

Article

Effects of Particle Size and Dust Concentration on Flame Propagation and Pressure Evolution of Pulverized Coal Cloud Explosions in a Vertical Pipeline

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Abstract

Pulverized coal explosions pose significant hazards during pneumatic conveying and handling in coal preparation and mining. To investigate flame propagation and pressure evolution under conditions representative of vertical conveying pipelines, explosion experiments were conducted using pulverized coal with defined particle sizes and dust concentrations. Flame propagation and pressure dynamics were synchronously captured via high-speed imaging and dynamic pressure measurements. Results showed that flame height exhibited a Logistic growth pattern, whereas flame propagation velocity followed an inverted parabolic trend, reaching a maximum value of 14.5 m s^{-1} at approximately 20 ms after ignition. Significant flame-front wrinkling, distortion, and oscillatory propagation were observed during explosion development, reflecting increasingly complex flame evolution within the confined vertical pipeline. Increasing dust concentration from 0.3 to 0.5 kg m^{-3} promoted flame acceleration and pressure development. For $45 \text{ }\mu\text{m}$ particles, the maximum explosion pressure increased from 0.710 to 0.948 MPa. At a constant concentration, decreasing particle size enhanced both flame propagation and explosion severity. Under 0.5 kg m^{-3} , the maximum pressure increased from 0.788 MPa for $200 \text{ }\mu\text{m}$ particles to 0.948 MPa for $45 \text{ }\mu\text{m}$ particles. The enhanced explosion intensity at higher concentrations and smaller particle sizes is attributed to accelerated heat and mass transfer together with more efficient combustion under confined conditions. These findings provide new insight into the coupled evolution of flame propagation and pressure development and contribute to explosion risk assessment in pulverized coal conveying systems.

Keywords: coal dust cloud explosion; flame propagation; high speed photography; explosive pressure



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1. Introduction

Pulverized coal is widely used as a primary fuel in the cement, power generation, metallurgy, and chemical industries [1–3]. In industrial production, vertical risers serve as critical lifting sections in pneumatic conveying and feeding systems, where pulverized coal is transported upward against gravity. The confined nature of these vertical pipelines, together with the suspension of combustible coal dust, creates conditions under which accidental ignition may lead to rapid flame propagation and severe explosion hazards,

threatening equipment safety, production continuity, and personnel safety [4–9]. Non-caking coal has a carbon content of 75–85% [10], a low ignition point, and a long burning time, and explosions are difficult to extinguish. There is no cohesiveness, no colloid is generated when heated, and it contains certain secondary humic acids [11–14]. Therefore, non-caking coal is a common type of coal used in thermal power plants [15,16]. In this paper, non-caking coal powder was used to study the influence of different particle diameters and concentrations of coal dust on flame propagation and explosion pressure during the explosion process.

Previous studies have established that the propagation of pulverized coal cloud flames is a complex process governed by the combined effects of flow motion [17], heat transfer [18], and heterogeneous combustion reactions [19]. The characteristics of the flow field strongly influence flame evolution, leading to flame-front wrinkling, deformation, and enhanced fuel–oxidizer mixing, which consequently accelerate combustion [20–23]. In confined spaces, the combined effects of flow disturbance and spatial confinement further promote flame propagation and energy accumulation, resulting in more severe explosion hazards [24].

Beyond flow effects, the combustion atmosphere and heat-transfer processes play essential roles in determining flame stability and propagation behavior [25]. Oxygen concentration directly affects reaction kinetics and combustion intensity, while conductive and radiative heat transfer influence energy transport within the flame zone [26]. These factors collectively control flame temperature, ignition behavior, and the sustainability of flame propagation [27].

The explosion characteristics of pulverized coal clouds are also highly sensitive to fuel properties and operating conditions [28]. Dust concentration, particle size, ignition energy, and the presence of combustible gases can significantly alter combustion efficiency and energy-release rates [29]. In particular, particle size and dust concentration are recognized as two critical parameters because they determine the available reactive surface area [30], fuel distribution [31], and combustion rate [32], thereby affecting both flame propagation and pressure development during explosions [33].

Although substantial progress has been made in understanding flame propagation mechanisms and explosion characteristics [34], most existing studies have focused on flame structure evolution, propagation velocity, temperature distribution, or single-factor effects under laboratory-scale conditions [35]. Their coupled effects on the transient evolution of flame propagation and pressure development in vertical conveying systems representative of practical coal transportation processes remain insufficiently understood [36,37]. In particular, the dynamic relationship between flame acceleration and pressure generation has rarely been quantitatively characterized.

To address these issues, the present study investigates the effects of particle size and dust concentration on flame propagation velocity and explosion pressure in non-caking coal dust clouds within a vertical pipeline. The objective is not only to quantify the influence of key parameters but also to reveal their roles in governing flame acceleration and explosion severity, thereby providing a theoretical basis for explosion risk assessment and prevention in industrial coal transportation systems.

2. Materials and Methods

2.1. Sample Selection and Preparation

The experimental samples consisted of non-caking coal. Raw coal samples were crushed and pulverized under a nitrogen atmosphere to minimize oxidation during sample preparation. The pulverized coal was then sieved into three particle-size fractions with average diameters of 45, 100, and 200 μm . After sieving, the samples were dried in a

vacuum oven at 50 °C for 6 h to remove moisture. A relatively low drying temperature was selected to avoid thermal decomposition and structural alteration of the coal during the drying process.

5E-MAG6700 automatic proximate analyzer (Changsha Kaiyuan Instruments Co., Ltd., Changsha, Hunan Province, China) and a Vario EL Cube automatic analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) were used for proximate analysis and ultimate analysis of experimental coal samples. The test results are shown in Table 1.

Table 1. Proximate analysis and ultimate analysis of pulverized coal.

