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Study of Explosion Characteristics and Mechanism of Sucrose Dust

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Abstract: In order to investigate the explosion mechanism of sucrose in the air atmosphere, the explosion intensity under different ignition delay times (IDT), powder input pressures (PIP), and concentrations were studied using a 20L-sphere. The sucrose particles were analyzed in a synchronized thermal analyzer (STA) and scanning electron microscope (SEM). The results are as follows: 1. The DSC curve has two endothermic peaks and one exothermic peak, respectively at T = 180.5 °C, 510.2 °C and 582.6 °C. 2. The explosion intensity varies with the experiment conditions. The maximum explosion pressure (P_{max}) appears when IDT = 90 ms, PIP = 1.5 MPa and concentration = 625 g/m^3. 3. The explosive mechanism is a homogeneous combustion mechanism based on particle surface pyrolysis and volatilization. Because of the decomposition, H_2, CO, furfural, and other flammable gas-phase products are released, then surface burn appears, which leads to the crystal rupture on account of thermal imbalance, resulting in multiple flame points and a chain explosion. As the temperature of the 20L-sphere rises, more explosive products are released, which causes a rapidly expanding explosion and eventually forms the explosion. This paper can be used as a reference for the prevention of explosion accidents in sucrose production processing.

Keywords: explosion intensity; process safety; dust explosion; explosion mechanism; 20L-sphere

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Citation: Liang, S.; Li, X.; Jiang, J.; Zhong, Y.; Sun, Y.; Jiang, Z.; Yang, L.; Hao, P. Study of Explosion Characteristics and Mechanism of Sucrose Dust. *Processes* **2023**, *11*, 176. https://doi.org/10.3390/pr11010176

Academic Editor: Zhihua Wang

Received: 23 November 2022
Revised: 22 December 2022
Accepted: 3 January 2023
Published: 6 January 2023

1. Introduction

Dust explosion accidents are fatal to industrial production and human life. Scorching debris from the explosion can be driven by the blast wave, which will cause more burns to people and damage to objects, and the blast wave will also raise the dust, leading to more serious secondary explosions or a series of chain explosions. With the rapid development of industry, dust explosion accidents happen frequently, and economic development and human safety are threatened [1,2]. Dust explosion accidents caused by food dust are the most frequent. Food dust is more closely related to people, so people do not pay as much attention to it as metal dust, and its safety investment is insufficient [3]. Sucrose dust is the third major cause of food dust explosion accidents [4]. Sucrose is not only an indispensable material in the food processing industry [5], but is also used in the production of pharmaceuticals [6] and alcohol products [7]. Demand for sucrose is expanding as downstream industries develop [8]. Therefore, to reduce the probability of sucrose-powder explosion accidents, the explosion characteristic parameters, thermal composition behaviors and explosion mechanism were studied in this study.

Statistics from an organization in Germany show that there were approximately 30 sucrose-powder explosions between 1932 and 2004, a large portion of which happened in the processes of grinding and transportation [9]. The dust-explosion accident in the Imperial Sugar Factory happened around the conveyor, which is because the dust deposited around the conveyor belt was kicked up and ignited [10]. After the accident, some scholars calculated a dust-explosion probability of 27% at the Imperial Sugar Factory using mathematical models [11]. Different from the heterogeneous reactions of metals [12], phase change and pyrolysis are considered to be the preconditions for the explosion of sucrose dust [13,14]. Some scholars have proposed that flames appear on the surface of sucrose particles [15]. After that, the flame temperature will rise rapidly [14]. During the emergence and propagation of the flame, heat transfer plays a major role [16]. After the explosion, the explosion pressure can be reckoned according to the residual gas of the explosive reaction [13].

The explosive characteristics of metal dust (such as aluminum dust, and magnesium dust) [17–19] and coal dust [20,21] have been investigated by many scholars. There have been studies on the explosive characteristics of corn dust [22,23] and wheat flour [24–26]. However, a very small number of people have analyzed the explosive mechanism of dust from the perspective of energy transmission.

The explosive behaviors and mechanism of sucrose dust have been mentioned by some researchers in previous studies, but the energy-transmission chain in the explosion process and the pyrolysis mechanism have not been elaborated on. There is no unified conclusion on the characteristics and variation law of dust explosion in the research field at present. In this study, the agglomeration and thermal composition behaviors of sucrose crystals were analyzed, and the explosive behavior was studied from the perspectives of heat transfer and microscopic stress. Sucrose is a carbonaceous compound, and its combustion and explosion require a phase transition. Through the analysis of experimental data on dust-explosion behaviors, this study summarizes the mechanism of sucrose-dust explosion from the perspective of thermal pyrolysis reaction and energy transfer.

2. Materials and Methods

2.1. Experimental Apparatus and Method

HY16426C Gas/Dust Explosion Parameter Test System (20L-sphere) was used to test the maximum explosion pressure (P_{max}) during the sucrose-dust explosion process. Experimental procedures were performed according to ASTM (2010) [27]. The main structure of the experimental system is shown in Figure 1, which consists of a 20L double-layer metal explosive vessel as well as high-speed injection valves, precision gas distribution system, and vacuum system. There is a vacuum environment between the double metal to maintain a constant temperature in the reaction process. There is a rebounce nozzle at the bottom of the 20L-sphere, which is connected by pipes and a dust inlet valve between the nozzle and dust chamber. The experiment was carried out at normal pressure and temperature (25 °C, 0.1 MPa), which are the same temperature and pressure as in a sucrose-production factory. The pressure mentioned in this paper is absolute pressure.

2.2. Experimental Materials

Sucrose dust used in this experiment was taken from the dust-screening workshop of Xiangshan Sugar Industry Ltd., Nanning, China. It can be seen from Figure 2 that some of the powder was floating in the air and some was deposited inside the factory.

The sucrose dust collected from the industry was screened. According to the screening results, particles with a size ranging from 49 to 150 µm accounted for 88% of the total weight. Therefore, the material for our experiments was sucrose particles with a particle size of 49–150 µm. The experimental results are more instructive for production practice. The sucrose dust collected from the factory was divided into two particle sizes of less than 48µm, and 49–150 µm, and placed it in a vacuum drying oven for 12 h.

