Experimental study of low-concentration gas explosion in large-scale pipeline

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Funding information
National Science and Technology Major Project of China, Grant/Award Number: 2016ZX05045004; Henan Polytechnic University, Grant/Award Number: WS2019B02; Natural Science Foundation of Chongqing, Grant/Award Number: cstc2019jcyj-bsh0041; State Key Laboratory of Coal Mine Disaster Dynamics and Control, Grant/Award Number: 2011DA105287-BH201903

Abstract
Low-concentration gas is one of the most realistic and reliable supplementary or alternative energy sources of conventional natural gas, which has a wide range of applications. However, this gas is flammable and explosive during pipeline transportation and easily causes an explosion. In order to achieve safe transmission, the explosion characteristics and propagation law of low-concentration gas are systematically studied through a large-scale pipeline experimental system. We found that the peak pressure of low-concentration gas explosion in pipeline has a quadratic function relationship with the propagation distance. Moreover, the peak pressure of gas explosion initially decreases from the explosion source, and then a turning point appears after a certain distance of propagation, which is followed by a sharp increase of peak pressure of gas explosion. The explosion pressure becomes maximum at the outlets of a pipeline. The arrival time of explosion flame is logarithmically relevant to propagation distance, while the speed of flame propagation gradually increases along with the increase of propagation distance. The flame propagation is faster at the exit point. In addition, the diameter of pipeline has also an important influence on the explosion propagation process of low-concentration gas. So, the larger the diameter, the higher the explosion pressure. The explosion pressure of DN700 pipeline is obviously higher than that of DN500, and the explosion pressure rises faster; the speed of flame propagation of gas explosion in DN700 pipeline is also higher than that in DN500 pipeline. This study provides a theoretical reference for the prevention and control of explosion accidents in low-concentration gas pipelines.

Keywords
explosion characteristic, flame propagation, large-scale pipeline, low-concentration gas

1 | INTRODUCTION

Coal is important basic energy and industrial raw material and has a very important strategic position in the development of national economy of China. China has the largest coal output and consumption, and most of its coal mines contain a lot of gases. With the increase of mining depth and intensity, the gas pressure and content gradually increase.1-3 Gas
has high efficiency and clean energy. The calorific value of gas with 100% methane concentration can reach 35,900 kJ/Nm³, which is about 2-5 times of coal. The calorific value of gas is equal to that of natural gas. It has high economic value and a wide range of applications.4-6 In 2015, China's coal mine gas extraction reached 13.6 billion cubic meters, and the utilization was 4.8 billion cubic meters. Improving the gas utilization rate, especially low-concentration gas, is of great significance to alleviate China's energy demand, improve energy structure, and protect the atmospheric environment.7 However, this gas is flammable and explosive, especially its transportation in the pipeline of transportation system is very dangerous. When it mixes with air or oxygen in a certain concentration, it causes an explosion with the ignition source, even more, destructive detonation, and its adverse consequences are very serious. Economic loss may become a bottleneck, restricting the safe and efficient use of gas.8-10 Therefore, it is of great practical significance to study the explosion and propagation characteristics of low-concentration gas in pipeline.

The main parameters to measure the characteristics of a gas explosion are flame propagation velocity, flame temperature, explosion pressure, and a rising rate of explosion pressure. Comprehensive national and international research has been reported on the characteristics of gas explosion.11-15 In the early 1980s, Richmond and Lebman have carried out an experimental study on the flame propagation process of gas explosion in a full-scale simulated coal mine roadway, to effectively prevent and control gas explosion accidents in coal mines. They analyzed the flame pressure and velocity curve of gas explosion in the roadway and carried out an experimental analysis of the effectiveness and characteristics of active and passive explosion-proof and explosion-suppressing devices. Their results show that the flame propagation velocity and overpressure change of gas explosion in the roadway are related to the inner wall structure of the roadway and the distribution of gas concentration.16,17 In China, the first roadway used for gas and coal dust explosion experiments was built in 1982 in Chongqing Branch of the General Academy of Coal Sciences. Since its establishment, the experimental system has completed about 1000 explosion experiments, which has contributed a lot of research on gas explosion and its prevention technology. Extensive experimental results show that under similar conditions, the maximum pressure peak increases with the increase of gas accumulation, and the corresponding maximum pressure peak is closer to the location of explosion source. It is also concluded that the explosion overpressure and flame propagation speed obviously increase with the increase of gas quantity. Furthermore, the length of flame area of gas explosion can reach 3-6 times the length of the original gas accumulation area. With the increase of gas quantity, the increase length of the explosion flame zone is relatively shorter.18-20