Sample	Proximate Analysis (wt/%)				Ultimate Analysis (ad, wt/%)				
	Moisture (Mad)	Ash (Aad)	Volatile Matter (Vad)	Fixed Carbon (FCad)	C	H	O	N	S
pulverized coal	3.84	22.25	29.45	44.46	80.12	3.02	14.65	1.91	0.30

2.2. Experimental Equipment and Conditions

2.2.1. Experimental Device

A laboratory-scale vertical pipeline explosion apparatus was employed in this study, as illustrated in Figure 1. The explosion tube was fabricated from transparent quartz glass to facilitate flame visualization, with an inner diameter of 100 mm, a wall thickness of 8 mm, and a total height of 1200 mm. The upper end of the pipeline was open to the atmosphere throughout the experiment, whereas the lower end was connected to the dust dispersion and ignition system, forming a semi-confined vertical explosion configuration representative of practical pulverized-coal conveying systems.

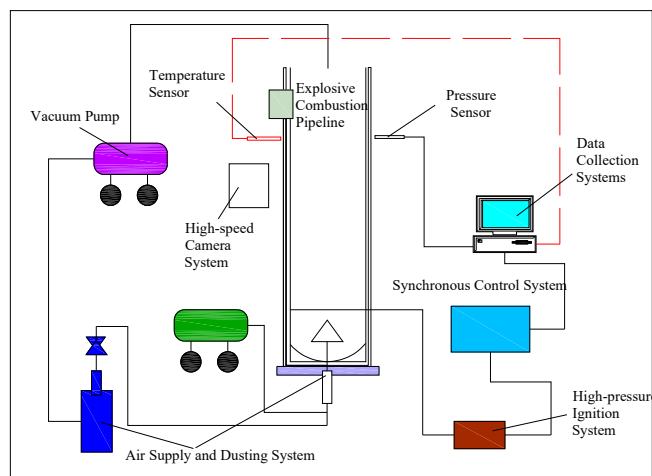


Figure 1. Schematic diagram of the explosion test device for a vertical pipeline.

The experimental system consisted of the vertical explosion pipeline, compressed-air dust dispersion system, high-energy spark ignition system, pressure acquisition system, temperature monitoring system, high-speed imaging system, synchronization controller, and data acquisition unit. The ignition electrode was installed along the pipeline centerline at 100 mm above the bottom of the tube to ensure stable ignition of the dispersed coal dust cloud. A dynamic pressure transducer was mounted on the pipe wall at a height of 300 mm above the ignition position to continuously record transient explosion overpressure. A high-speed camera was positioned perpendicular to the transparent observation section at a distance of approximately 2.5 m from the pipeline, covering the entire effective flame

propagation region. The imaging system provided a spatial resolution of approximately $0.6 \text{ mm pixel}^{-1}$, with a field of view covering the full height of the transparent section.

2.2.2. Experimental Conditions

In accordance with ASTM E1226 standards [38,39], before the experiment, the vertical pipeline body was vacuumed (gauge pressure of -0.02 MPa). The experimental parameters were as follows: ignition delay time = 200 ms; inflation pressure = 0.05 MPa ; high-speed camera shooting speed = 2000 frames per second; data acquisition rate = 1 million/s; and laboratory temperature = $20 \text{ }^{\circ}\text{C}$. The pressure of the air tank was adjusted to 0.55 MPa , and then the air tank was opened. When the pressure of the explosion pipeline was close to 0 MPa , the electric spark ignition mode was adopted with an ignition energy of 10 KJ. To acquire the dynamic images of pulverized coal flame propagation, a darkroom environment was built.

To ensure experimental repeatability and enable consistent inter-group comparisons, key operating parameters—including dust dispersion pressure, ignition delay time, loading procedure, and ignition energy—were strictly maintained across all tests. Under these standardized conditions, the nominal dust concentration was calculated from the loaded coal mass and the effective volume of the explosion tube. Each experimental condition was repeated at least three times under identical operating conditions to evaluate the repeatability of the experiments. The flame images and pressure histories presented in this paper are representative results selected from repeated tests exhibiting consistent flame propagation characteristics and pressure evolution trends. The conclusions of this study are based on the overall consistency observed among the repeated experiments.

2.3. Experimental Method

1. All equipment and devices were connected as shown in Figure 1 to ensure that the explosion test device could operate normally.
2. A known amount of pulverized coal particles was weighed with an electronic balance and placed in the dispersion dish at the bottom of the pipeline.
3. The air bottle was filled with compressed air.
4. The test was started, and the different controllers were set according to relevant instructions to make the high-speed camera, data acquisition instrument, high-pressure ignition system and each device work according to the set values.
5. The data collected by the high-speed photography system, temperature acquisition system and pressure sensor were saved on the computer.
6. The combustion products in the vertical pipeline were cleaned.
7. Each system of the explosion test device was checked to ensure normal test conditions, and then repeatability tests were performed.
8. Flame propagation characteristics were quantified from high-speed images using MATLAB R2021a (MathWorks, Natick, MA, USA). Original images were converted to grayscale, filtered, and binarized to isolate the luminous flame region. The flame boundary was extracted via edge detection, and the flame-front height was determined for each frame based on spatial calibration using the pipeline's inner diameter. Propagation velocity was calculated via finite-difference differentiation of the flame-front position and smoothed with a moving-average filter to reduce noise-induced fluctuations. The detailed processing procedure is illustrated in Figure 2.

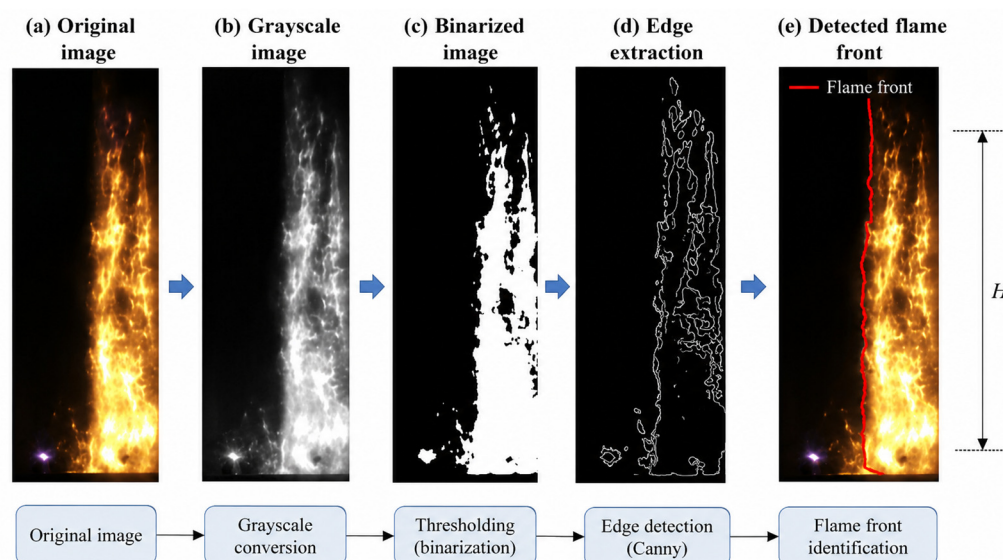


Figure 2. Image-processing workflow for flame-front extraction and flame height determination.

