Computation method of the propagation velocity of methane explosion flame based on image correlation coefficient

Bai-sheng Nie[1, 2, 3], Xue-qiu He[1,2], Chen Zhang[1,2]
1. State Key Lab of Coal Resources and Safe Mining(China University of Mining & Technology), Beijing 10083, China
2. School of Resource and Safety Engineering, China University of Mining & Technology(Beijing), China, 100083
3. State Key of Laboratory of Explosion Science and Technology(Beijing Institute of Technology), Beijing, 100083, China
Beijing, China

1 Introduction

Methane explosion is one of the severest disasters happening in coal mines. In China, there were 25 fatal accidents that is over one hundred deaths after the founding of the People's Republic of China, of which were 21 methane (or methane-coal dust) explosion accidents. Therefore, it is important to understand the mechanism of methane explosion and especially the propagation rules of methane explosion flame. Currently, photoelectric conversion method and Particle Image Velocimetry (PIV) are used to measure dynamic flame propagation velocity with images photographed by high speed camera. However, photoelectric conversion method cannot measure the average propagation velocity inside the flame, and PIV measurement cannot be used to solve previous gas explosion experiments. Recently, image processing method were used use to reveal the propagation law of methane explosion flame by many researchers [5-9]. But current measurements and computations merely concentrate on the propagation speed of flame front and the velocity of the total process of gas explosion was not available. In this paper the image correlation coefficient method will be used to compute and analyze the dynamic change characteristics of flame during the process of methane explosion.

2 High-speed Photographing Experiment of Methane Explosion Flame in Pipe

The schematic of the methane explosion experiment system is demonstrated in literature [10]. The system consists of: explosion pipe, gas distribution system, ignition system, data acquisition and analysis system, explosion pressure measurement system, and high-speed photographing system. The distribution of flame sensors is shown in Fig.1, which is used to measure the average propagation velocity of flame front between two adjacent sensors. The experimental pipe is the 20m long with an 80mm*80mm intersection and 10mm thick skin. Both ends of the pipe are closed and there is no obstacle in the pipe. The spark frequency of ignition device is 6~ 12/s and one single storage is 70J.

Observation windows are placed 2m away from the ignition device and its size is 190×70mm^2. Through the window, a MEMRECAMci-3 high-speed camera used in the experiment was manufactured by NAC Ltd, Japan. The resolution of the photos is 252×186 pixel.