The experimental pipeline is cost-effective and widely used for the investigation of propagation process of a gas explosion.21-25 Moen and Oh et al26 studied the instability and acceleration of gas explosion flame. They found a turbulence-type mechanism for the flame acceleration. Small disturbance of obstacles could also cause the acceleration of flame and the sharp rise of pressure in pipes, and the propagation speed of flame in spiral channels. The rate was nearly 24 times higher than that of without obstacles. Lu et al27 have studied the propagation characteristics of explosive shock waves of combustible gas in a pipeline. They qualitatively described the influence of obstacles on the explosive shock wave pressure. Fairweather28 carried out experimental and theoretical studies for the flame propagation process of premixed methane-air combustible gas in a circular pipe. Their work confirmed the acceleration effect of obstacles on the flame. Furthermore, Dunn-rankin and Mccann29 carried out an experimental study for the overpressure of obstacle accelerating flame propagation, in a turbulent explosion of a long pipe. They established a two-dimensional mathematical model for the obstacle accelerating flame propagation. Lin et al30 studied the flame propagation law and the accelerating mechanism, during a gas explosion in a steel square gas explosion pipe. Their results show that the speed of flame propagation will rapidly increase with obstacles, and the resulting shock wave may increase the power of gas explosion. Wang et al31 investigated the effect of concentration and obstacles on methane-air mixture deflagration to detonation transition in a long duct. They found that the larger the obstacle blockage ratio, the stronger the interaction of the unburned mixture with a shock wave, which is highly beneficial for the acceleration of explosion flame. Ritsu32 reported systematic research, using flame propagation phenomena, for the serious damages, caused by a gas explosion. Nie et al33 have employed an image processing method and found instability in the velocity and structure of gas explosion flame when propagated in a pipeline. In addition, the flame undergoes an alternating cycle of mutual acceleration and deceleration.

It is obvious from the literature that a laboratory-scale experimental pipeline is commonly used for the investigation of the characteristic and propagation process of gas explosion. The laboratory results can reproduce the full-scale tests to a certain degree but still some differences are found between them. Therefore, we have carried out experiments on low-concentration gas explosion, in a large-scale pipeline. The low-concentration gas adopted in this manuscript is composed of CH₄ with concentration of less than 25% and air. Our method can accurately reflect the properties of a low-concentration gas transportation system. This study aims to investigate the characteristics and flame propagation of low-concentration gas explosion. Finally, this work
may provide a reference to effectively prevent and control the occurrence of gas explosion accidents in pipeline, and reducing the severity of consequences, caused by gas explosion.

2 | EXPERIMENT

2.1 | Explosion experiment system

The gas explosion system is mainly composed of an explosion pipeline, gas distribution system, ignition device, pressure/flame measurement system, data acquisition, and analysis system. The explosion pipeline has a similar pipeline connection as that of a low-concentration gas transportation system (shown in Figure 1). This can truly reflect the confined space characteristics of the gas explosion in the pipeline. The explosion pipeline is divided into two sizes; the one with a nominal diameter of 500 mm and full length of 66.5 m pipeline; the other with a nominal diameter of 700 mm and full length of 99.1 m pipeline. Both pipes are designed to withstand pressure of 2.5 Mpa. In addition, a vacuum pump circulating system is used as a stirring device to uniformly fill the CH₄/O₂ mixture in the pipeline during the explosion experiment. The ignition device adopts an industrial chemical ignition head, which can generate about 375 mJ ignition energy. CYG solid piezoresistive pressure sensor (produced by Baoji Sensor Research Institute, China) is adopted and connected with the dynamic data analysis system. This sensor has optimal temperature range of −30°C ~ 80°C and a signal output range of 0～20 ma. Its accuracy can be reached up to 0.5, including linearity, hysteresis, and repeatability. The gas explosion flame is monitored by a photoelectric sensor, which can convert the optical signal of flame to an electric signal, for analysis. It has high sensitivity, wide response range, and short response time (<1 ms).