3. Results and Discussion

3.1. Analysis of the Flame Propagation Processes of Pulverized Coal Cloud Explosion

Figure 3a–c are the transient images of the flame propagation of pulverized coal clouds with an average particle size of $200\ \mu\text{m}$ and concentrations of 0.3, 0.4 and $0.5\ \text{kg}/\text{m}^3$, respectively, taken at different times by high-speed cameras. As shown in Figure 2, the high-pressure ignition system started to ignite at 0 ms, and a little flame appeared at the instant of ignition. During the flame propagation process from 0 to 10 ms, the flame evolution process was not obvious. Over time, the flame propagation process evolved. After 20 ms, a distinct reddish flame began to appear, and the flame propagation speed increased significantly compared with 0–10 ms. At 40 ms, the flame had completely spread to the pipe wall. Due to the restriction of the bottom and inner wall of the pipe, the gas generated by the pulverized coal explosion and combustion reaction accumulated at the bottom of the pipe. These gases moved toward the open end during the process of flame propagation, resulting in flame propagation acceleration, and the upward propagation speed of the flame gradually increased. In addition, the flame propagation front presented a very irregular phenomenon. One possible reason was that the pulverized coal in the dish at the bottom of the pipe formed the pulverized coal cloud due to the action of the dry compressed air in the air storage bottle, and the dry compressed air itself entered the pipe to form the air flow, resulting in the irregular, turbulent flow of the air in the pipe, which acted on the upward propagation of the pulverized coal cloud flame, resulting in the irregular flame shape. During the period of 40–60 ms, the flame propagated toward the tube wall, and the flame front remained generally continuous. As the flame developed upward, buoyancy and flow disturbance gradually caused the flame front to become increasingly wrinkled, distorted, and partially stretched, exhibiting an approximately parabolic profile. Subsequently, the flame propagated more rapidly toward the top of the pipeline than toward the bottom owing to precursor flame development and pressure-wave reflection from the tube base. At approximately 60 ms, discontinuous flying sparks and localized ignition kernels became visible, accompanied by increasingly irregular flame-front structures. These phenomena are considered to be associated with the combined effects of flow instability within the pipeline and buoyancy induced by volatile combustion. By 110 ms, the expansion of combustion products became increasingly constrained by the pipe wall and bottom boundary. As fuel consumption proceeded, the combustion reaction gradually weakened, resulting in

reduced flame propagation velocity, slower flame-height growth, and eventual filling of the entire explosion tube.

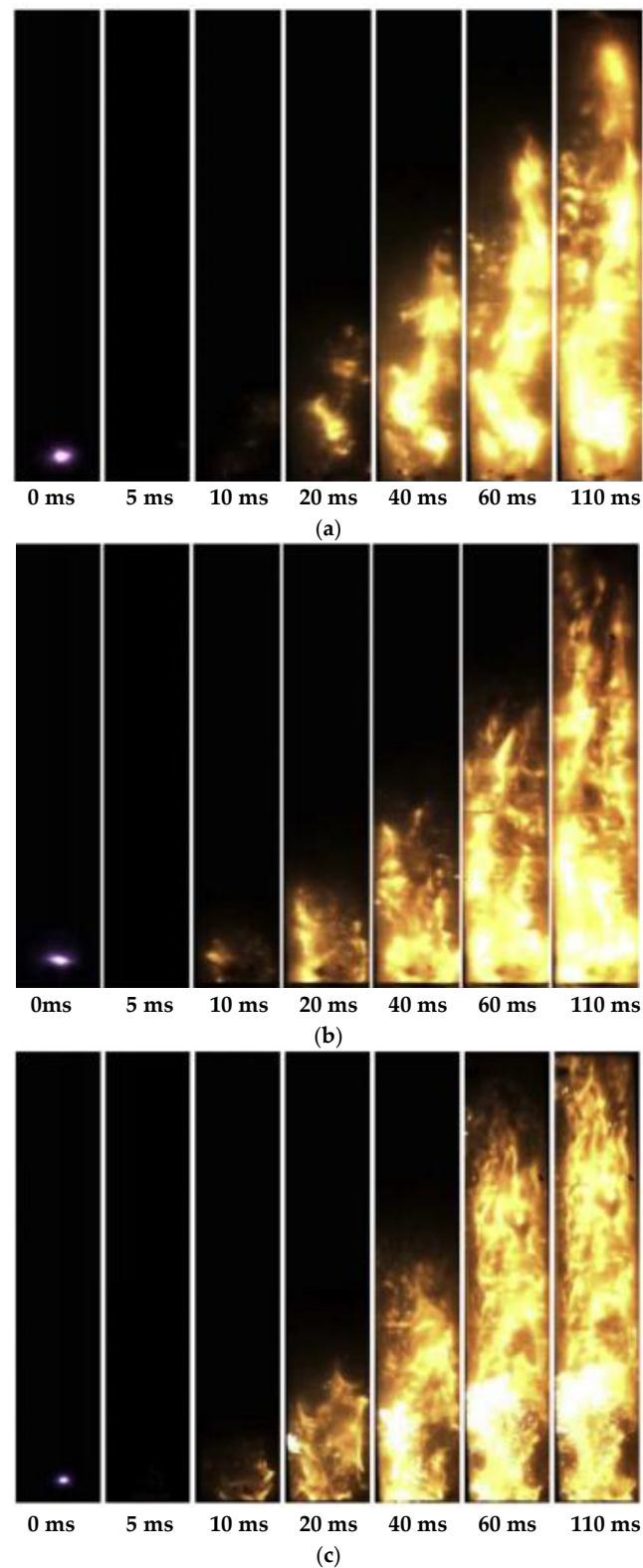


Figure 3. Transient images of different concentrations of pulverized coal cloud propagating over time with an average particle size of 200 μm . (a) Pulverized coal cloud with concentration of 0.3 kg/m^3 . (b) Pulverized coal cloud with concentration of 0.4 kg/m^3 . (c) Pulverized coal cloud with concentration of 0.5 kg/m^3 .

