus on the surface combustion reaction of dust particles: for example the five factors of dust explosion, as shown in Figure 9, such as combustible dust, oxidant, mixing (or suspension), confinement, and ignition, respectively [31–34]. Domino and Bayesian networks theories can be derived from the five factors [35]. The combustion of any substance is a chemical reaction of its molecule; if active metal Na and K are put into water, H_2 and NaOH or KOH will be produced by the electrolysis of water, and the quantity of heat will be released, so combustion can occur without any ignition source. The combustion phenomenon is not that active metals are burning but that active metals and water react chemically, and H_2 produced by electrolysis burns on the surface of water. Similarly, sucrose dust explosion can be explained by chemical changes of its molecules under the action of electrode discharge or high temperature.

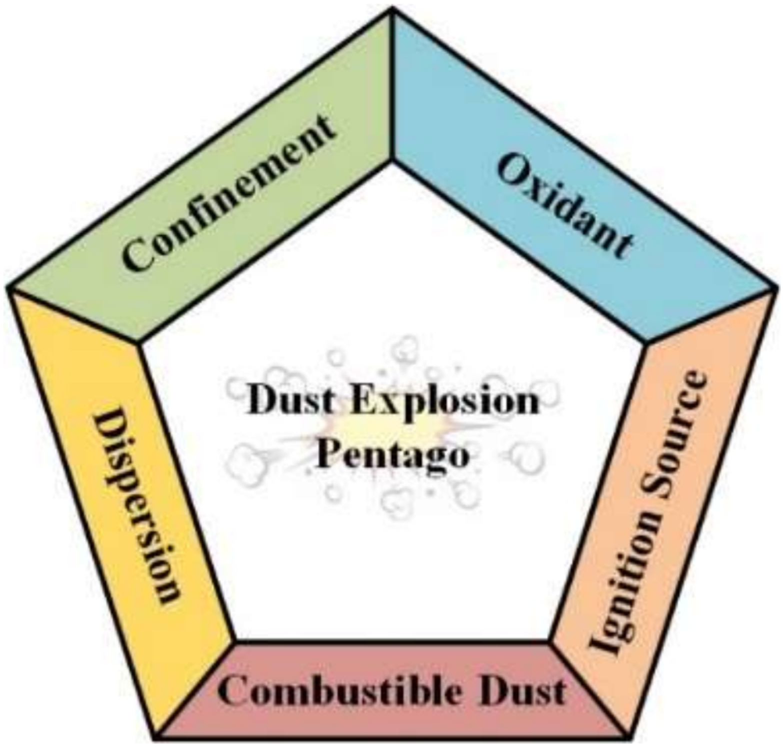

Figure 9. The five factors of dust explosion [35].

The sucrose molecule has an organic hydroxyl structure; its molecular formula is $C_{12}H_{22}O_{11}$, and its structure is shown in Figure 10. There are six hydroxyl groups in each sucrose molecule; in the "C–O–H" structure, the oxygen atoms contain solitary pairs of electrons, which make the electron cloud between hydrogen and oxygen atoms transfer to the direction of oxygen atoms. As a result, the "C–O" bonds are stronger and the "O–H" bonds are easier to break. In the experiment, the sucrose dust was ejected by high-pressure gas, the initial velocity was higher, and the velocity of the dust was slowed down after being ejected by air resistance and gravity.