FIGURE 1 Experimental representation of pipelines for an explosion

The arrival time of flame is obtained from the variation of wave jumping. The data acquisition and analysis system adopt the PXI-50612 dynamic signal synthesis test system (produced by TOPO Digital Equipment Co., China.). At one time, this system can collect data signals of 32 channels and the highest sampling frequency can reach 50 Msp/s, as shown in Figure 2. The sampling length, frequency, and sampling channel can be adjusted according to the experimental requirements.

2.2 | Experimental scheme

2.2.1 | Experimental conditions

In order to extensively study the explosion characteristics of low-concentration gas in pipeline, DN500 and DN700 pipelines were separately used to carry out gas explosion experiments. The experiments were conducted outdoor in Chongqing, China. The average temperature was 25°C, and the temperature variation from one day to another was about 2°C-3°C. The relative humidity was about 80%. In case of a gas explosion experiment, two layers of plastic film (thickness of 0.12 mm) were used to seal the corners of pipeline and form a confined space. The total volume of DN500 pipeline is 13 m³ while that of DN700 is 35.8 m³. The gas/air mixture with different volume fraction is filled in two different sizes of pipelines, to meet the requirements of different gas concentration, as listed in Tables 1 and 2.

2.2.2 | Measuring points arrangement

As the size and length of DN500 and DN700 pipelines are different, so, different layout schemes are required for measuring points, to arrange pressure and flame sensors of the pipeline wall, as shown in Figure 2. This arrangement has been employed for a comprehensive and accurate characteristic parameter of gas explosion propagation, at two different transmission conditions.

In case of DN500 pipeline, the ignition device is set to 3.5 m apart from the initial section of pipeline. Flame sensors start at 9.5 m from the beginning of pipe, each of them is 3 m apart from each other and 9 m apart from each group. So, a test can be performed when the flame reaches the sensing point. Ten pressure sensors are arranged at 3.5 m from the beginning of pipeline, at 6 m intervals. The maximum pressure and presentation time of shock wave pressure at the sensor placement point are tested.

In case of DN700 pipeline, the distance between the ignition device and pipeline initial section is 4.3 m. Flame sensors are separated into five different groups, where two of them are 3 m apart from each other in group one and start at 14.5 m from the initial section of pipeline. First, second, and third sets of flame
sensors are 13.2 m apart, the third and fourth groups are 12 m apart, and the fourth and fifth groups are 19.5 m apart. The pressure sensor is located at 4.3 m from the beginning of pipe, each of them is located at 10 m interval.

### 2.3 Experimental method

The ignition, pressure sensors, and flame sensors are arranged according to the measuring points for the determination of the low-concentration gas explosion experiment in pipeline. The ends of pipe are sealed with plastic film. Gas explosion experiments must be carried out in highly sealed conditions, especially for the large-scale experimental pipelines, used in this paper. In case of poor airtightness, the internal flammable gas can leak from the pipeline and mix with the air of the surrounding environment. Once there is an ignition source around, the mixed flammable gas can be easily denoted and cause an explosion accident, posing a great threat to experimentalists and pieces of equipment. In addition, due to gas leakage, the gas/air mixture concentration and initial pressure of the pipeline cannot be constantly maintained, which can cause great errors in the experimental results. Therefore, the whole experimental pipeline leaks must be properly checked before charging and distributing gas, in each explosion experiment. After the gas tightness check is qualified, the amount of filling the gas can be calculated from the required gas concentration and pipe volume. According to the basic principle of the partial pressure method, the mixture of gas/air is prepared and poured into the pipeline which has been evacuated to vacuum. After this, the mixing system is opened to evenly mix the gas/air mixture in the pipeline. Finally, the gas/air mixtures

| CH₄ concentration (%) | Ignition energy (mJ) | Ignition position (m) |
|-----------------------|----------------------|----------------------|
| No.1 7.5 | 375 | 3.5 |
| No.2 8.5 | 375 | 3.5 |
| No.3 9.7 | 375 | 3.5 |
| No.4 9.8 | 375 | 3.5 |

TABLE 2 Experimental conditions of DN700 pipeline

| CH₄ concentration (%) | Ignition energy (mJ) | Ignition position (m) |
|-----------------------|----------------------|----------------------|
| No.1 7.5 | 375 | 4.3 |
| No.2 9 | 375 | 4.3 |
| No.3 9.2 | 375 | 4.3 |
| No.4 10 | 375 | 4.3 |
are ignited for an explosion. After every explosion experiment, ventilation should be carried out on the explosion experimental pipeline to completely discharge the residual gas of gas explosion in the pipeline. This can help the next explosion experiment.

