Perspectives in Science (2016) 7, 277—281

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Characteristics of flame velocity of gas explosion with obstruction in pipeline☆

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Received 26 October 2015; accepted 20 November 2015
Available online 12 December 2015

KEYWORDS
Propagation velocity;
Gas explosion;
Image processing method;
Correlation coefficient

Summary The velocity of flame propagation caused by gas explosion is very difficult to be measured in experiment. A new image processing method is applied to calculate the velocity based on correlation coefficients of images. Experiment of gas explosion with 9.5% gas is carried out. The images photographed during the experiment are processed by the new method. And the change law of velocity of flame propagation is calculated. The results show that the velocity and structure of the flame are both unstable when it propagates in the pipeline. The propagation of flame is not away in acceleration state, but acceleration and deceleration are mutual alternation. And the velocity is in shock statement till the flame extinct during the whole flame propagation. The results also show that the metal wire mesh in the pipeline can accelerate the velocity of flame propagation but reduce the damage caused by gas explosion. And this method also covers the shortage of experimental method.

Introduction

Gas explosion is one of the severest disasters which can cause property damage and casualties in coal mine. In China, 21 fatal accidents of gas explosion and coal dust and gas explosion happened which cause over one hundred deaths since 1949. In recent years, as the development of research on gas explosion and standardization of production management, gas explosion seldom occurs. But it occurs

☆ This article is part of a special issue entitled ''Proceedings ofthe 1st Czech-China Scientific Conference 2015''.

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http://dx.doi.org/10.1016/j.pisc.2015.12.003

occasionally in high gas coal mines. The research on flame propagation velocity and temperature field of gas explosion can help to design the device for reducing the damage caused by gas explosion.

The gas explosion process in a container was studied and results show that the ignition location and the gas concentration have a great effect on the explosion intensity (Phylaktou and Andrews, 1993). The gas explosion propagation when placing obstacles in tubes was researched and the results show that flame propagation through the vessels, up until flame front venting, is found to be substantially laminar, with significant overpressure only being generated in the later stages of explosions(Salzanoa et al., 2002; Fairweather et al., 1999). Experimental trials in three different pipes (single bend, *U*-shaped and *Z*-shaped) were performed and the results show that the explosion strength was significantly enhanced because of the turbulence induced by increasing the number of turns (Chuanjie Zhu et al., 2010, 2011). Nie Baisheng researched the explosion flame propagation characteristics in empty pipe and in the presence of Al_2O_3 and SiC foam ceramics were experimentally investigated. The two-dimensional temperature distribution field of premixed gas explosion flame based on the radiation thermometry was calculated and flame propagation velocity was researched through experiment (Nie et al., 2011). Nie Baisheng simulates and theory analyzes the overpressure transmission rule when gas explosion takes place in different type of roadways and explosion flame propagation characteristics in empty pipe and in the presence of Al_2O_3 and SiC foam ceramics were experimentally investigated and the results show that Al_2O_3 and SiC foam can hinder the propagation of the flame caused by gas explosion (Nie et al., 2014; Yan et al., 2011).

Currently, photoelectric conversion method and particle image velocimetry (PIV) are used to measure velocities of dynamic flames with images photographed by high speed camera (Hirasawa et al., 2002; Stella et al., 2001; Dong et al., 2002). Zhou Huai-chun et al. developed a calculation method of monochrome image temperature field based on the reference point by means of radiation law and attained temperature field by comparing monochrome images with radiation strength of one reference point in images (Zhou et al., 1996). Researchers use image processing method to reveal the propagation rules of methane explosion. However, current measurements and computational method (Wang, 2001, 2006; Na'inna et al., 2013) merely focus on velocity of flame front other than areas after flame front.

The experiment of gas explosion in pipeline with obstruction

The experimental system

Schematic diagram of experimental system is as shown in Fig. 1. The experimental system includes pipeline system, pre mixed gas system, ignition system, synchronous control system, high speed photography system, data acquisition system and so on. The section shape of pipeline is square and size is 80 mm × 80 mm. The pipeline consist two shout pipelines which are connected by flange. And metal wire mesh is installed in the flange which separate two short pipelines. The two side faces are transparent organic glass with high strength. Safety valve is installed in the up side to guarantee the safety of the experiment.