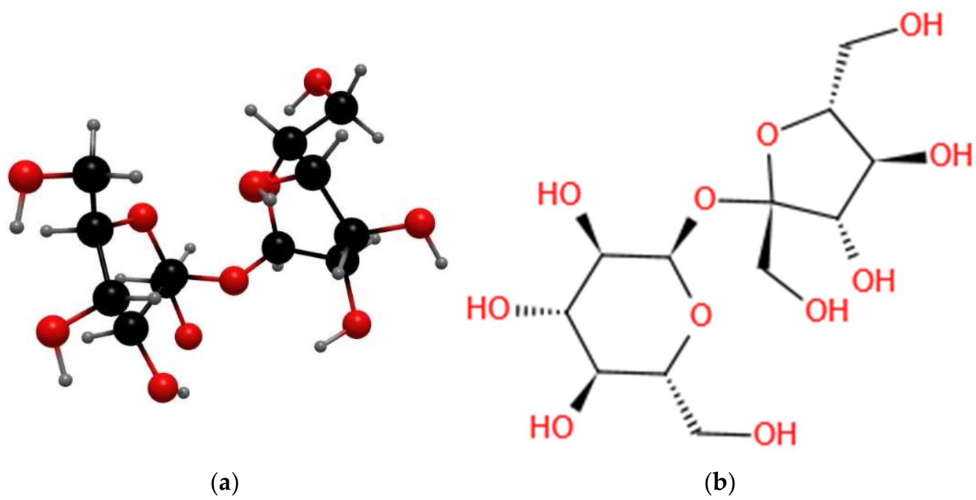

Figure 10. Sucrose molecular structure: (**a**) the black sphere, red sphere, and silver sphere represent C, O and H respectively; (**b**) Description of chemical structure of sucrose.

After ejecting for a certain distance, the dust particles move up along the Hartmann tube in the form of diffusion. The heat generated by friction between the dust particles and the air makes the dust surface liquefied or gasified, enhances the activity, increases the molecular distance, increases the discharge of the electrodes, and bombards the sucrose. On the surface of the dust, the sucrose molecule on the surface is activated to break the hydroxyl "O–H" bonds in the sucrose dust molecule. Therefore, the hydroxyl group of the sucrose molecule will break when heated or discharged by electrodes or fires. Hydrogen ions will be released after the hydroxyl group breaks, and an explosive mixture of gas is formed with CO_2, CO, and other gases generated, as shown in Figure 11.

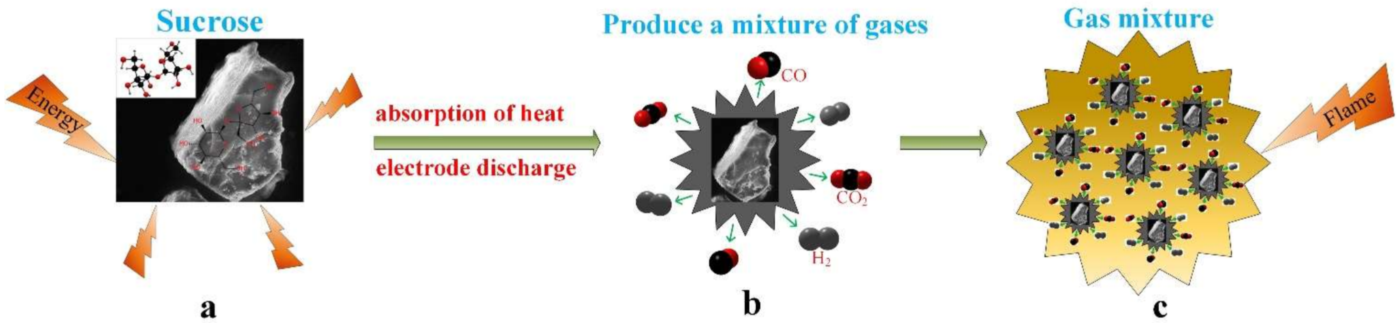

Figure 11. The explosive process of sucrose dust. (**a**) The electrodes discharge and the sugar dust absorbs heat; (**b**) The chemical bond breaks to create a mixture of gases (**c**) It explodes when it encounters a source of flame.