3 | RESULTS AND DISCUSSION

3.1 | Propagation rule of explosion pressure

3.1.1 | Maximum explosion pressure propagation law

The maximum explosion pressure of each measuring point is shown in Figure 3. From Figure 3, we can see that the explosion pressure is measured in DN500 and DN700 pipelines which is between 0.7 and 1.9 MPa. When the gas concentration of pipeline approaches 9.5% of the optimum equivalent concentration of gas explosion, a larger maximum pressure peak value is measured in the pipeline. In case of DN500 pipeline, the maximum pressure peak value is 1.845 MPa when the gas concentration is 9.7. While for DN700 pipeline, the maximum peak pressure is 1.856 MPa at 9.2% gas concentration. In case of other two concentrations such as 10% and 9%, the obtained maximum explosion pressures are 1.850 and 1.848 Mpa, respectively, which are slightly smaller than that of 9.2% concentration. Previous reports have shown that when the gas concentration is close to 9.5%, then CH₄ can completely react with the oxidation and combustion of oxygen in the air, more heat release, explosion reaction is very intense, and greater explosive power is produced. Comparative analysis of the pressure peaks at different locations led us to conclude that the maximum explosion pressure is a “√” shaped distribution, with increasing propagation distance in DN500 and DN700 pipelines. The maximum pressure of pipeline in the initial section is much lower than that of end section. At the front of pipeline, initially, the maximum explosion pressure decreased from the ignited location and reached to a minimum value in the middle of pipeline. Then, along with further increase of propagation distance, the maximum explosion pressure dramatically increased from 50m in DN500 and DN700 pipelines and reached the maximum value at the end of pipeline. The dramatic increase of explosion pressure is mainly related to the flame acceleration and restriction of sealing film. When CH₄/air mixtures are ignited, the combustion flame first propagates in the form of a laminar flame. When the propagation distance is increased, the laminar flame gradually accelerates and transforms into a turbulent flame. The generation of turbulent flame can aggravate gas combustion and increased the temperature of mixed gas and volume, leading to a dramatic rise in pressure of the pipeline. On the other hand, when the explosion spreads throughout the pipeline, the propagation of shock waves is restricted by the sealing of the pipeline outlet. The reflection and superposition of shock wave rapidly occurred, causing a further increase in explosion pressure.³⁴,³⁵

In case of DN500 test pipeline, the measured explosion pressure of eight pressure sensors has a similar inverted "U" shaped distribution, except for the explosion pressure measured by two pressure sensors near the seal of a pipeline, as shown in Figure 4. So, with the increase in distance from the ignition source, initially, the explosion pressure decreases and then increases. The first pressure sensor is arranged near the starting of pipe, and the shock wave of an explosion is restricted by the closed pipe during transmission. These waves reflect and overlap with the wall of pipe which increases the pressure. In this work, the peak of measured explosion pressure is relatively large. As the explosion propagates to the outlet of the pipeline, the explosion pressure gradually decreases, and then the explosion pressure rises again due to the self-acceleration of the explosion process.³⁶

If another end of the pipeline is completely open, then the explosion pressure gradually decreases along with the increase of propagation distance. On the other hand, in case of low-concentration gas pipeline transportation, the explosion pressure gradually increases with the increase of propagation distance which results in intense explosion power. The reason behind this is a full pipeline of gas-air mixture after the explosion.