It can be seen from Figure 3 that the shape of the sucrose particles was mostly an irregular polyhedron, which has a larger specific surface area and is conducive to the contact between particles and oxygen molecules [28]. It was observed that smaller sucrose particles were absorbed by larger sucrose particles, and no agglomeration was formed.

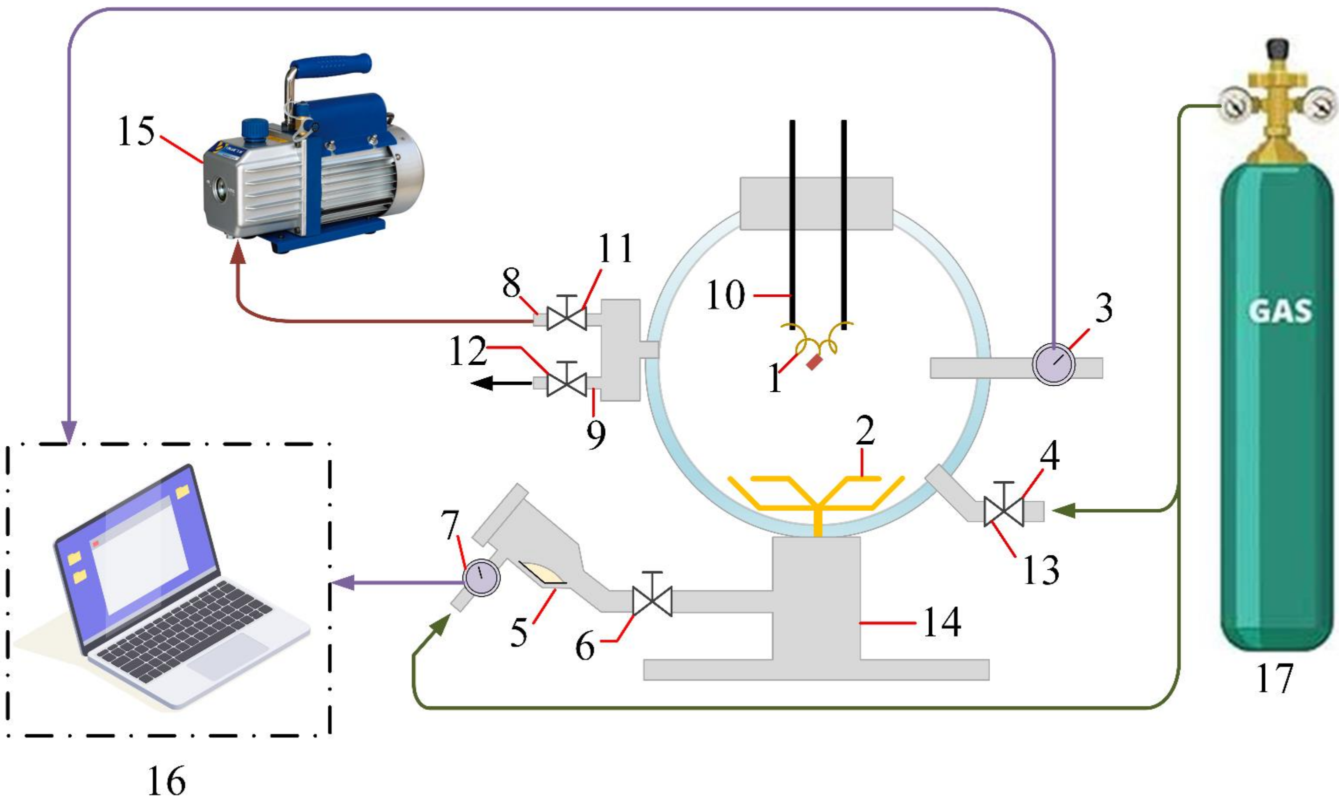

Figure 1. 20L-sphere structure. (1) Chemical igniter; (2) Rebounce nozzle; (3) Pressure sensor; (4) Gas inlet valve; (5) Dust chamber; (6) Dust inlet valve; (7) Pressure sensor; (8) Vacuumizing line; (9) Exhaust line; (10) Ignition leads; (11) Vacuumizing valve; (12) Exhaust valve; (13) Explosion chamber inflatable valve; (14) Reactor base; (15) Vacuuming machine; (16) Data receiving equipment (PC); (17) Compressed air.