At the three concentrations, the flame propagation patterns of the pulverized coal clouds were quite different. The flame front height increases with the increase in the mass concentration of the pulverized coal cloud, which is due to the increase in the mass concentration of the pulverized coal cloud when the particle size and ignition time are fixed, the number of pulverized coal particles per unit volume is relatively large, and the particle collision is more frequent, which greatly reduces the time of oxygen diffusion to the particle surface, accelerates the heat release, and the combustion reaction intensity is relatively large and the explosion is more intense. For all that, when the mass concentration of pulverized coal cloud exceeds a certain value, excessive unburned pulverized coal particles will absorb part of the heat released by combustion, resulting in a decrease in flame propagation temperature and a slower combustion reaction rate of pulverized coal. At the same time, due to the limitation of oxygen content in the pipeline, the explosion combustion reaction decreases with the increase in dust cloud concentration.

3.2. Flame Propagation Velocity

3.2.1. Temporal Evolution of Velocity

The flame propagation speed was defined as the transition and evolution of the flame from the ignition area to the unburned area at a specific speed after the ignition electrode ignited the local part of the pulverized coal cloud. This specific speed was the flame propagation speed, i.e., the movement speed of the front of the flame in the normal direction. Based on the flame cloud image obtained by experimental tests and data post-processing, MATLAB image processing technology was used for binarization, edge extraction and other processing, and the change law of flame front height and flame velocity with time in the explosion process under this working condition was obtained. Figure 4 shows the change in the pulverized coal cloud flame propagation with a particle size of 200 μm and a concentration of 0.3 kg/m^3 over time.

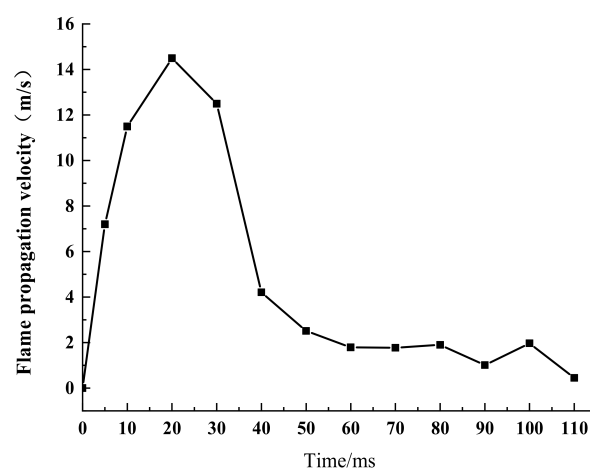


Figure 4. Change in velocity of the pulverized coal cloud flame.

From Figure 4, the flame propagation speed of the pulverized coal cloud first increased and then decreased. At 20 ms, the flame propagation speed reached the maximum of 14.5 m/s. This was because the ignition system in the pipeline was close to the bottom of the pipeline, and the gas and explosion impact force generated by the explosive combustion of the pulverized coal contributed to the upward propagation of the flame, resulting in the accelerated flame propagation speed. However, at 20 ms, the flame propagation speed gradually decreased due to the restriction of the pipe outlet on the flame and the heat absorption and compression effect of the explosion products. After approximately 60 ms, the flame velocity of the pulverized coal oscillated. The flame velocity of pulverized

coal had obvious oscillation characteristics. The main reason for this phenomenon is the instability of the reaction rate during the diffusion combustion of the pulverized coal cloud. The endothermic characteristics of solid residues and gas products produced after combustion and explosion seriously affect the characteristics of the temperature field and diffusion process. In addition, in the vertical pipe, the pulverized coal dust explosion is a domino chain reaction process, and the flame propagation process goes through three stages: ignition stage, vertical propagation stage and free diffusion stage. In the ignition stage, the pulverized coal particles emit weak light spots after ignition and propagate around slowly. After that, with the development of the explosion, the flame propagates vertically along the pipe, and the explosion pressure and temperature increase rapidly in the confined space. After the flame is released from the vertical pipe to the free space, the flame propagation enters the free diffusion stage. At this stage, the hot gas diffuses and settles around, while the cold airflow at the bottom rises rapidly under the heating and entrainment of the hot airflow, resulting in the oscillation effect of the flame propagation velocity.

3.2.2. Effect of Dust Concentration

Figure 5a–c shows the flame propagation velocity curves of the pulverized coal clouds with average particle sizes of 45, 100 and 200 μm with three mass concentrations (0.3, 0.4 or 0.5 kg/m^3).