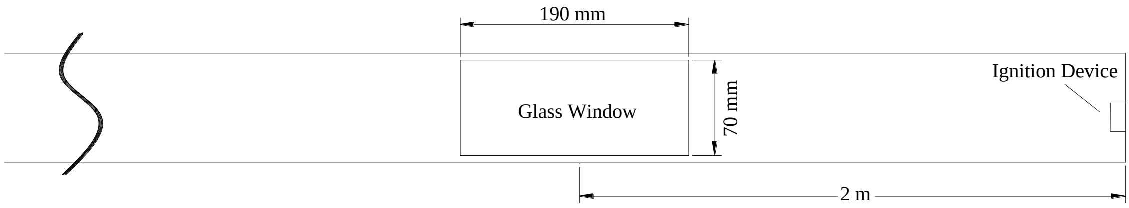


Fig. 1 Distribution of measuring positions

3 Computing Principle of Flame Propagation Velocity Based on Image Correlation Coefficient

3.1 Hypothesizes of Mathematical Model

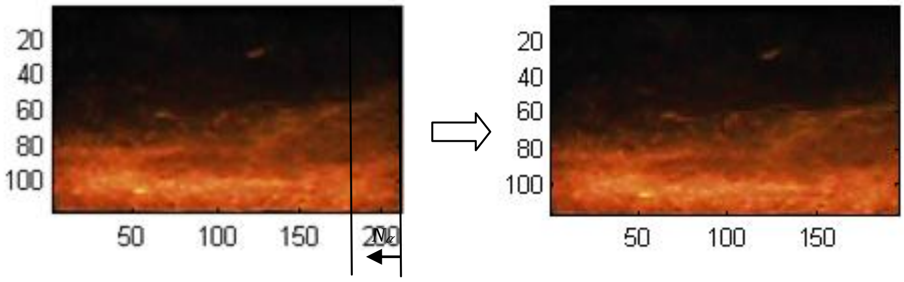
To build the mathematical model of flame propagation velocity calculation based on image correlation coefficient and calculate the average propagation velocity of the flame passed the window, it is need to add hypothesizes to the actual process of flame propagation and simplify the problem. The brightness and shape of flame are continually changing during the process of gas explosion flame propagation, which may affect the accuracy of flame propagation velocity. However, photographing speed of high speed camera is so high that the change of flame brightness and shape between two neighboring images is small. So it is assumed that flame is invariant when flame propagates from one position to another position. Otherwise, photographing speed, based on the Nyquist sampling theorem[11], is so high that flame cannot move to surpass the window completely in the photographing interval if photographing speed is greater than or equal to twice of the maximum flame propagation velocity.

3.2 Computation principle for the propagation speed of explosion flame

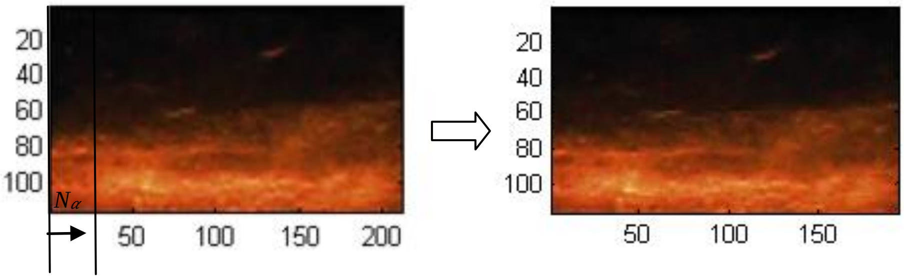
If the photographing is fast enough, the first flame image moves forward through the distance ΔL, at which time the second flame image is photographed. Shown in Fig.2, the propagation direction of flame is from the left side to the right side. If the first image is trimmed on the right side with the moving distance of flame and the second one is trimmed on the left side with the same distance. By comparison, both the trimmed images should be maximal approximation. Therefore, to compute, the first image is trimmed one by one pixel along the propagation direction from the right side, written as $1, 2, \cdots, N_i, \cdots, [N_x / 2]$ (N_x is the length of image, pixel. $[N_x / 2]$ represents the integral part of $N_x / 2$). At the same time, the second image is trimmed from the left side. When each pixel is trimmed, the correlation coefficient of both trimmed images is calculated that is written as $\sigma 1, \sigma 2, \cdots, \sigma i, \cdots, \sigma_{[Nx/2]}$. The trimmed pixels corresponding to maximum correlation coefficient $\sigma_{N\alpha}$ is exactly the moving pixel distance N_α, shown as Equation (1):

$$\sigma_{N\alpha} = \max_i \{\sigma_i\}, \; i = 0, 1, \cdots, [N_x / 2] \quad (1)$$

This method can be utilized to calculate the flame speed no matter whether the entire window is full of flame or not. From the results of images the propagation direction of flame may be forward or reverse. Therefore, the direction of flame propagating from the right to left side is stipulated as the positive direction because the ignition device is on the right side of the pipe. So N_α may be positive or negative.