3.1.2 | Change law of explosion pressure present time

The explosion pressure present time of each measuring point in DN500 and DN700 pipelines is shown in Figure 5. It is obvious that the larger the distance away from the ignition location, the lower the explosion pressure present time of each measuring point. The peak value of explosion pressure initially appeared at the sealing point, near the end of pipeline. In addition, the peak value of explosion pressure is latest near the ignition source, but the time difference between them is varied from 50 to 100 ms. The difference in time between the peak value of minimum explosion pressure and the peak value of maximum explosion pressure in DN700 pipeline was larger. This is due to the relatively long length of DN700 pipeline. As the plastic sealing film at the outlet of explosion test pipeline will break during shock wave, so, the pressure of pipeline can be quickly released. In this case, there will be no reflection and superposition of shock wave. Therefore, the measured explosion pressure, using a pressure sensor which is located at the sealing of the end pipeline, can quickly achieve the maximum value. The pressure sensor at the ignition point is near to the closed initial section.
of the experimental pipeline, and the reflection, oscillation, and superposition of the explosion shock wave will occur on the wall of the pipeline, during the propagation process. Consequently, this will continuously increase the explosion pressure at the measuring point and the present time of the maximum explosion pressure is lower than that of other measuring points.

The peak time of explosion pressure in DN500 and DN700 pipelines is obviously different at different gas concentrations. In case of DN500 pipeline, when the gas concentration is 7.5%, the explosion pressure present time of each measuring point appears relatively late, such as in the range of 1325 to 1375 ms. When the gas concentration is 9.7%, the pressure present time of each measuring point is obviously less and decreases by about 28% compared with that of former. Here, it changes between 950 and 1000 ms. For DN700 pipeline, the gas concentration of the shortest present time of explosion pressure is 9.2%, while the gas concentration of the longest present time of explosion pressure is 7.5%. The difference in explosion pressure present time at different locations of two kinds of explosion experimental pipelines with concentration shows that there is a certain relationship between the propagation process of explosion pressure of low-concentration gas in pipelines, the diameter, and length of pipelines.

### 3.1.3 Relationship between explosion pressure and propagation distance

We have found a good bi-function relationship between the gas explosion pressure and the propagation distance, through the direct fitting of measured explosion pressure in DN500 and DN700 pipelines. The location of measuring points and the linear correlation coefficient is above 0.85 as shown in Figure 7.

From the fitting curves of the explosion pressure and propagation distance, shown in Figure 6, it can be seen that the explosion pressure gradually decreases from the ignition location. It reaches the minimum explosion pressure value after a certain propagation distance, followed by an inflection point. Furthermore, the explosion pressure begins to rise along with the increase of propagation distance of an explosion. The inflection point of explosion pressure in DN500 pipeline is about 24 m from the initial section of pipeline, while the inflection point of explosion pressure in DN700 pipeline is about 27 m away from the initial section of pipeline. At
the rising stage of explosion pressure, the explosion pressure of DN700 pipeline is much larger than that of DN500. From the fitting relationship between the explosion pressure and the propagation distance of pipeline, we can see that if the propagation distance increases, the explosion pressure of the pipeline will continue to increase, which consequently increases the explosion intensity. In order to design and arrange the anti-explosion measurements for low-concentration gas pipelines, the relationship between the explosion pressure and the propagation distance (pipeline length) can determine the optimum anti-explosion position and effective distance. Moreover, the installation of anti-explosion device in segments up to a certain distance can improve the anti-explosion effect and prevent the spread of gas explosion of the pipelines.

3.2 | Flame propagation law

3.2.1 | Variation of flame propagation velocity

The flame generated by the gas explosion passes through the flame sensor, which is set on the wall of the pipeline. This depends on the time difference between the flame reaching the two adjacent sensors and the distance between the two adjacent sensors. The average speed of flame propagation is obtained with the help of Formula (3) \[^6\]

\[
V = \frac{L}{T_2 - T_1}
\] (1)
where, \( V \)—flame propagation velocity, m/s; \( L \)—the distance between two adjacent flame sensors, m; \( T_1, T_2 \)—the time for the flame front to reach the first and second adjacent flame sensors, respectively.