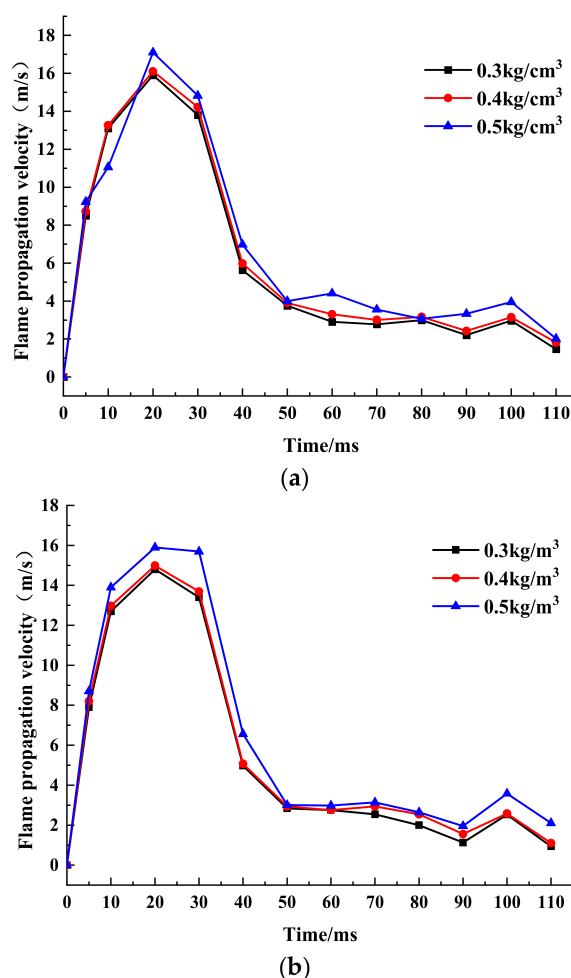


Figure 5. Cont.

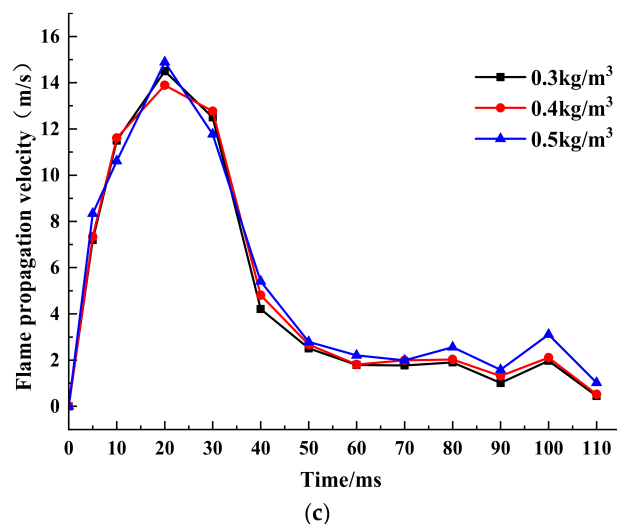


Figure 5. Flame propagation velocity curves for pulverized coal clouds with the same average particle size and different mass concentrations with time. (a) 45 μm average particle size; (b) 100 μm average particle size; (c) 200 μm average particle size.

As shown in Figure 5, the flame propagation speed obviously increased from 0 to 20 ms, and the peak value appeared when the flame propagated to 20 ms. From 20 to 60 ms, the flame propagation speed decreased with increasing time. After 60 ms, the flame propagation speed showed an oscillation phenomenon. During the flame propagation process, for each pulverized coal particle size, the flame propagation speed was higher with a pulverized coal cloud concentration of 0.5 kg/m^3 than with a concentration of 0.3 or 0.4 kg/m^3 .

Taking the pulverized coal particle size of 45 μm as an example, with the increase in flame propagation time, there was a positive correlation between flame propagation speed and flame concentration during the whole flame propagation process. When the concentration of coal dust was low, less heat was released from the coal dust per unit volume, resulting in a slower heating rate of the pulverized coal particles. As the concentration of pulverized coal cloud increased, the heat emitted by the pulverized coal cloud per unit volume increased, and the reaction became more intense. Increasing the nominal dust concentration provided more combustible particles per unit volume, resulting in greater overall heat release during combustion. The enhanced heat release strengthened heat transfer from the flame front to the surrounding unburned dust cloud, thereby accelerating flame propagation and promoting pressure development.

3.2.3. Effect of Particle Size

Figure 6a–c presents the time-varying curves of the flame propagation velocity of coal dust cloud with mass concentrations of 0.3, 0.4 and 0.5 kg/m^3 in the pipeline with different average particle sizes.

As shown in Figure 6, during the whole pulverized coal cloud flame propagation process, the pulverized coal particle size had a negative correlation with the flame propagation speed. This was primarily because smaller particle sizes led to larger specific surface areas, which provided more opportunities for pulverized coal particles to come into contact with oxygen and increased the combustion reaction rate at a microscopic level, which in turn made the pulverized coal particles burn hotter. Conversely, when the pulverized coal particles were larger, as the combustion process proceeded, the inside of the pulverized coal particles could not be completely burned due to insufficient oxygen supply, resulting in a relatively difficult release and transfer of combustion heat. Thus, increasing pulverized coal particle sizes resulted in decreasing flame propagation speeds.