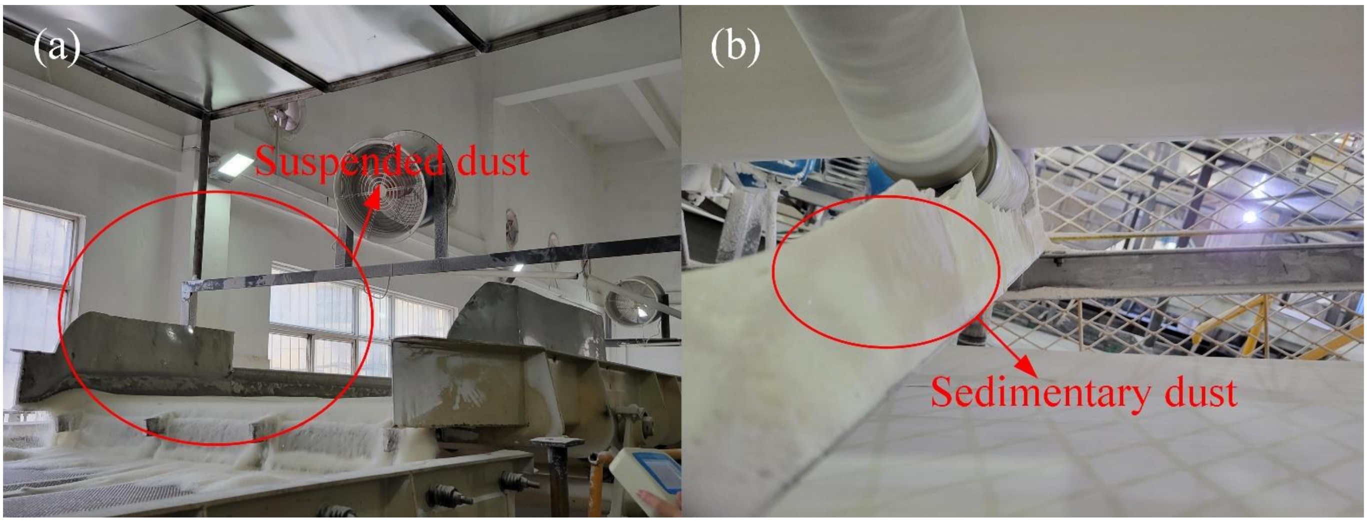

Figure 2. (**a**) Suspended dust and (**b**) Sedimentary dust in screening workshop of Xiangshan Sugar Industry.

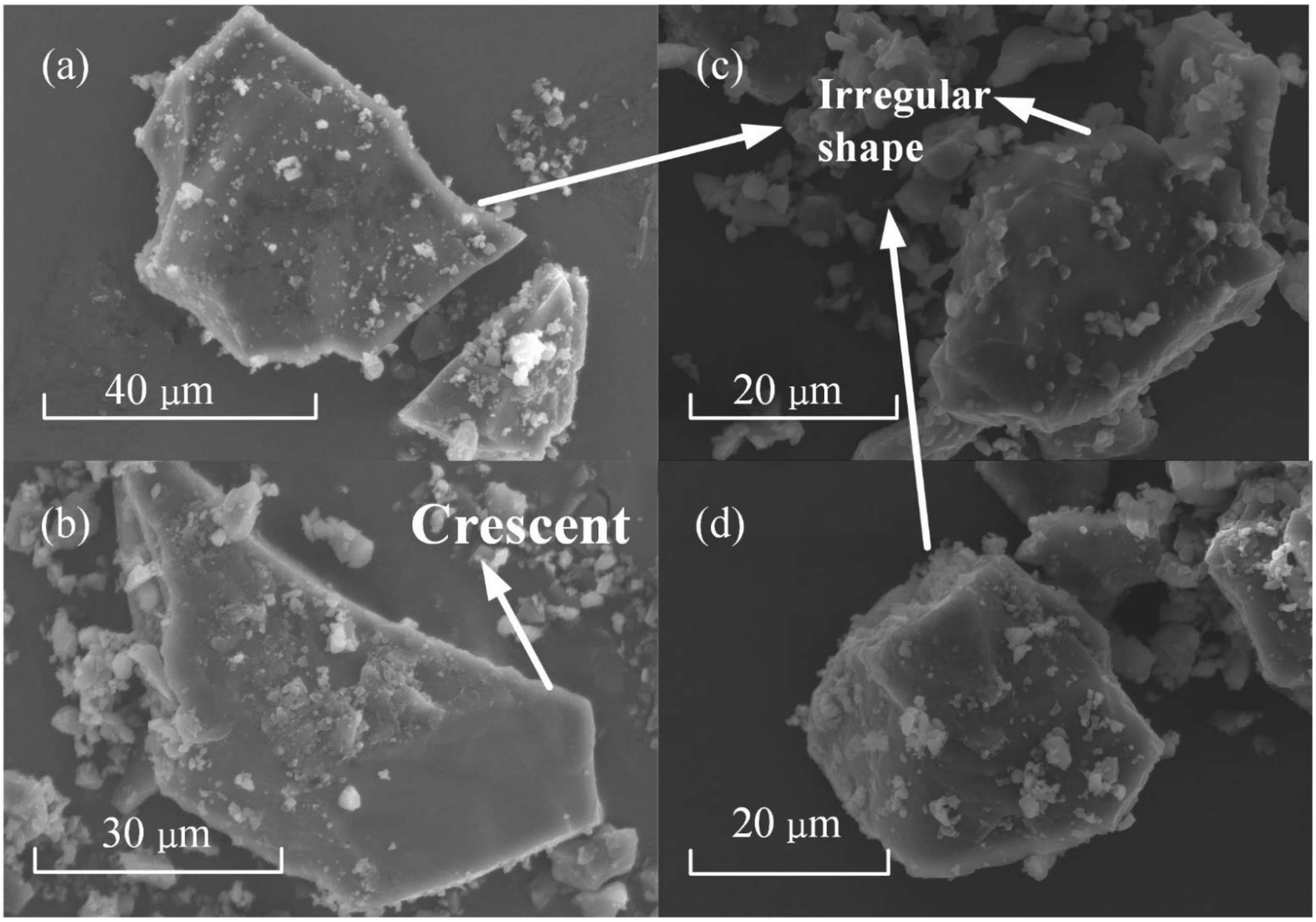

Figure 3. Scanning electron microscope (SEM) of (**a**,**b**) 150–75 µm, (**c**,**d**) 74–47µm.

2.3. Pyrolysis Analysis of Sucrose

Thermal decomposition characteristics of sucrose are key to the analysis of mechanism; before the sucrose explosion experiments, a synchronized thermal analyzer (STA) was used to perform thermogravimetric analysis (TG) and differential scanning calorimetry (DSC). The temperature range of STA was set from 25–1000 °C with a heating rate of 10 °C/min at the atmospheric pressure of air.

According to the results in Figure 4 and Table 1, the pyrolysis process of sucrose dust can be divided into three stages. The first stage is the evaporation and melting stage (T < 204 °C), and the rate of weight loss in this stage is 1.1%, indicating that the water content of sucrose dust is 1.1%. In this stage, the DSC curve appears as an endothermic peak at 180.5 °C and the TG curve seems to maintain a horizontal line, which indicates that sucrose dust begins melting at this moment. The second stage is the rapid pyrolysis stage (204 °C < T < 546.2 °C); the TG curve drops rapidly with a mass loss of 97.249%, and the DSC curve appears as an endothermic peak at 510.2 °C. The thermal decomposition rate is very fast, and a large amount of combustible decomposition products are released in this stage. When the temperature exceeded 546.2 °C (third stage), the TG curve reached a stable value with a mass loss of 0.089%. However, when the temperature was 582.6 °C, the DSC curve showed an exothermic peak, indicating that the pyrolysis products generated in the second stage oxidized and released heat at this stage. Therefore, the third stage is the reaction stage.

