PROPAGATION LAW OF FLAME IN A PIPELINE PRODUCED IN GAS EXPLOSION
Numerical Analysis and Experimental Verification

by

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Serious accidents of gas explosion always result in massive casualties, however the propagation law of flame during gas explosion is not clear yet, though it is important for prevention and control of such accidents. This paper designs a piping gas explosion system for numerical revealing the propagation law, which is then verified experimentally.

Key words: *gas explosion, piping test system, gas concentration, flame front*

Introduction

It is a known fact that 95% of China's coals have been exploited by the underground mining technology under complex geological conditions and poor working environment with possibly serious disasters of gas explosion, which is difficult to be predicted and controlled. With the increase of mining depth, serious risk might rocket remarkably [1-17]. To guarantee the safety of the underground mining, it is the very time to investigate the flame's propagation in the gas explosion process, so that we can prevent and control the flame to reduce the explosion hazard. In this paper we will reveal the propagation law of flame in a pipeline numerically and experimentally.

Propagation law of flame in a pipeline

It is extremely important to have an explicit propagation law of flame in a pipeline to reveal the main factors affecting the flame propagation in the pipeline. Based on the previous experimental observation, the flame propagation is greatly affected by pipeline corner angles. In order to simulation the flame propagation characteristics in pipeline, the paper adopted the pipeline model with three pipeline corner angles: 45°, 90°, and 135°. The pipeline model is shown in fig. 1, where the flame sensors are installed to measure the flame speed and temperature. The pipeline is made of a square steel plate with a cross of 80 mm × 80 mm. The

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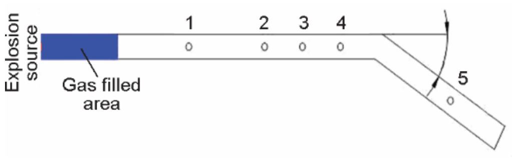

Figure 1. The studied pipeline with six flame sensors, the gas filled area is colored

length of gas filled pipeline is chosen as 4 m, 5 m, and 6 m, respectively, the straight line of the pipeline is set to 10 meters, and the bend pipe length is 1 m, the total length is 11 m for all experiments.

Determination of parameters of pipeline model

- The wall thickness is 10 mm, and the design pressure of the device reaches 20 MPa. The time of gas explosion propagation is very short and the speed of flame propagation is very fast, therefore, the heat loss at the wall surface can be ignored and the wall surface is set as an heat insulating wall. The right end of the pipeline is open and the left end is closed. The right end is set as a pressure outlet. The ignition source is semicircular with a radius of 5 mm.
- The gas in the pipeline is uniformly mixed, and the reaction is in a normal temperature and pressure environment, and the gas is in a static state.
- The process of gas explosion is a one-step irreversible reaction.
- Without considering the coupling effect between the space wall and the gas-flow, the closed space boundary is set as a rigid wall.

Numerical approach to flame propagation in the pipeline system

The cloud figure of flame propagation process at the corner of the pipeline can be obtained through calculation. The temperature distribution in pipeline is shown in figs. 2(a) and 2(b) is the cloud figure of flame propagation process on condition that the pipeline is filled with 4 m gas and its turning angle is 45°. Figures 2(c) and 2(d) are the cloud figure of flame propagation process on condition that the pipeline is filled with 5 m gas and its turning angle is 90°. Figures 2(e) and 2(f) are the cloud figure of flame propagation process on condition that the pipeline is filled with 6 m gas and its turning angle is 135°.

By analyzing calculation data in fig. 2, it could be known that, when the gas is ignited for 5 ms, a tiny semicircular flame surface is formed, its maximum temperature is 1900 K. The unburned gas expands when heated under the influence of reflection of pipeline wall surface. After the gas is ignited, the axial length of the flame becomes longer and longer, forming an obvious cone shape. The flame surface affected by turbulence starts to deform after this moment. At the same time, the flame surface starts to increase, which greatly increases the gas combustion rate nearby area, so the flame speed near the wall surface is greater than that in the center of the pipeline. When the gas is ignited for 850 ms, the flame spread forward in a column shape, its maximum temperature is 2240 K, this shows that the gas combustion speed is accelerated. When the gas is ignited for 980 ms, the gas combustion became quite intense, the flame has obvious folds, its maximum temperature is 2400 K. From this time on, the chemical reaction of the mixed gas proceeds rapidly, and the gas combustion enters the accelerated propagation stage. When the flame passes through the corner of the pipe, the flame speed increases rapidly, the main reason is that shock wave diffusely reflects at the corner of the pipeline and generates oblique shock wave, which makes unburned gas produces severe turbulence, causing serious fold deformation of flame front. The gas combustion rate increases.