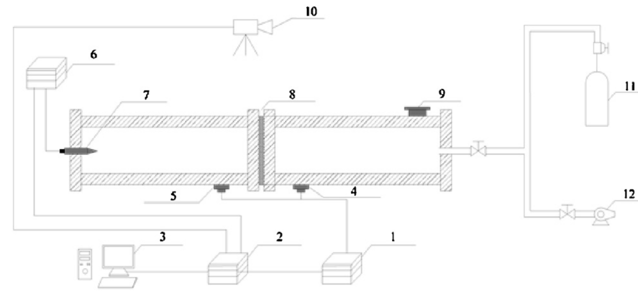

Figure 1 Schematic diagram of experimental system. 1 — High speed data acquisition instrument, 2 — PLC synchronous controller, 3 — computer system, 4 — 2# air pressure sensor, 5 — 1# air pressure sensor, 6 — high energy ignition device, 7 — ignition electrode, 8 — metal wire mesh, 9 — pressure relief, 10 — high speed camera valve, 11 — pre mixing tank, 12 — vacuum pump.

The volume fraction of the pre mixed air is 9.5% methane and 90.5% air. The ignition energy is 5 J. And the initial temperature and pressure are 300 K and 1.013 × 105 Pa separately.

Experimental procedure and method

(1) Injecting air into the pipeline to check the air tightness of the experimental system. The next step can be carried out till the air tightness is good.
(2) Evacuating the pipeline till the vacuum degree is 0KPa. And then premixed air with 9.5% methane is injected into the pipeline.
(3) Open all the data acquisition software and control system. Triggering ignition electrode after all the works are ready.

Experimental results and analysis

The frame rate is 2000 and some images of flame propagation shot by high speed camera are as shown in Fig. 2.

It can be seen from Fig. 2 that the velocity and structure of the flame are both unstable when it propagate in the pipeline. The propagation of the flame is affected by shock waves greatly. So the law of propagation of flame is similar with that of propagation of shock wave. The velocity accelerates firstly and then decay when it arrive the metal wire mesh. When the flame arrives another side of the pipeline, the flame front propagates reversely due to it is reflected by another side of pipeline.

It also can be seen from Fig. 2 that the color of the flame varies greatly in different time. In the beginning, the flame is blue and the shape of flame is cone with a fairly smooth front. This is because the propagation velocities on edges are obviously smaller than those in the middle as a result of friction of pipe wall and cohesion of gas. The temperature of flame which passes the metal wire mesh is lower than the temperature of flame before the metal wire mesh.

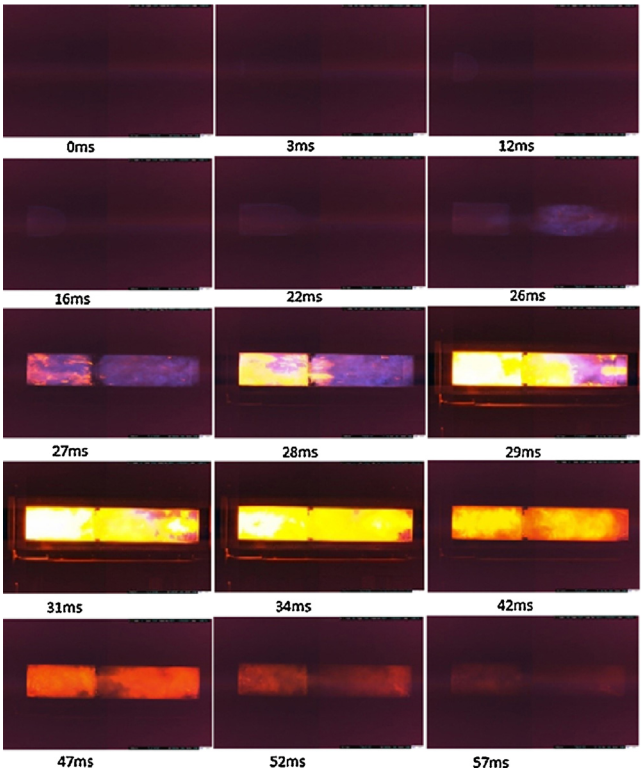

Figure 2 The images photographed by high speed camera during gas explosion.