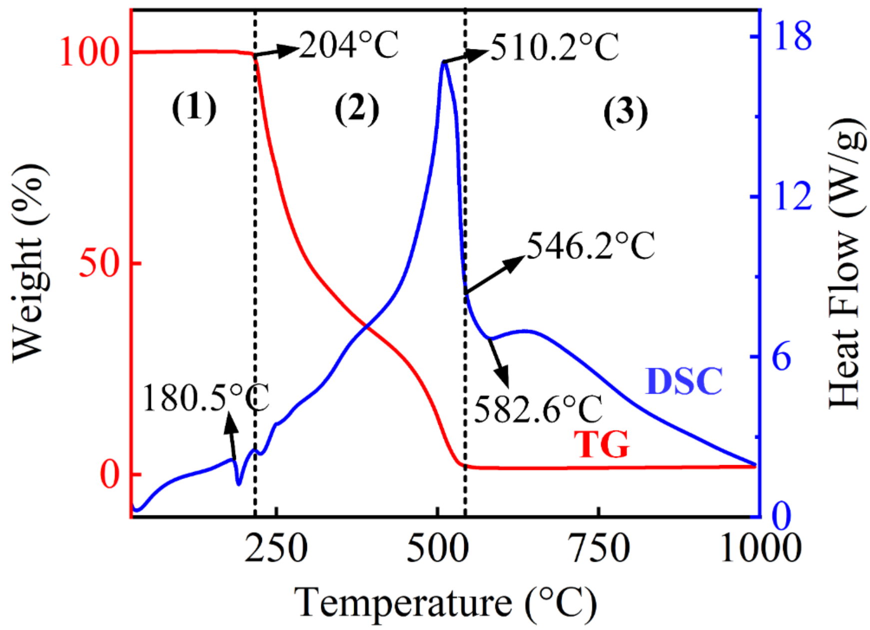

Figure 4. TG-DSC curves of sucrose.

Table 1. Pyrolysis behaviors of sucrose dust at different temperature.

Temperature Range	**<204 °C**	**204–546.2 °C**	**<546.2 °C**
Percentage of mass loss	1.10	97.25	0.098
Pyrolysis stage	Evaporation and melting stage	Rapid pyrolysis stage	Reaction stage
Pyrolysis process	(1)	(2)	(3)

3. Results and Discussion

3.1. The Influence of IDT on P_{max}

Figure 5 shows the P_{max} values and the pressure variation curve of a sucrose dust explosion in different IDT. With an increase of IDT, the value of P_{max} first increases and then decreases.

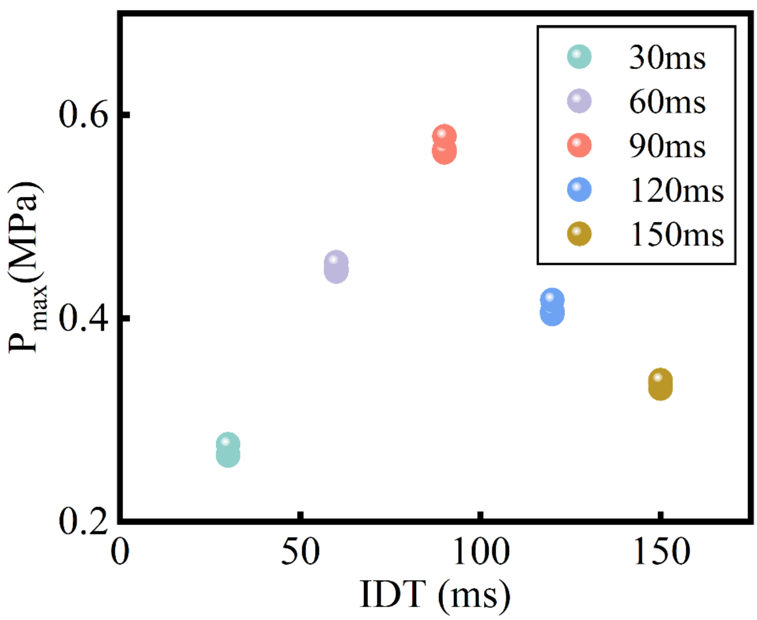

Figure 5. The variation of P_{max} with different IDT.

The IDT mainly affects the dust distribution and turbulence in the 20L-sphere [29,30]. When the IDT is 30 ms, the sucrose dust moves for only a short time after it leaves the rebounce nozzle. At this moment, the distribution of dust in the 20L-sphere is not uniform, and the concentration of dust near the ignitor is low. With the release of energy from the igniter, combustible gas which is produced by the pyrolysis reaction of sucrose distributed near the igniter begins to burn. However, the concentration of the flammable gas is small, which plays a small role in promoting the energy propagation in the 20L-sphere, so the average value of P_{max} = 0.269 MPa.

When IDT = 90 ms, the average value of P_{max} = 0.569 MPa. At 90 ms after the dust ejection, owing to the disturbance of particles, the turbulent kinetic energy in the 20L-sphere is high, which indicates that the air molecules are moving rapidly. The energy transmission among particles is achieved by collisions between particles and air molecules, which means that fluid flow plays a significant role in energy transmission. Therefore, strong turbulence is beneficial to the heat exchange among particles and the pyrolysis of sucrose crystal, and it can provide advantageous conditions for the deflagration of combustible products produced by the thermal decomposition of sucrose. The dust begins to settle at 120 ms after the dust leaves the nozzle [28]. Therefore, the turbulence intensity is weakened compared with 90 ms, and the particles involved in the explosion per second are fewer, then the explosion severity decreases. As shown in Figure 5 and Table 2, at the moment when IDT = 150 ms, the average value of P_{max} is 0.339 MPa, so it can hardly be ignited.