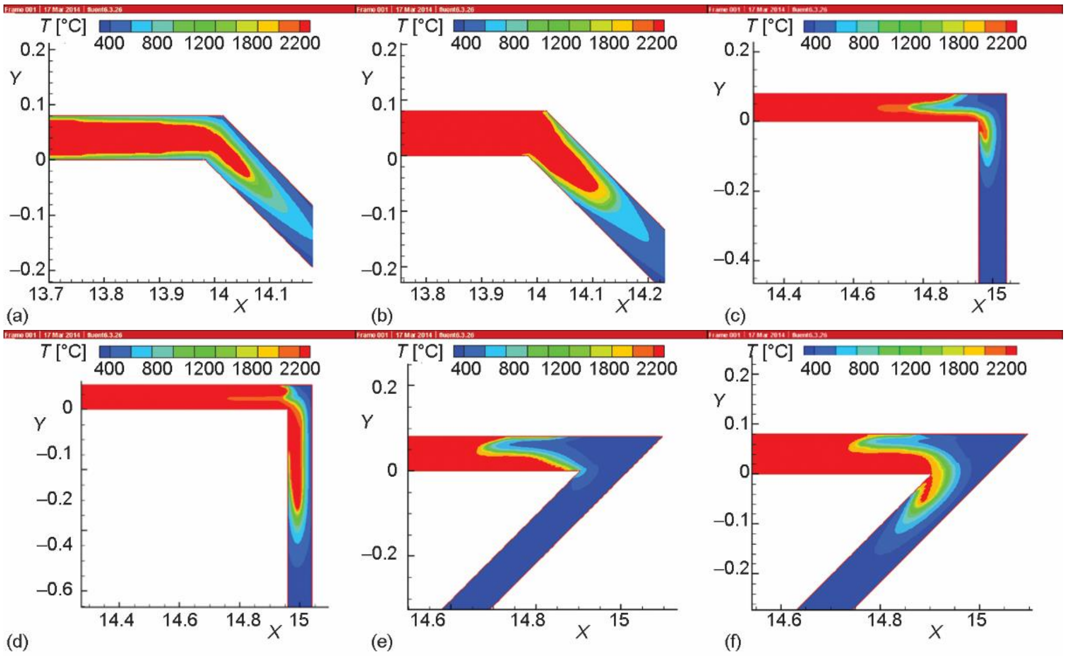

Figure 2. Cloud figures of flame propagation process on condition of pipeline turning angles is different

Computational data analysis

The flame speed catastrophe coefficient is defined before processing the data, which is used to describe the propagation characteristics of the flame. The coefficient of mutation is defined as the ratio of the flame velocity of the measuring point 5 to that of the measuring point 3, which reflects the change of the speed at the corner when the flame propagates forward in the pipeline, expressions are:

$$\lambda = \frac{v_5}{v_3} \tag{1}$$

where v_5 is the flame speed at the measuring point 5 and v_3 – the flame speed at the measuring point 3.

When the gas is ignited in the filling area, the speed of the flame reaching each measuring point in the system shown in fig. 1 is recorded. Figure 3 shows that under the same corner angle of 45° condition, the velocity of the gas explosion flame propagating to each measuring point. Figure 4 shows that under the same gas filling condition (the length of gas filling in the pipeline is 5 m), the velocity of the gas explosion flame propagating to each measuring point.

Figures 3 and 4 show that under the condition of the same filling length, the larger the angle of the pipeline corner, the higher the flame propagation speed in the pipeline. The flame propagation speed changes abruptly at the corner of the pipeline. Under the angle of the pipeline corner condition, the gas filling length of the pipeline is longer, the flame wave propagation speed is higher. When the gas filling length increases, the gas combustion speed in the pipeline increases slightly.

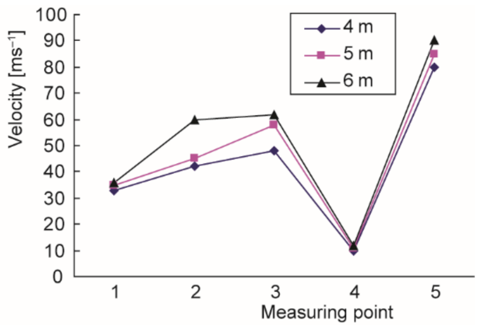

Figure 3. The flame wave velocity of each measuring point under the same corner angle of 45° condition

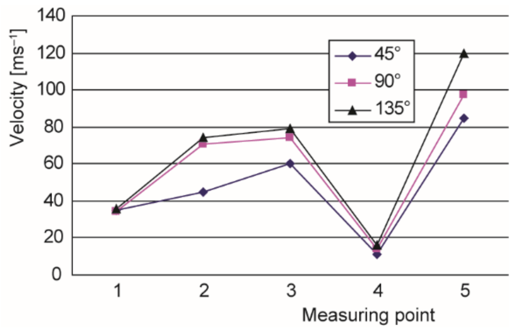

Figure 4. The flame wave velocity of each measuring point under the same gas filling length of 5 m condition