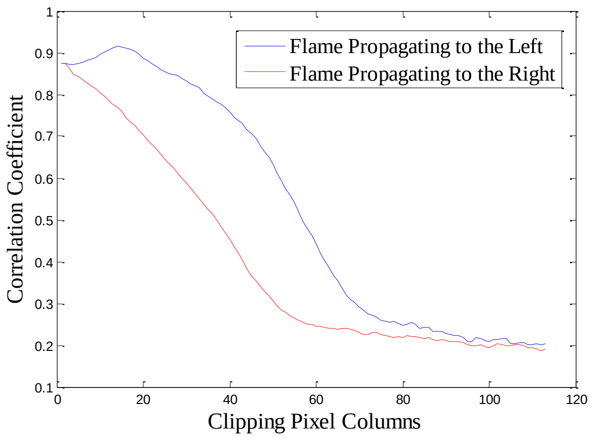
(a) The first image



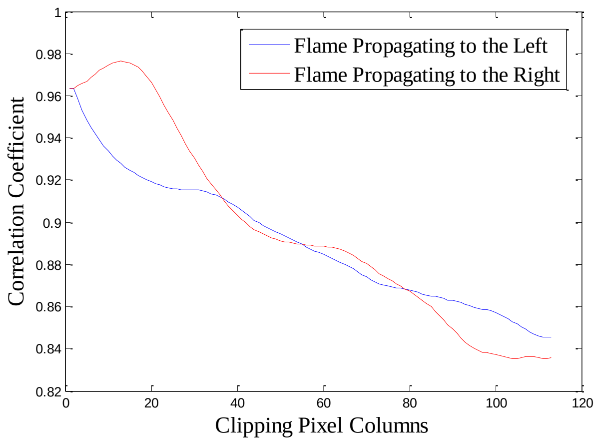
(b) The second image

Fig.2 Schematic of two adjacent flame propagation images

The correlation coefficient results of the two adjacent images are shown in Fig.3. Because flame propagation direction cannot be determined in advance, the correlation coefficients should be calculated by both positive and negative direction. From Fig. 3(a), flame moves from the right side to the left. The maximal correlation coefficient $\sigma_{N\alpha} = 0.9225$ when N_α=17. From Fig. 3(b) flame moves from the left side to the right and the maximal correlation coefficient $\sigma_{N\alpha} = 0.9781$ when N_α =14.



(a)



(b)

Fig.3 Correlation coefficient computing results of the two adjacent images in the process of clipping

3.3 Corresponding Relationship between Pixel Size and Actual Size

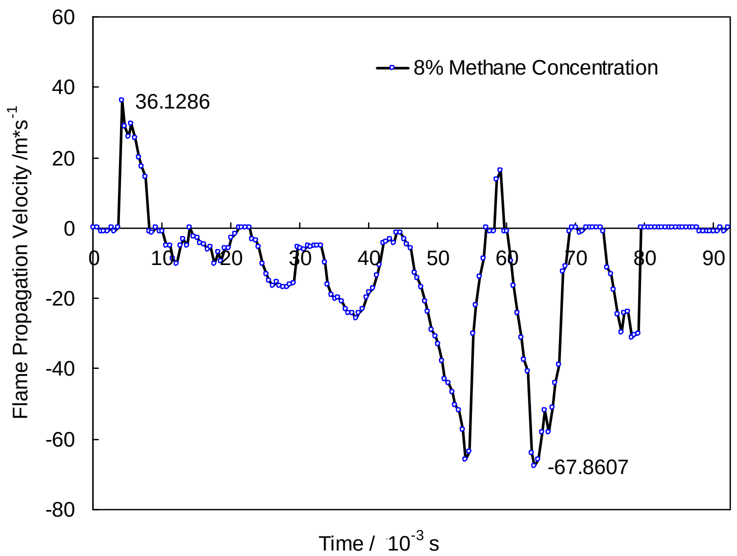
With the flame moving pixel distance N_α between the two neighboring images, the actual distance of flame propagation ΔL can be calculated with the proportionality factor k of and ΔL, written as $\Delta L = N_\alpha \times k$. Then flame propagation velocity v can be computed with Equation (2):