Table 2. The explosion severity with different IDT.

IDT (ms)	P_{max} (MPa)			Average Value of P_{max} (MPa)
30	0.265	0.266	0.276	0.269
60	0.446	0.449	0.455	0.45
90	0.563	0.566	0.579	0.569
120	0.404	0.407	0.418	0.41
150	0.331	0.336	0.351	0.339

In conclusion, when the IDT is small (IDT = 30 ms), the high-pressure airflow carrying dust moves in the 20L sphere, but the dust distribution is not uniform, and the concentration of sucrose dust near the ignitor is low. When the IDT is excessively large (IDT = 120 ms), the degree of turbulence in the 20L-sphere is significantly reduced, which is not conducive to heat propagation and explosion pressure increasing. When the IDT is 90 ms, the concentration of dust around the igniter is large, and the turbulence intensity is conducive to the thermal and material transfer in the explosion process.

3.2. The Influence of PIP on P_{max}

From Figure 6, it is clear that the P_{max} first increases and then decreases with the increase of dust pressure. When the PIP = 1.1 MPa, the average value of P_{max} is merely 0.436 MPa. After leaving the nozzle, particles move upward under the drive of forces including pressure gradient force, gravity, buoyancy, and Saffman lift force [31]. Pressure gradient force (1) and Saffman lift force (2) are the driving forces of the particles' upward movement. From Equations (1) and (2), it can be seen that the numerical values of pressure gradient force and Saffman lift force increase with the increase in PIP. When the PIP is 1.1 MPa, the movement of particles is limited to the lower part of the 20L-sphere due to the limitation of initial kinetic energy, which is not conducive to the thermal exchange between particles, thus affecting the development of the explosion process.

$$F_p = -V_p grad p \tag{1}$$

$$F_S = 1.61\left(\mu_g \rho_g\right)^{\frac{1}{2}}\left(v_g - v_p\right) d_p^2 \left|\frac{dv_g}{dt}\right|^{\frac{1}{2}} \tag{2}$$

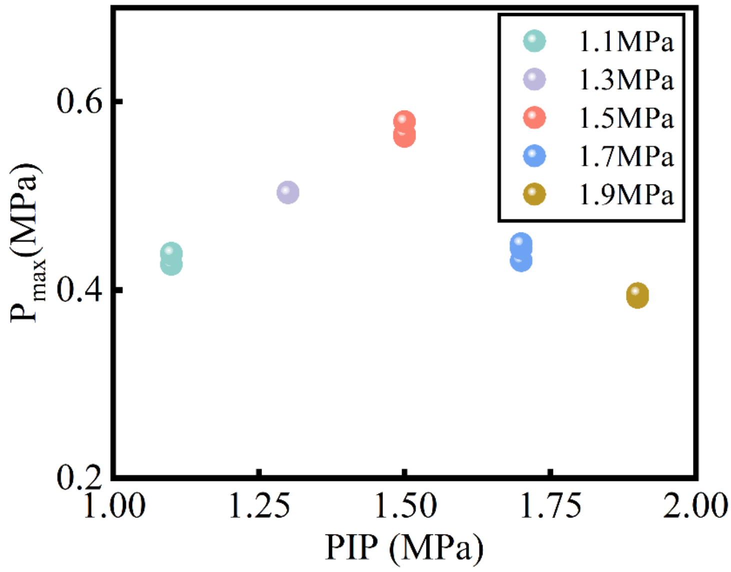

Figure 6. The variation of P_{max} with different PIP.

Theorem 1. *F_p—Pressure gradient force (N); grad p—pressure gradient; F_s—Saffman life (N); μ_g—Aerodynamic viscosity coefficient, v_g—gas flow speed (m/s); v_p—Particle velocity (m/s).*

As Figure 6 and Table 3 shows, with the PIP increasing to 1.5 MPa, the initial kinetic energy carried by the particles becomes larger, so the particles can move upward to greater heights and a small part of the dust will crash with the inner wall. Most of the dust that collides with the wall will return to the 20L-sphere for free movement, and a small part of the dust will adhere to the wall. Compared with PIP = 1.1 MPa, particles that have returned to free movement in the air take longer to reach their settling velocity. As a result, more particles are concentrated near the igniter when the ignitor is activated. Therefore, there are many combustible substances generated in the process of sucrose pyrolysis, and the average value of P_{max} = 0.569 MPa.

Table 3. The explosion severity with different PIP.

PIP (MPa)	P_{max} (MPa)			Average Value of P_{max} (MPa)
1.1	0.427	0.438	0.439	0.435
1.3	0.504	0.504	0.511	0.506
1.5	0.563	0.566	0.579	0.569
1.7	0.431	0.444	0.449	0.441
1.9	0.392	0.395	0.396	0.394

When PIP reaches 1.7–1.9 MPa, sucrose particles rush out of the rebound nozzle with huge energy, resulting in a large number of particles colliding with the inner wall of the 20L-sphere and adhering to the wall. Therefore, the concentration of suspended dust in the 20L-sphere is reduced, the concentration of substances generated through the thermal decomposition of dust is greatly reduced, and the explosion intensity is restrained. The energy released from the explosion is not enough to make the dust adhering to the wall explode.

3.3. The INFLUENCE of Concentration on P_{max}

According to Figure 7, the P_{max} first increases and then decreases with the increase in dust concentration. As shown in Figure 7bi, when the dust concentration is 250 g/m^3, the distance between particles is far because the dust concentration is small. Considering that the propagation of thermal radiation is related to distance, it is difficult to finish heat conduction through collision because of the long distance among particles in free movement. Therefore, the thermal radiation effect has no chance to play a dominant role which will result in low efficiency in energy propagation. Under the action of limited energy, the heating-layer thickness of the sucrose crystal surface is smaller, which inhibits the thermal decomposition and chain reaction during deflagration and further affects the explosion intensity.