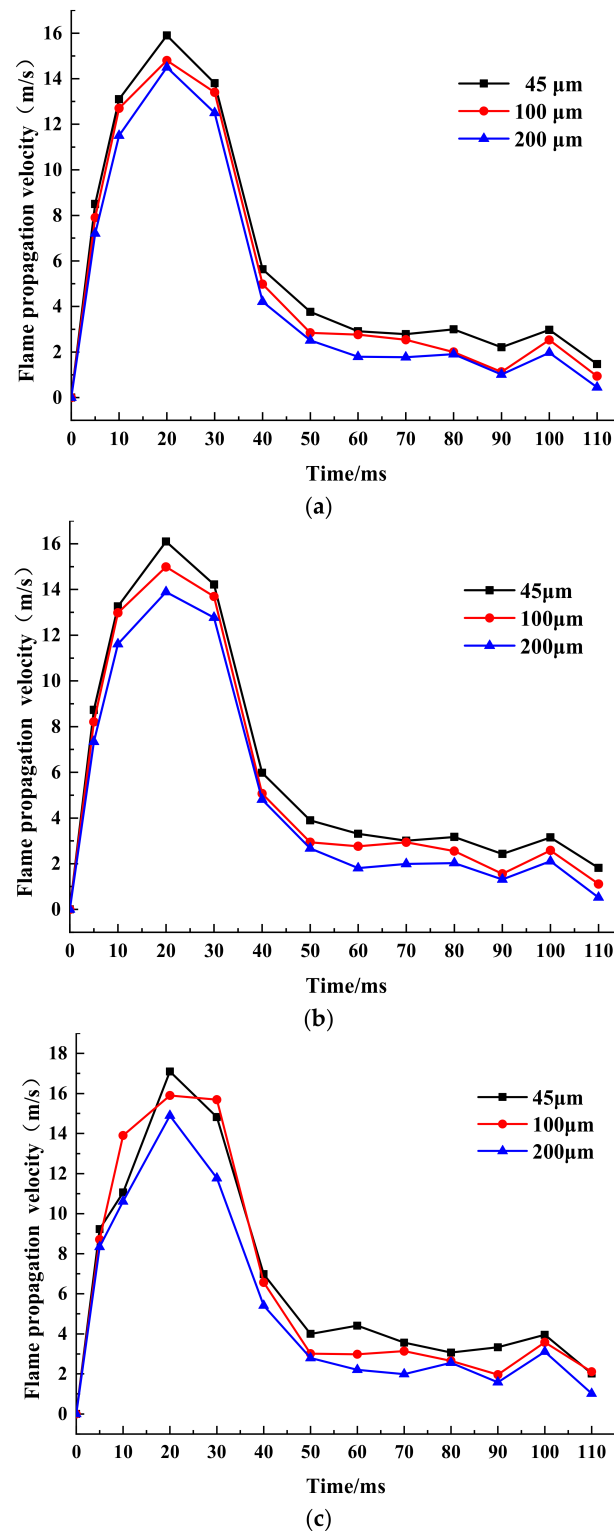


Figure 6. The curves of cloud flame propagation velocities with different particle sizes and constant mass concentrations with time. (a) 0.3 kg/m^3 ; (b) 0.4 kg/m^3 ; (c) 0.5 kg/m^3 .

3.3. Explosion Pressure Characteristics

3.3.1. Temporal Pressure Evolution

Pressure measurements were employed to investigate the transient overpressure behavior during pulverized coal cloud flame propagation in the vertical pipe. Figure 7 presents the representative pressure-time history for a coal cloud with a particle size of $200 \mu\text{m}$ and a concentration of 0.3 kg m^{-3} .

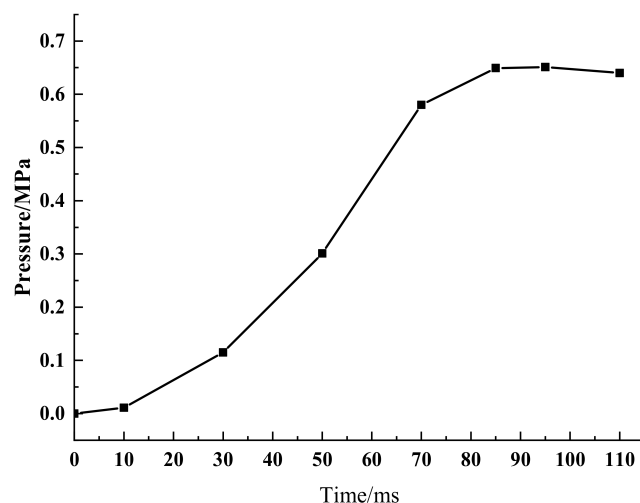


Figure 7. Characteristics of explosion pressure with time during flame propagation.

As shown in Figure 6, with the continuous pulverized coal explosion flame propagation in the pipeline, the pressure in the pipeline was in direct proportion to time. During the initial stage (0–10 ms), no significant combustion-induced pressure rise was observed following ignition. The slight pressure fluctuation recorded within this period is attributed solely to the transient aerodynamic disturbance generated by dust dispersion prior to ignition. Then, the explosion entered the middle stage (10–85 ms), and the explosion pressure increased more slowly. The reason was that during the middle of the explosion, the explosive products of pulverized coal expanded rapidly, and the gas–solid two-phase flow was affected. The pressure of the explosion system increased rapidly with increasing time and reached the peak pressure of 0.651 MPa at 85 ms.

During the later stage of the explosion (85–110 ms), the explosion pressure dropped slightly compared with the peak pressure, which was a large pressure difference with the outside world after the explosion pressure reached the peak value. The experimental instrument was not absolutely closed and was not an ideal adiabatic environment, and the pressure value slightly dropped.

3.3.2. Effect of Dust Concentration

Figure 8a–c are the time-dependent pressure curves of pulverized coal with mass concentrations of 0.3, 0.4 and 0.5 kg/m³, respectively, in a vertical pipeline when the average particle size was fixed (45, 100 and 200 μm).

As shown in Figure 8, when the particle size of pulverized coal was fixed, the mass concentration was directly proportional to the explosion pressure, i.e., during the whole flame propagation process, the explosion pressure of the pulverized coal cloud with a mass concentration of 0.5 kg/m³ was significantly higher than that of the other mass concentrations. When the particle size of the pulverized coal cloud was 45 μm, the maximum explosion pressures corresponding to the pulverized coal cloud with mass concentrations of 0.3, 0.4 and 0.5 kg/m³ were 0.71, 0.748 and 0.948 MPa, respectively. When the particle size of the pulverized coal cloud was 100 μm, the maximum explosion pressures corresponding to the pulverized coal cloud with mass concentrations of 0.3, 0.4 and 0.5 kg/m³ were 0.688, 0.712 and 0.911 MPa, respectively. When the particle size of the pulverized coal cloud was 200 μm, the maximum explosion pressures corresponding to the pulverized coal cloud with mass concentrations of 0.3, 0.4, and 0.5 kg/m³ were 0.651, 0.696 and 0.788 MPa, respectively. This was because increasing concentrations of the pulverized coal cloud resulted in more pulverized coal cloud particles involved in the reaction, more violent combustion reactions, more total heat released by combustion, and greater explosion pressures.