Therefore, the process of sucrose dust explosion can be described as the following: in the production process, the space is filled with a large amount of sucrose dust, and the local dust concentration reaches the lower limit of explosion. Then, dust is gasified first when it encounters the energy of electrode discharge or high temperature, dust near the energy source, and electrons bombardment of sucrose molecules by electrode discharge or high temperature. Then, the "O–H" bonds of the sucrose molecule hydroxyl break, and the process continues. Absorbing energy makes hydrogen ions separate to form H_2. Electrode discharge or high temperature provide continuous energy to ignite the H_2 and hydrogen–oxygen mixture. The MIE of the H_2 is very low (0.02 mJ), and the combustion value is very high (1.4×10^8 J/kg). The energy source ignites H_2, which produces a large amount of energy to ignite the gasified dust. The energy generated by the ignition and detonation spreads rapidly to the surrounding areas in the form of a spherical wave, so that the surrounding sucrose dust enters into one and continues to ignite to form a detonation wave. The larger particles of sedimentary sucrose dust are raised and participate in the explosion, forming multiple explosions until all the concentration of combustible dust in the air dropped below the lower limit of explosion. In addition, in Figure 3, we can see that the sucrose dust has an irregular shape and sharp corners. From the individual characteristics of the sucrose particles, the sucrose particles are irregular lenses. The surface of the sucrose particles has a certain adsorption effect, which can absorb smaller sucrose particles. The sucrose particles can easily bond with each other, making many large granular sucrose particles with a loose surface. As a result of the existence of an irregular shape and sharp angle, sucrose dust has a larger specific surface area and is easier to ignite. Montoya et al. [36] found that when the temperature continued to rise to a certain extent, the volatile part of the sucrose solution part precipitated, and the main components of the volatile components were H_2, CO_2, CO, acetic acid, formic acid, sucrose alcohol, etc. It can be used as evidence for hydrogen ion production from sucrose hydroxyl cleavage.

In summary, the energy required for the explosion of sucrose dust is only to break the "O–H" bonds of the sucrose molecule hydroxyl when heated or discharged by electrodes or high temperature, release hydrogen ions, ignite a certain amount of H_2 with the remaining energy, and then ignite the fueled sucrose dust to form an explosion. Therefore, sucrose enterprises should use explosion-proof equipment without sparks in production sites and pay close attention to the temperature changes of equipment.

4. Conclusions

In this paper, based on the experiments of MIE and MIT of sucrose dust, the basic parameters of sucrose dust explosion were obtained and analyzed theoretically. The conclusions can be summarized as follows.

(1) The experiments of MIE of sucrose dust showed that the relationships between MIE and three cases were an open-up quadratic polynomial. The MIE values of dust quantity, IDT, and PIP were 0.5 g (417 g/m^3), 90 ms, and 150 kPa, respectively. The MIE was 58.9 mJ, 62.6 mJ, and 52.4 mJ. Considering dust concentration, IDT, and PIP as factors that influence MIE, they can instruct sucrose producers to prevent dust explosion accidents.

(2) The experiments of MIT of sucrose dust showed that the MIT was positively correlated with the particle size of sucrose dust. The specific surface area of small particle size dust was larger, the contact with oxygen was more sufficient, the more fully burned, and the dust could be ignited under lower temperature. The MIT was 340 °C. So, the ignition source had better be eliminated as much as possible in the sucrose industrial production.

(3) The theory of sucrose dust explosion based on sucrose molecule hydroxyl groups broken by the discharge of electrodes was put forward. From the point of view of the sucrose molecular formula, the "O–H" bonds of sucrose molecule hydroxyl groups were broken by the discharge of electrodes or high temperature, and H_2 was generated. The combustion of H_2 caused the surrounding sucrose dust to participate in the explosion, and it made the deposited dust rise. Then, there were larger particles of sedimentary sucrose dust, which smashed and participated in the explosion, forming multiple explosions, thus reciprocating, until all raised sucrose dust ignition ended, the concentration of combustible dust in the air dropped below the lower limit of explosion, and the dust explosion stopped. Next, we will further study the microscopic mechanism of sucrose dust explosion through various experiments and tests (TGA/DSC, XRD, etc.) to prove that the theory of sucrose dust explosion was put forward based on the breaking of hydroxyl groups.

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