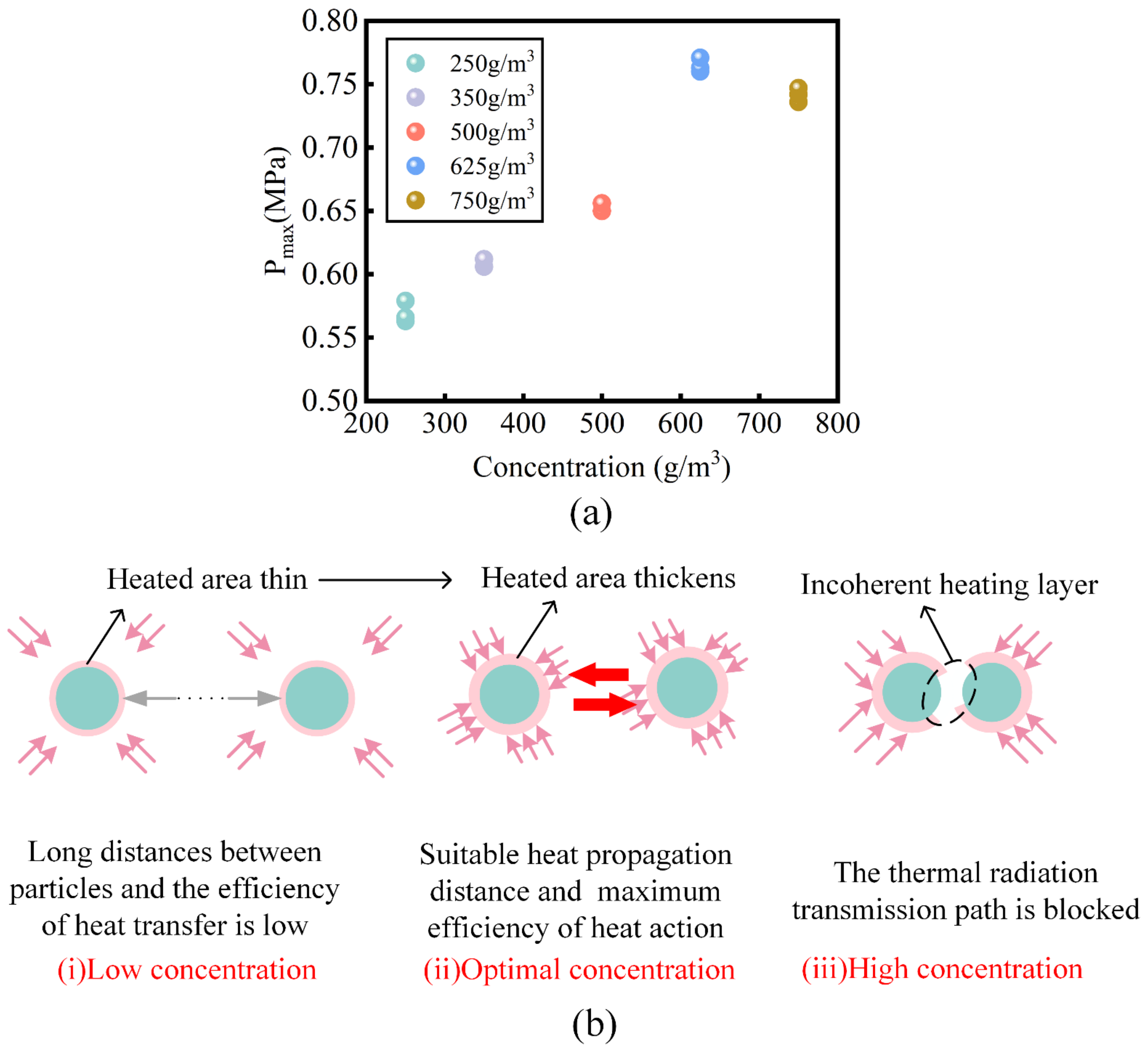

Figure 7. (**a**) The curve of the variation of pressure with time with different concentration; (**b**) thermal transfer model in different concentration.

When the dust concentration was 625 g/m^3, the explosive intensity of sucrose dust was the highest with an average value of P_{max} = 0.765 MPa. The increase in dust concentration means that the distance between the particles is even shorter, which not only increases the amount of heat transmitted through thermal radiation but also increases the probability of collisions between particles, one of the ways of heat conduction. The frequent heat exchange among particles promotes the thermal decomposition of sucrose and further facilitates the chemical reaction that produces combustible pyrolysis products and the reaction process of elementary reaction in the combustion process, so finally, the explosive intensity in the 20L-sphere reaches its peak.

When the sucrose-dust-cloud concentration = 750 g/m^3, the average value of P_{max} = 0.742 MPa, and the collision probability among sucrose particles is greatly increased due to the increase in dust concentration. However, as shown in Figure 7biii, due to the small distances among particles, in the process of thermal radiation transmission, other particles will appear along the energy transmission path, so the heat transmission is hindered, and the heating layer is incomplete.

Under appropriate IDT and PIP, increasing dust concentration can increase energy-transfer efficiency and the concentration of combustible products released from the sucrose dust, resulting in an increase in explosion intensity. Thus, many factories are equipped with concentration-monitoring instruments to determine the dust concentration. When the dust concentration increases, the 20L-sphere is a closed space with limited oxidant content, therefore the explosion pressure cannot continue to rise, resulting in the explosion intensity decreasing due to the reduction of energy transmission efficiency. The experimental data of explosion intensity are shown in Table 4.

Table 4. The explosion severity with different dust concentration.

Concentration (g/m^3)	P_{max} (MPa)			Average Value of P_{max} (MPa)
250	0.563	0.566	0.579	0.569
350	0.606	0.612	0.612	0.609
500	0.65	0.65	0.664	0.654
625	0.76	0.763	0.771	0.765
750	0.736	0.742	0.747	0.742

3.4. Discussion

The study of explosion characteristics is essential for accident protection in the production industry. According to the experimental results, the explosion intensity of dust may increase under certain conditions, so this situation needs to be noted. According to Figure 8, the turbulence intensity reaches its maximum when the PIP = 1.5 MPa and IDT = 90 ms, and the active substances involved in the explosion are the most, and the explosion intensity is strong. The following research on dust explosion mechanisms explore the dust in the explosion chamber heat, decomposition and reaction process.