Computational principle for flame propagation velocity

Digital image consists of *M***N* or *N***M* sample points. A matrix is formed by these sample points. The coordinate valve of origin is (0,0) and the matrix is as shown in formula (1). Every element in matrix correspond a pixel in the image.

$$f(x,y)=\begin{bmatrix} f(0,0) & f(0,1) & \ldots & f(0,N-1) \\ f(1,0) & f(1,1) & \ldots & f(1,N-1) \\ \ldots & \ldots & \ldots & \ldots \\ f(N-1,0) & f(N-1,1) & \ldots & f(N-1,N-1) \end{bmatrix} \tag{1}$$

Corresponding represents the close degree of two variables. Assuming that the pixel and gray valve of the image is limited, the correlation coefficient can be defined as formula (2) (Gao and Xia, 2007)

$$r=\frac{\sigma_{fg}}{\sigma_f\sigma_g} \tag{2}$$

where, r is correlation coefficient of two images, is covariance of two matrix,, are the mean variance of two matrix separately. And these values can be calculated as following.

$$\sigma_{fg}=\frac{1}{N_xN_y}\sum_{X=0}^{N_x-1}\sum_{y=0}^{N_y-1}f(x,y)g(x,y)-\mu_f\mu_g \tag{3}$$

$$\sigma_f=\left[\frac{1}{N_xN_y}\sum_{X=0}^{N_x-1}\sum_{y=0}^{N_y-1}\{f(x,y)\}^2-{\mu_f}^2\right]^{1/2} \tag{4}$$

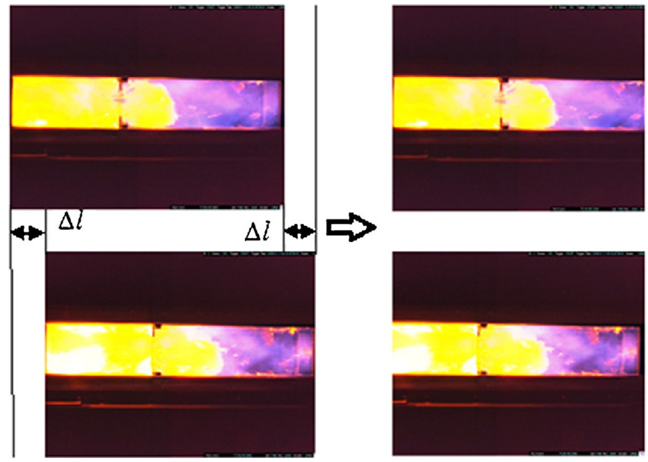

Figure 3 The relationship between pixel size and actual size.

$$\sigma_g=\left[\frac{1}{N_xN_y}\sum_{X=0}^{N_x-1}\sum_{y=0}^{N_y-1}\{g(x,y)\}^2-{\mu_g}^2\right]^{1/2} \tag{5}$$

$$\mu_f=\frac{1}{N_x*N_y}\sum_{X=0}^{N_x-1}\sum_{y=0}^{N_y-1}f(x,y) \tag{6}$$

$$\mu_g=\frac{1}{N_xN_y}\sum_{X=0}^{N_x-1}\sum_{y=0}^{N_y-1}g(x,y) \tag{7}$$

The adjacent images were cut from right side to left side and the correlation coefficients were calculated. The cutting length is the propagation distance of flame when the correlation coefficient is the largest. The cutting images are shown in Fig. 3. These two images are adjacent images. Under the condition that the shooting speed is so quick, assuming that the flame propagates after the first image is shot and the second image is shot. The image obtained by cutting the length that the flame propagates in this time of first image has high similarity with the image obtained by cutting the same length of second image.