The resulting flame propagation velocities of DN500 and DN700 pipelines are shown in Figure 7. It is observed that the flame propagation velocity, measured by the flame sensor near the ignition source is relatively small compared with that of other measuring points. Moreover, with the increase of distance from the ignition source, the flame propagation velocity measured by other flame sensors gradually increases and the flame propagation velocity near the outlet of the experimental pipeline is highest. This is due to the initial stage of gas explosion reaction. Initially, the gas/air mixture of pipeline forms a thin laminar combustion flame to spread outward, and the propagation speed is relatively small. However, when the explosion reaction proceeds, the heat released by the combustion reaction of gas, heats the mixture in the unburned area of the pipeline. This speeds up the flow of the unburned mixture, accelerates the volume expansion of the gas, and forms precursor shock waves. Under the action of the precursor shock wave, the unburned gas mixture of the pipeline forms turbulence. The generation of turbulence wrinkles the explosion flame, the burning area and the burning rate increases. This phenomenon changes the laminar flame into turbulent and increases the flame propagation speed. The high flame propagation will, in turn, promote more combustion reaction centers to form inside the combustion flame. This further enhances the turbulence and increases the velocity of shock wave propagation and flame propagation.\(^{37,38}\)

The positive feedback between turbulence degree and flame propagation velocity repeatedly occurs in the process of a gas explosion. So, the flame propagation velocity of a gas explosion increases with the increase of propagation distance. By comparing the gas explosion propagation velocity of DN700 and DN500 experimental pipelines, it is found that the flame propagation velocity of DN700 pipelines is greater than that of DN500 pipelines. The maximum flame propagation velocity can reach 1500 m/s which is obviously higher than that of DN500 pipelines (1050 m/s). In the middle and rear sections of pipeline, the high speed of flame propagation of gas explosion in DN700 pipeline is also greater than that of DN500 pipeline. This shows that different diameter and length of pipeline have a significant impact on the speed of flame propagation gas explosion. Therefore, in the process of low-concentration gas transmission, the size of pipeline should be fully considered.

### 3.2.2 | Change in flame arrival time

In order to intuitively analyze the flame propagation characteristics of gas explosion in pipeline, the flame arrival time at the ignition location is considered as 0. The flame arrival time at later measuring points is superimposed in the time difference. The measured flame arrival time for DN500 and DN700 pipelines are illustrated in Figure 8.

At the location of measuring point, near the explosion source, the curve of flame arrival time is steeper. This indicates the initiation point location of the first set of flame sensors, where the flame propagation time is relatively long, and the speed of flame propagation is relatively low. With the increase of propagation distance, the interval of flame arrival time of two adjacent flame sensors gradually decreases. Moreover, the flame arrival time curve becomes smooth which indicates that the flame propagation speed...
gradually increases and reaches the maximum speed of flame propagation, at the exit of pipeline. The variation law of flame arrival time of each measuring point in DN500 and DN700 pipelines is consistent with that of flame propagation velocity, as discussed in section 3.2.1. On considering the flame arrival time at each measuring point of the whole pipeline, the flame arrival time at the farthest measuring point of DN700 pipeline is about 450ms from the initiation point, which is much lower than that of 750ms of DN500 pipeline. Although DN700 pipeline is longer than DN500 pipeline, the gas explosion flame can be transmitted to the outlet of pipeline in a shorter time due to its faster propagation speed of explosion flame.

3.2.3  Relationship between flame arrival time and propagation distance

A logarithmic function relationship is found between the fitting of arrival time and propagation distance of explosion flame in DN500 and DN700 pipelines. The fitting degree is above 0.97 and these fitting lines are shown in Figure 9.

The explosion flame arrival time at each measuring point of DN500 and DN700 pipelines logarithmically increases with the increase of propagation distance and in the second half of the pipes. This fitting curve becomes smooth which indicates that the flame propagation time interval continuously
decreases. On the other hand, the flame propagation velocities increase. The relationship between the flame arrival time and propagation distance indicates that once an explosion accident occurs in a long-distance and low-concentration gas transmission pipeline, the propagation speed of gas explosion flame will continuously accelerate. Near the other end of pipeline, the explosive flame may react with the explosive shock wave and responsible for the critical state of detonation.  

According to explosion mechanics, once the detonation is generated, it can generate extremely high local pressure and causes severe damage. Therefore, in the design of a low-concentration gas pipeline, water mist and flame arrester should be installed or arranged at appropriate distances, to avoid the phenomenon of acceleration of explosion flame.

### 3.3 Comparison of low-concentration gas explosion characteristics in pipelines with different diameters

In order to further analyze the influence of pipe diameter on gas explosion characteristics, explosion experiments were carried out in DN500 and DN700 pipelines. In these pipelines, similar gas concentration (7.5%) and ignition energy (375 mJ) were employed. Finally, the maximum explosion pressure and flame propagation velocity were compared and analyzed.