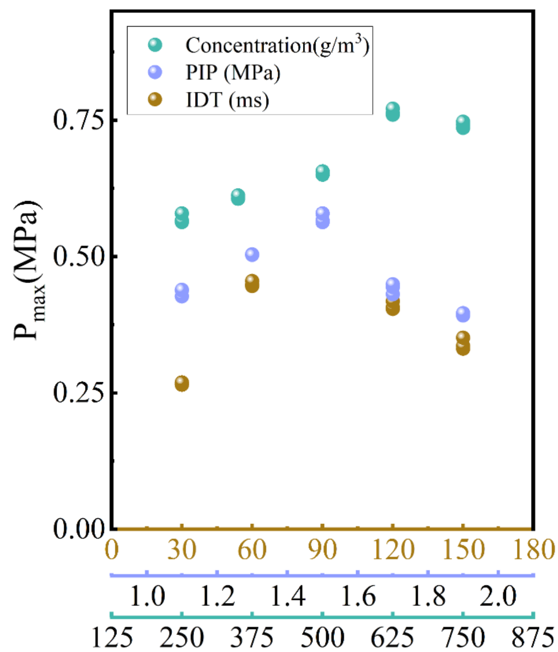

Figure 8. Effects of the different factors on explosion severity.

4. Explosion Mechanism

Different from the heterogeneous oxidation mechanism dominated by the surface oxidation reaction of metal-dust particles, sucrose is an organic substance with a low melting point of 180.5 °C shown in Figure 4; therefore, the dust-explosion process is more complex. The surface of sucrose particles first melts into liquid after being heated. With further heating, sucrose begins to decompose and release pyrolysis products, which leads to an explosion. The explosive mechanism of sucrose is a homogeneous combustion mechanism based on the pyrolysis and volatilization of the sucrose surface. During the time between the sucrose dust leaving the rebounce nozzle and having the explosion reaction, the dust cloud will go through the following three stages:

Stage 1: The dust is heated to decompose the flammable products. The sucrose dust is first exposed to the heat released from the ignitor. The particles distributed near the igniter are the first to reach their melting point [29]. At different IDT, the concentration of dust around the ignitor is different. It can be seen in Figure 9i that the particle surface transforms from unsmooth to smooth. When the temperature rises to 204 °C, the pyrolysis reaction begins. The hydroxyl group is the most active group in sucrose molecular structure, and the "O-H" bond and "C-H" bond breaks and produces CO and H_2 [14]; with temperature rising, the ether bond in the sucrose molecules will break, producing and releasing combustible products, which are mainly furfural, hydroxyl acetaldehyde and 5-methyl furfural [32]. While most dust is in the thermal decomposition stage due to heat, some sucrose particles receive a limited amount of heat, which does not convert sucrose molecules into activated molecules, but only supports the sucrose particles to complete the phase conversion. This part of sucrose molecules consumes the heat released by the ignitor but does not have enough energy to release combustible products, which can be seen as a "waste" of energy. Energy is transmitted in the following three ways: heat conduction caused by collisions among particles; thermal convection between fluid and particles; and thermal radiation received by particles or igniter. In the process of the explosion reaction, the sucrose particles complete the thermal decomposition process in an instant and produce combustible products.

Stage 2: combustible products mixed with air. The combustible products from the pyrolysis of sucrose molecules diffuse around in the form of a gas phase and mix with oxygen. In the mixture, oxygen molecules collide with combustible gas molecules, causing a small range of combustion reactions which act as a heat source to transmit heat to particles around and in the air medium. Owing to the continuous collision between sucrose molecules and oxygen molecules, more localized explosions are generated in the 20L-sphere, which not only transport energy to the sucrose particles by way of heat conduction but also heat the surrounding dust by way of heat radiation, promoting the pyrolysis of sucrose molecules in the 20L-sphere. Under the action of the igniter and heat source, combustible active molecules are accumulated at a certain concentration in the 20L-sphere, and the mixture with oxygen molecules is relatively sufficient.

Stage 3: Combustible products reach the lower explosion limit, and an explosion occurs; After Stages 1 and 2, the combustible active molecules in the 20L-sphere, including H_2, CO, furfural, and other combustible products, form a combustible gas mixture. If abundant oxygen molecules collide with the combustible gas molecules, the first small-range sucrose-dust-cloud explodes. After the first local explosion, the temperature and pressure in the 20L-sphere increase, further triggering subsequent chain explosions. The explosion quickly expands from local to the whole. After the explosion, the 20L-sphere can be divided into three regions: explosion zone; thermal decomposition zone; and non-pyrolytic zone. The non-pyrolytic zone and the pyrolytic zone are heated by the explosion zone, and the heat released from the explosion zone leads to the temperature rise of the pyrolytic zone, and sucrose further decomposes into new combustibles to participate in the explosion [30]. Moreover, after the non-pyrolytic zone is subjected to the heat released from the explosion zone, the sucrose molecules are pyrolyzed, increasing the area of the pyrolytic zone.