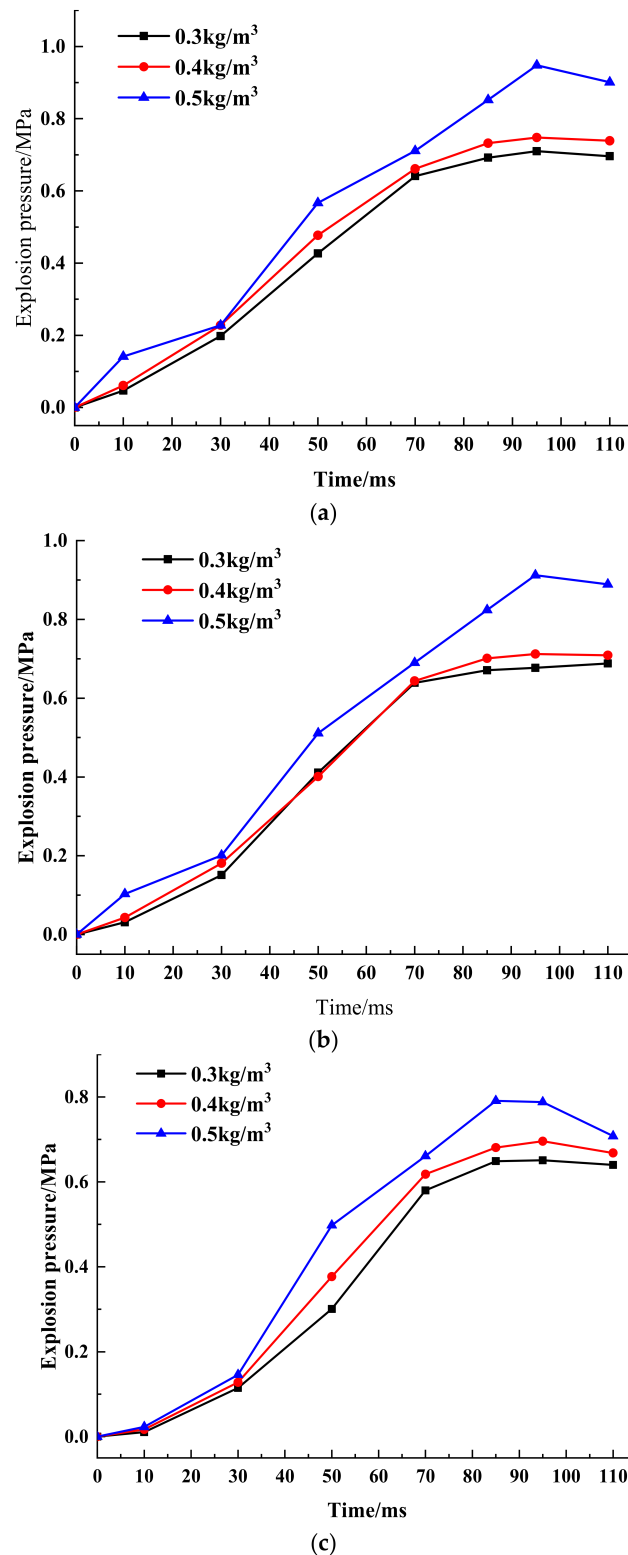


Figure 8. The explosion pressure curves with time during pulverized coal cloud flame propagation with constant average particle sizes and different mass concentrations. (a) 45 μm average particle size; (b) 100 μm average particle size; (c) 200 μm average particle size.

3.3.3. Effect of Particle Size

Figure 9a–c are the characteristic curves of pressure change with time during pulverized coal flame propagation with an average particle size of 45, 100 and 200 μm , respectively, in a vertical pipe when the mass concentration was fixed (0.3, 0.4 or 0.5 kg/m³).

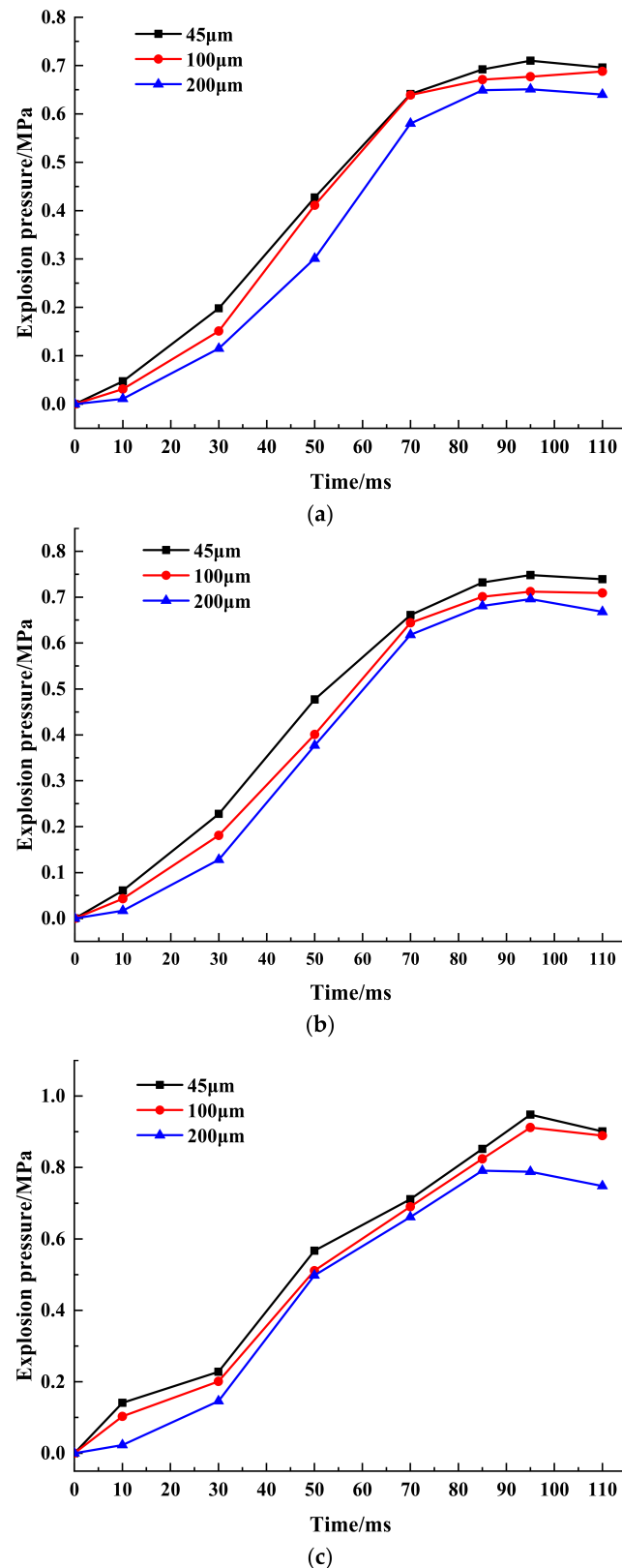


Figure 9. Explosion pressure curves with time during the process of cloud flame propagation of pulverized coal with certain mass concentrations and different particle sizes. (a) 0.3 kg/m³; (b) 0.4 kg/m³; (c) 0.5 kg/m³.