By analyzing the flame propagation velocity data, the main factor of the flame speed catastrophe coefficient is the turning angle of the pipeline, and the gas filling length has little influence on the mutation coefficient. The flame propagation speed increases slightly when the gas filling length increases, so the influence of the gas filling length on the catastrophe coefficient of flame propagation speed can be ignored. The catastrophe coefficient of flame propagation speed at the pipeline corner changes with the pipeline bend angle, the larger the pipeline bend angle, the greater the catastrophe coefficient of flame propagation speed, showing a power function relationship. When the bend angle of the pipeline changes at 30° to 150°, the catastrophe coefficient of flame propagation speed is between 1.3-1.7, and the change relation is:

$$y = 1.342x^{0.1431} \tag{2}$$

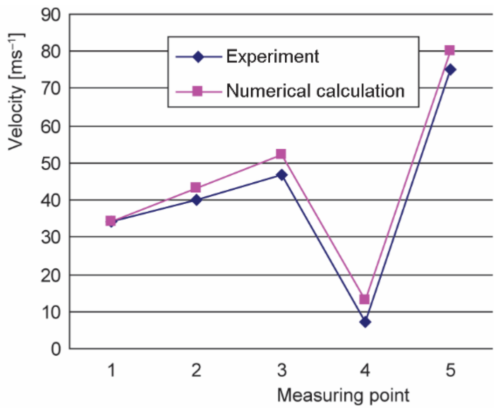

Figure 5. Flame propagation velocity in the pipeline filled with 4 m gas comparison analysis between experiment and calculation

where y is the catastrophe coefficient of flame propagation velocity and x – the turning angle of the pipeline.

Comparative analysis of numerical calculation results and experimental results

Comparative analysis the numerical calculation results with the experimental results, the flame propagation velocity in the 45° bend angle pipeline filled with 4 m, 5 m, and 6 m of gas is shown in figs. 5-7. The influence of the gas filling length on the flame propagation velocity in the pipeline and the influence of the pipe turning angle on the flame propagation velocity in the pipeline are consistent between the experimental conclusion and the numerical result. The velocity of flame reaching each measuring point is within the error range, which shows that the numerical simulation results are consistent with the experimental

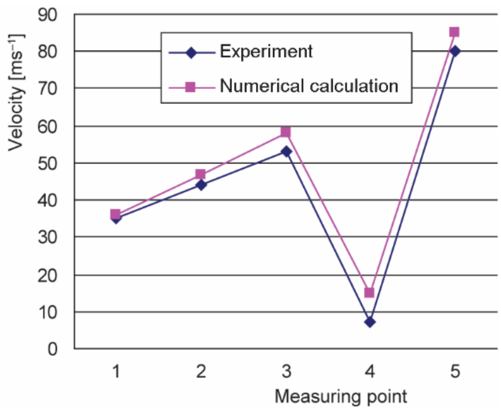

Figure 6. Flame propagation velocity in the pipeline filled with 5 m gas comparison analysis between experiment and calculation

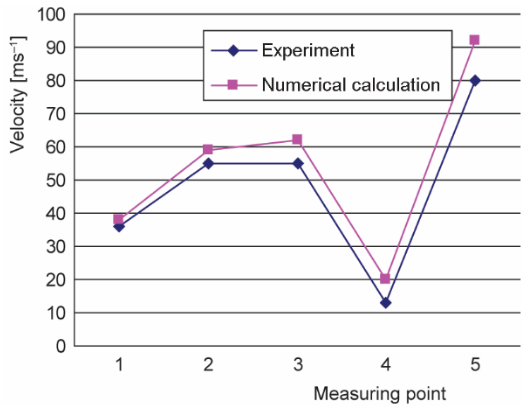

Figure 7. Flame propagation velocity in the pipeline filled with 6 m gas comparison analysis between experiment and calculation

results and confirm the reliability of the numerical calculation results. This shows that eq. (2) for calculating flame catastrophe coefficient and pipe turning angle is reliable.

Conclusions

Through numerical simulation research, the flame propagation characteristics at the corner of the pipeline are studied, and the conclusions are as follows.

- Under the same filling length in the pipeline condition, the bending angle of the pipeline has a significant influence on the flame propagation velocity. The greater the pipe bend angle is, the faster the flame propagation travels. The flame propagation speed changes abruptly through the turning point.
- When the bend angle of the pipeline is fixed, the flame propagation speed in the pipeline with different gas filling lengths is different, and the greater the gas filling length is, the higher the flame wave propagation speed is.
- The main factor of the flame speed catastrophe coefficient is the turning angle of the pipeline, and the gas filling length has little influence on the mutation coefficient. The flame propagation speed increases slightly when the gas filling length increases, so the influence of the gas filling length on the catastrophe coefficient of flame propagation speed can be ignored.

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