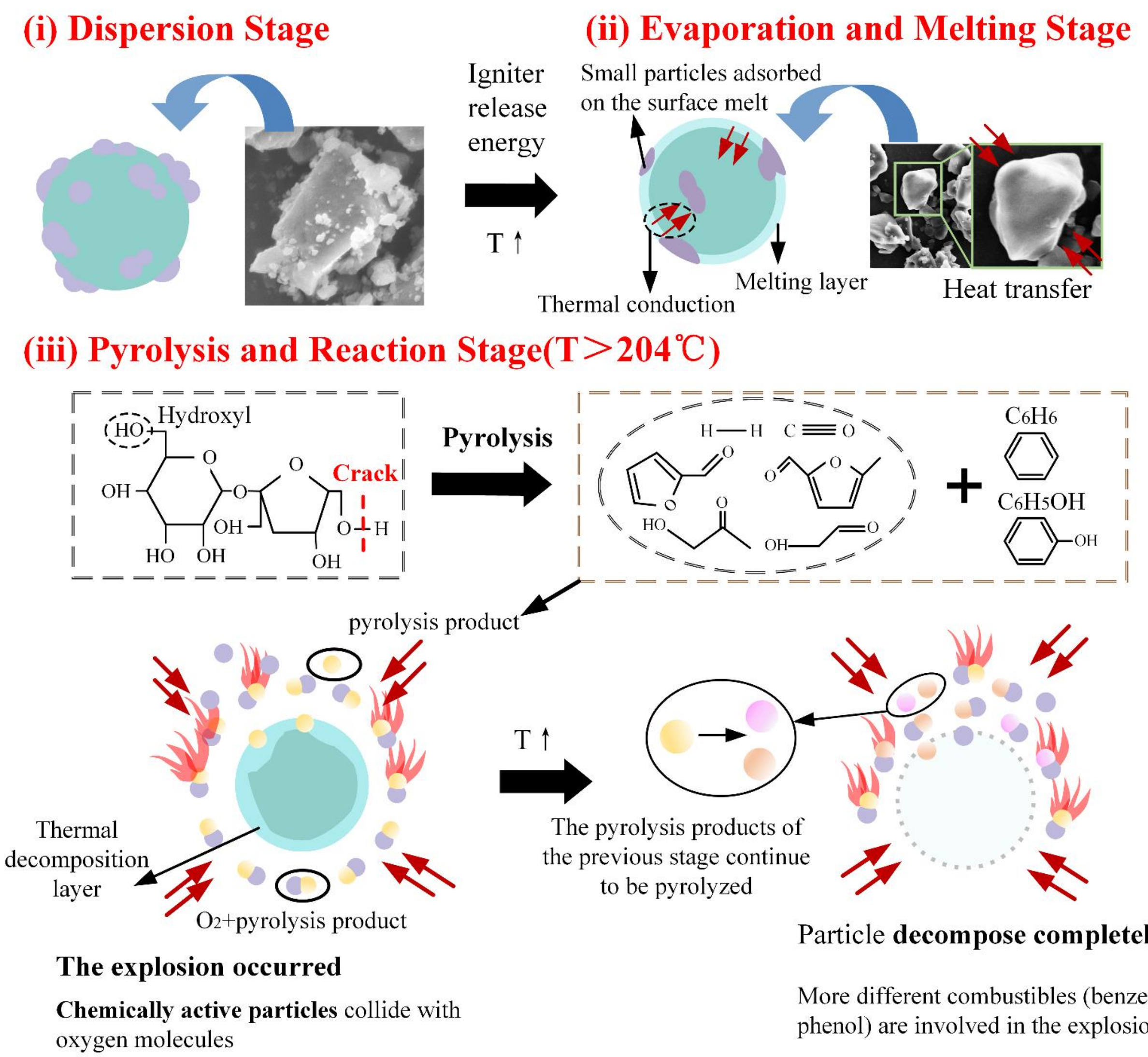

Figure 9. Sucrose-dust explosion mechanism.

5. Conclusions

In this study, the effects of different IDT, PIP and dust concentrations on the explosion characteristics of sucrose dust were investigated using a 20L-sphere. Finally, this study summarizes the explosion mechanism from the perspective of energy transfer and thermal decomposition. The conclusions are as follows:

The thermal decomposition behavior of sucrose dust in air atmosphere was studied. The thermal decomposition behavior is divided to three stages, the first stage is the evaporation and melting stage (<204 °C), the second stage is the rapid pyrolysis stage (204–546.2 °C), and the third stage is the reaction stage (>546.2 °C). In the first two stages, the dust of sucrose was endothermic with the endothermic peaks appearing at 180.5 °C and 510.2 °C, respectively. In the third stage, the dust was exothermic with the exothermic peak appeared at 586.2 °C.

According to the experimental results, the optimal explosion condition is when the IDT = 90 ms and the PIP = 1.5 MPa. The P_{max} appears when the dust concentration is 625 g/m^3, and the average value of P_{max} = 0.765 MPa, six times the atmospheric pressure.

The dust explosion mechanism can be divided into three stages according to the time sequence. The first stage is the process of sucrose molecules heated and decomposed, which is heated in three ways: thermal convection, heat conduction, and heat radiation. Sucrose molecules produce H_2, CO, and other explosive gas-phase products at a certain temperature. When the gas-phase product is produced, it enters the second stage, the combustible gas molecules mix with oxygen molecules. When the mixture of combustible gases reaches the lower limit of the explosion, the system enters the third stage. According to the explosive mechanism of sucrose dust, the following three aspects can be considered to prevent the occurrence of sucrose explosion accidents: blocking the heat transfer channel among particles; reducing the concentration of combustible materials in the 20L-sphere to make it unable to reach the lower limit of the explosion; and reducing the concentration of oxygen in the system to inhibit the reaction between combustible molecules and oxygen.

Author Contributions: Conceptualization, X.L.; data curation, S.L. and J.J.; investigation, S.L., J.J., Y.Z., Y.S., L.Y. and P.H.; methodology, X.L.; visualization, S.L.; writing—original draft, S.L.; Writing—review and editing, X.L. and Z.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant No.52264014) and the Guangxi Natural Science Foundation Project (Grant No.2020GXNSFAA297037).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge financial support from the National Natural Science Foundation of China (Grant No. 52264014) and the Guangxi Natural Science Foundation Project (Grant No. 2020GXNSFAA297037), and also acknowledge Nanning Sugar Industry Co., Ltd., China, for providing the sucrose dust samples.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

IDT	ignite delay time
PIP	powder input pressure
SEM	scanning electron microscope
STA	synchronized thermal analyzer
TG	thermogravimetric analysis
DSC	differential scanning calorimetry
P_{max}	the maximum pressure during an explosion process

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