Under a constant dust concentration, the average particle size exhibited a clear negative correlation with explosion pressure. As shown in Figure 9, decreasing the particle size resulted in a progressive increase in the peak explosion pressure. At a concentration

of 0.3 kg m^{-3} , the maximum pressure increased from 0.651 MPa for 200 μm particles to 0.710 MPa for 45 μm particles, corresponding to an increase of 9.1%. Similarly, at concentrations of 0.4 and 0.5 kg m^{-3} , the peak pressure increased by 7.5% and 20.3%, respectively, as the particle size decreased from 200 μm to 45 μm . The influence of particle size became more pronounced at higher dust concentrations.

This behavior can be attributed to the larger specific surface area and shorter characteristic heat transfer distance of finer particles, which facilitate oxygen transport and particle heating, thereby promoting volatile release during combustion. Consequently, the combustion reaction proceeds more rapidly, resulting in a faster pressure rise and a higher peak explosion pressure. In contrast, coarse particles exhibit lower combustion reactivity due to their reduced specific surface area and longer oxygen diffusion paths. Furthermore, particle settling during dust dispersion becomes more significant for larger particles, reducing the effective concentration of suspended combustible dust and weakening the explosion intensity. As a result, both the pressure rise rate and the maximum explosion pressure decrease with increasing particle size.

3.4. Coupling Mechanism Between Flame and Pressure

Although particle size and dust concentration independently affect flame propagation and explosion pressure, the experimental results indicate that these two parameters simultaneously regulate the evolution of flame acceleration and pressure accumulation rather than acting as isolated variables. As particle size decreases or dust concentration increases, the enhancement of combustion intensity is reflected not only in a higher flame propagation velocity but also in a more rapid pressure rise and a larger peak overpressure. These two responses evolve synchronously throughout the explosion process, suggesting that flame acceleration and pressure development are governed by the same underlying energy-release mechanism. Figure 10 shows the peak velocity of pulverized coal cloud flame propagation under different mass concentrations when the particle size of pulverized coal was 45, 100 and 200 μm .

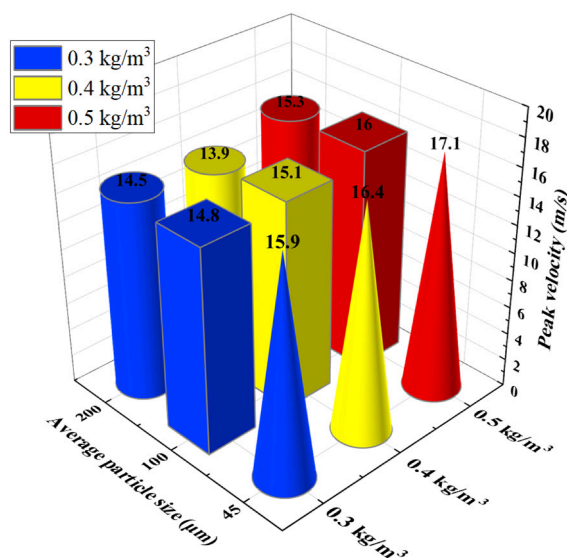


Figure 10. Peak velocity of the flame propagation of pulverized coal clouds with different particle sizes and different mass concentrations.

The synchronized evolution of flame propagation and pressure development demonstrates that flame acceleration can be regarded as a direct manifestation of the combustion rate, whereas pressure accumulation reflects the integrated consequence of heat release under confinement. Therefore, the coincidence of higher flame velocities with larger explo-

sion pressures is attributed primarily to enhanced combustion intensity and gas expansion within the confined vertical pipeline. The observed flame-front wrinkling and irregular propagation may contribute to this behavior by increasing the effective flame surface area.

Furthermore, the influence of particle size becomes increasingly significant as dust concentration increases. Under higher dust concentrations, fine particles provide substantially larger reactive surface areas and shorter ignition delay, allowing combustion to spread rapidly through the dust cloud before significant particle settling occurs. Consequently, the combined effect of fine particles and high dust concentration exhibits a synergistic enhancement of explosion severity rather than a simple linear superposition of two independent parameters.

These findings indicate that particle size and dust concentration should not be considered as separate explosion parameters in vertical conveying systems. Instead, they jointly regulate flame acceleration, pressure generation, and explosion severity through coupled combustion kinetics, flame-front evolution, and confined heat-release processes. This interpretation provides a more comprehensive understanding of pulverized coal explosion evolution and offers guidance for explosion hazard assessment and operational control in industrial conveying systems.

4. Conclusions

1. Pulverized coal flame structure is governed by coupled flow evolution and particle combustion. Elevated dust concentrations induce pronounced flame-front wrinkling and irregular propagation, highlighting complex combustion dynamics and advancing the understanding of flame propagation in vertically confined coal dust explosions.
2. Particle size is a key parameter controlling flame propagation characteristics. Decreasing particle size enhances the available reactive surface area and accelerates heterogeneous and homogeneous combustion reactions, resulting in higher flame propagation velocities. Within the investigated range, increasing coal dust concentration further intensifies combustion, demonstrating a synergistic effect of particle fineness and concentration on flame acceleration.
3. Explosion pressure development exhibits a strong dependence on both particle size and concentration. Smaller particles and higher dust concentrations promote more rapid energy release and pressure accumulation, leading to greater explosion severity. The coincidence of the maximum flame propagation velocity and maximum explosion pressure under identical conditions suggests that flame acceleration and pressure generation are controlled by the same combustion kinetics and energy-release mechanisms. Consequently, fine pulverized coal clouds at elevated concentrations represent the most hazardous explosion scenario in vertical pipeline systems.

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remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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