The first image was cut from left side to right side and the second image was cut from right side to left side according to unit length. Column number of unit pixel is recorded as $1, 2, \ldots, N_i$, $[N_{x/2}]$. The correlation coefficients of two images were recorded as $\sigma_1, \sigma_2, \ldots, \sigma_i, \ldots, \sigma N_{x/2}$ every time the images were cut by unit pixel. If Nα number column was cut and the correlation coefficients of two images reach maximum value.

$$\sigma_{N_\alpha}=\max\{\sigma_i\},\quad i=0,1,\ldots,\left[N_{x/2}\right] \tag{8}$$

where, N_α is pixel distance of flame propagation. In the experiment, the flame propagates to the right side and it also can propagate to the left side. So N_α may be positive value and negative value. In this paper, the distance to the right is positive value and distance to the left is negative value.

The length of pipeline l_1 in the image can be measured by ruler and the actual length of pipeline l_2 is 1m. Setting $k=l_2/l_1$. And pixel distance of flame propagation N_α can be confirmed by calculating the correlation coefficient of two adjacent images. So the actual distance of flame propagation $\Delta l=N_\alpha{}^*k$. Because frame rate is 2000, the time interval

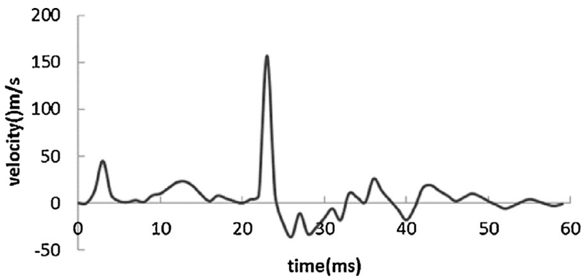

Figure 4 Propagation velocity of explosion flame with 9.5% methane concentration.

between two images is 0.005s. The actual velocity of flame propagation $v = \Delta l/\Delta t = N_\alpha * k/\Delta t$.

The velocity of flame propagation with 9.5% methane concentration at every moment was calculated through above method. As shown in Fig. 4.

It can be seen from Fig. 3 that, in the beginning, the flame spreads to the right and velocity reached 45 m/s quickly. And then, the velocity reduces to 3 m/s 3 min later. The velocity various at different moment and flame show phenomenon of turbulence. When time comes to 22 s, the flame arrives at the metal wire mesh. The velocity of flame passing through the mesh rises to 157 m/s rapidly. And five minutes later, the flame arrives at the right end face. After the flame arrives at the right end face, the flame propagates to the left because the flame is reflected by the right end face. The interaction between flames from two directions accelerates the dramatic change of propagation velocity. The velocity of flame propagation decays to 0 after shocking several times.

The velocity of flame propagate is accelerated by the metal wire mesh. But the energy of the flame is weakened by the mesh which can be seen from Fig. 2. The metal wire mesh can be used to reduce the damage caused by gas explosion.

Discussions

(1) The flame velocities computed are average values. If the value is '0', it does not mean that the instantaneous velocity of flame is null and the flame is stationary. It just denotes that the average value of flame velocity is '0' and the flame might be still transforming dynamically.
(2) In this new method for calculating the flame velocity, the accuracy of cutting length of the image is very important to calculate the velocity of flame propagation. And the cutting length of the image is determined by the calculation of maximum value of correlation coefficients. The calculation workload is very hard and a calculation program will be written in the future.
(3) Applicable conditions for the method are that the photographing rate of a high-speed camera should observe Nyquist Sampling Theorem, which means that the photographing rate must be high enough to exceed twice of the maximum flame velocity.
(4) In this method, the shape and bright of the flame in two adjacent images need to be same or similar. Under this condition, the two images obtained by cutting two adjacent images will have high correlation coefficients.

Conclusion

(1) The image processing method is effective in calculating the velocity of flame propagation. The change law of flame velocity with time is obtained through this method.
(2) The velocity and structure of the flame are both unstable when it propagates in the pipeline. The propagation of the flame is affected by shock waves greatly. The propagation of flame is not away in acceleration state, but acceleration and deceleration are mutual alternation.
(3) The metal wire mesh in the pipeline can accelerate the velocity of the flame, but the energy of the flame is weakened by the mesh. The metal wire mesh can be used to reduce the damage caused by gas explosion.

Conflict of interest

The authors declare that there is no conflict of interest.

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