$$v = \Delta L / \Delta t = N_\alpha \times k / \Delta t \quad (2)$$

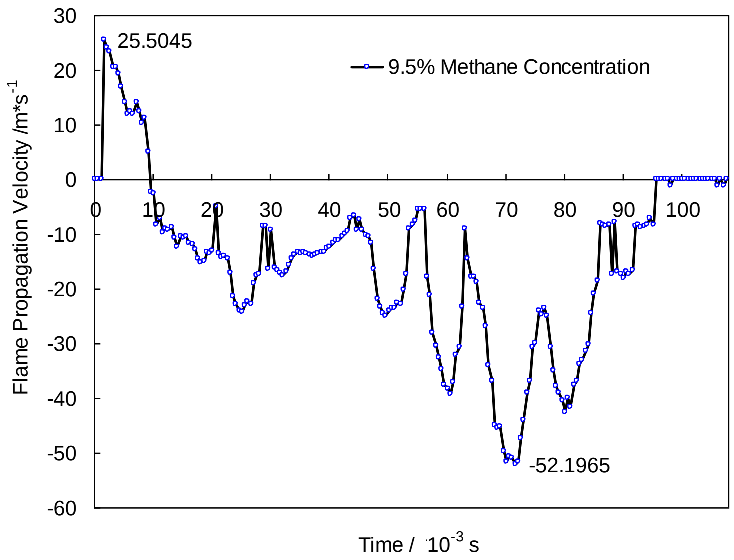
Where, Δt is the photographing interval time between the neighboring images.
For example, the proportion factor $k = 0.8444$ at methane concentration 9.5% and $\Delta t = 0.5ms$. So the flame propagation velocity at Fig. 3(a) is 28.7096*m/s*, and velocity at Fig. 3(b) is 23.6432m/s.

4 Propagation Law of Flame on the Window

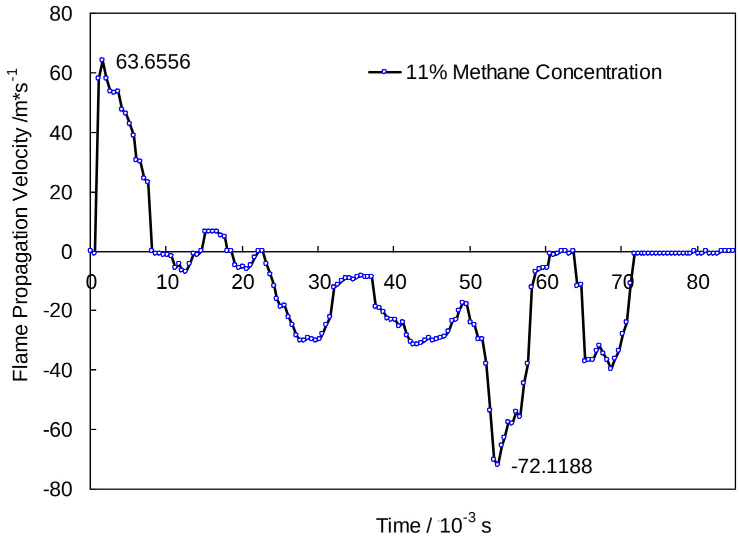
From Fig.4 (a) (b) (c) the propagation speed of methane explosion flame was obtained according to the above method at methane concentration 8vol%, 9.5vol% and 11vol% respectively. It can be known that the propagation speed varies with the time. At first, the flame accelerates rapidly to the maximum value (36.13 m/s, 25.50 m/s and 63.66 m/s respectively), and then gradually decelerates to zero and oscillates. In addition, the flame accelerates and decelerates for many times. The maximal reverse speed is 67.86 m/s, 52.36 m/s and 72.12 m/s respectively, which is larger than the maximal forward propagation speed, indicating that the energy induced from reverse propagation of the explosion flame after encountering the end of the pipe is also very high.
The flame undergoes an unstable propagation process characterized by acceleration, deceleration, reverse acceleration and deceleration. The occurrence of that phenomenon has two aspects of reasons. Firstly, both ends of the pipe are closed and the shock wave reflects when it hits the end of the pipe, so the flame oscillates and propagates reversely is driven with the reflected shock wave. Secondly, in the process of flame propagation, the flame front passes forward and the unburned gas forward burns and generates the shock wave whose orientation is both positive and negative, and the shock wave with negative direction drives the flame propagating reversely. Thus, the second reason is the main factor which results in the unstable propagation.
In Fig.4, the maximum propagation speed of the flame at 9.5vol% methane concentration is lower than 8vol% and 11vol% in the position of glass window, which may be different from the opinion that explosive capacity is biggest at 9.5vol% in theory. Indeed, the maximum propagation speed of the flame at 9.5vol% methane concentration [12] is biggest than other methane concentrations in the whole process of flame propagation. However, in the position of glass window, which is 2m far from the ignition device, the gas explosion flame is in the process of development, and the development of the flame is different at different methane concentration. So the computed results are not contradicted with opinion in theory.