In case of similar gas concentration and ignition energy, the maximum explosion pressure measured in DN700 pipeline is about 1.24 MPa, while that of DN500 pipeline is about 0.71 MPa, as shown in Figure 10. This indicates that once the gas explosion occurs in pipeline, the pipeline with larger diameter may produce greater explosive power and cause serious damage. In addition, the DN700 pipeline has a longer length, so, when the shock waves are generated by a gas explosion, they are transmitted to the second half of the pipeline (i.e., the location of the measuring point is 50-80 m). The explosion pressure sharply increases which is much larger than that of near the initiation source. It is found that with the increase in length of pipeline, the degree of turbulence increases by gas explosion process, which greatly improves the propagation speed of the explosion shock wave. Finally, a rapid increase in the peak explosion pressure is achieved.

It can be analyzed from Figure 11 that with the increase of pipe diameter, the arrival time of flame propagation at each measuring point in DN700 pipeline is earlier than that of DN500 pipeline. On the other hand, with the increase of propagation distance, a gentle variation trend is observed in the flame arrival time of DN700 pipeline. Furthermore, this trend is more obvious in DN700 pipeline than that of DN500 pipeline which indicates that the flame of gas explosion in DN700 pipeline is faster.

### 4 CONCLUSIONS

In order to study the propagation characteristics of low-concentration gas explosion in pipeline, two different sizes of experimental pipelines such as DN500 and DN700 were employed to analyze and study the gas explosion pressure and flame propagation law, under different conditions. The following conclusions were drawn:

1. With the increase of propagation distance, initially, the explosion pressure of pipeline decreases and then increases. A maximum explosion pressure is observed near the outlet of a pipeline. The maximum explosion

![FIGURE 10](image1)  Maximum explosion pressure in pipelines with different diameters

![FIGURE 11](image2)  Flame arrival time in pipelines with different diameters
pressure at explosion source appears later than that of other measuring points. This is due to reflection and oscillation of gas explosion shock waves in pipeline. There is a good quadratic function relationship between the maximum explosion pressure and the propagation distance of the pipeline. The maximum explosion pressure gradually decreases from the source point, and the inflection point appears after a certain distance, the explosion pressure begins to rise with a higher rate.

2. The gas explosion flame of the pipeline propagates backward from the source of the explosion. The speed of flame propagation continuously increases due to its turbulence nature and reaches to the maximum at the outlet of pipeline. There is a good logarithmic function relationship between flame arrival time and propagation distance at each measuring point of the pipeline.

3. The diameter of pipeline has obvious influence on the propagation process of a gas explosion. A maximum explosion pressure and high rate of explosion pressure are observed in DN700 experimental pipeline, which are much larger than that of DN500 pipeline. The reason behind this is a larger diameter of pipeline. The flame propagation velocity of DN700 pipeline is also significantly higher than that of DN500 pipeline. Therefore, the diameter of pipeline should be sufficiently taken into consideration during the design of a low-concentration gas pipeline.

Our experimental conclusions can provide a theoretical and reference basis for the determination of installing distance of various explosion-proof, and explosion-suppressing equipment in the process of low-concentration gas transmission. Finally, this work can provide the safety of low-concentration gas, in the process of transmission.

ACKNOWLEDGEMENTS
This work was financially supported by the National Science and Technology Major Project of China (2016ZX05045006), the State Key Laboratory Cultivation Base for Gas Geology and Gas Control (Henan Polytechnic University) (WS2019B02), Natural Science Foundation of Chongqing, China (cstc2019jcyj-bsh0041), the Postdoctoral Science Foundation Project Funded by State Key Laboratory of Coal Mine Disaster Dynamics and Control (2011DA105287-BH201903).

CONFLICT OF INTEREST
The authors declared that they have no conflicts of interest to this work.

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How to cite this article: Li L, Zhang Z, Liu P, Wang K, Zhang J, Li X. Experimental study of low-concentration gas explosion in large-scale pipeline. *Energy Sci Eng*. 2020;8:2129–2140. [https://doi.org/10.1002/ese3.652](https://doi.org/10.1002/ese3.652)