(a)



(b)



(c)

Fig.4 Propagation speed of explosion flame with the different concentration of CH_4

5 Conclusions

(1) The explosion flame propagation process of methane at different concentrations is investigated experimentally, and the dynamic propagation process is photographed by a high-speed camera system. Macro analyses suggest that there exist two features – instability of flame propagation speed and instability of flame structure during the process of explosion.

(2) The method is put forward that calculate the flame propagation velocity. The two adjacent explosion flame images are trimmed transversely from both sides separately, and the correlation coefficient of both the trimmed images can be got. The number of pixels trimmed is obtained in case that the correlation coefficient is maximal. The real distance of pixels is the movement distance. The photographing interval time between the neighboring images is the time of movement.

(3) According to this computational method, the explosion experiment results of the methane at concentration of 8vol%, 9.5vol% and 11vol% is obtained respectively. The propagation velocity of the explosion flame is quantitatively computed. It is found that reverse speed is sometimes larger than forward speed and the flame propagation undergoes an unstable propagation process characterized by acceleration, deceleration, reverse acceleration and deceleration.

Acknowledgements

The research is supported by National Natural Science Foundation Project of China (10672175), the Fundamental Research Funds for the Central Universities (2009kz03) and State Key of Laboratory of Explosion Science and Technology Foundation of Beijing Institute of Technology (KFJJ12-10M).

References

[1] T. Hirasawa, C.J.Sung, A. Joshi, Z. Yang, (2002). H. Wang and C.K. Law. Determination of Laminar Flame Speeds Using Digital Particle Image Velocimetry: Binary Fuel Blends of Ethylene, N-Butane, And Toluene. Proc. Combust. Inst. 29: 1427.

[2] Chen Dong, Qulan Zhou, Qinxin Zhao, Yaqing Zhang, Tongmo Xu, Shien Hui. (2009). Experimental study on the laminar flame speed of hydrogen/carbon monoxide/air mixtures. Fuel. 88: 1858.

[3] A.R. Masri, R.W. Dibble, R.S. Barlow. (1996). The structure of turbulent nonpremixed flames revealed by Raman-Rayleigh-LIF measurements. Progress in Energy and Combustion Science. 22: 307.

[4] S.K. Marley, S.J. Danby, W.L. Roberts, M.C. Drake, T.D. Fansler. (2008). Quantification of transient stretch effects on kernel–vortex interactions in premixed methane–air flames. Combustion and Flame. 154: 296.

[5] Salah S. Ibrahim, Graham K. Hargrave, Tim C. (2001). Williams. Experimental investigation of flame/solid interactions in turbulent premixed combustion. Exp. Therm. Fluid Sci. 24: 99.

[6] S.N.D.H. Patel, S. Jarvis, S.S. Ibrahim and G.K. Hargrave. (2002). An Experimental and numerical investigation of premixed flame deflagration in a semiconfined explosion chamber. Proc. Combust. Inst. 29: 1849.

[7] Zhen-min Luo, Jun Deng, Hu Wen. (2007). Experimental Study on Flame Propagation Characteristics of Gas Explosion in Small-scale Duct. China Safety Science Journal, 17: 106.(in Chinese)

[8] Quan Wang. (2006). Investigation on Propagation of Premixed Methane-air Explosion Flame in Tube. Anhui University of Science and Technology, Heifei, China.(in Chinese)

[9] Dal Jae Park, Anthony Ronald Green, Young Soon Lee, Young-Cheng Chen. (2007). Experimental studies on interactions between a freely propagating flame and single obstacles in a rectangular confinement. Combustion and Flame. 150: 27.

[10] Cong-yin Wang, Xue-qiu He. (2001). An Experimental Study of Flame Thickness in Gas Explosion. Explosive Materials. 30: 28. (in Chinese)

[11] Mikio Takagi and Shimoda Korehisa. (2004). Handbook of Image Analysis. Science Press, Beijing.

[12] Cong-yin Wang. (2001). Study on the Property of High Cohesive Force And Propagation Mechanism of Flame for Gas Explosion. China University of Mining &Technology, Xuzhou, China. (in Chinese)