Experimental study of particle flow field and gas flow field in the flame of pyrotechnic combustion

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Abstract: The particle image velocimetry (PIV) and high-speed photographic camera (HSC) photography were employed to study two-phase flow properties of gas flow field and burning particle flow field in the flame of the pyrotechnics. Particle image velocimetry tested the gas flow field of burning flame of pyrotechnic powder, while the high-speed photographic apparatus captured the pyrotechnic flame of burning particles through full-course after filtering out the impact of gas flame radiation and soot by setting the exposure time. The coordinate of each burning particle in the image was determined by the image processing method. Moving trajectory for each burning particle was calculated according to continuous images, and then got the velocity vector diagram of burning particles. Furthermore, particle and gas flow fields of burning particles were comparatively analyzed. This study provided a simple method of analyzing the flame structure of burning particles for the combustion mechanism of pyrotechnics.

Key words: pyrotechnics; flame; burning particles; flow field

CLC number: E932.6 **Document code**: A **DOI**: 10.3788/IRLA201645.0511002

烟火药燃烧火焰中粒子与气体流场的实验研究

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摘 要: 基于粒子图像速谱仪(PIV)和高速摄影仪(HSC)研究了烟火药火焰的气体流场与正在燃烧粒子流场的两相流特性。首先利用 PIV 获取了烟火药燃烧的火焰气体流场;同时利用 HSC,通过设定合理的曝光时间,实验全程过滤了气体火焰辐射和烟尘的影响,获取了烟火药燃烧火焰中正在燃烧的粒子,用图像处理方法确定了图像中各粒子的坐标,根据获取的连续图像,计算每个正在燃烧粒子的运动轨迹,得到正在燃烧粒子的速度矢量图,进而比较分析了正在燃烧粒子的流场与火焰气体流场;该研究为分析烟火燃烧机理中正在燃烧粒子的火焰结构提供了一种简便的方法。

关键词: 烟火药; 火焰; 正在燃烧粒子; 流场

收稿日期:2015-10-10; **修订日期:**2015-11-15

基金项目:国家自然科学基金 (51076066, 21207066)

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0 Introduction

Pyrotechnic is energetic composite material usually manufactured through the processes of mechanical mixing, granulating, pressing and so on using the materials of combustible agents, oxidants, binders and other powder materials; it is a typical non-uniform porous media. When burning, many particles which are not fully gasified and reacted are carried into the flame, which improves the ignition and radiation performance of pyrotechnic, but this flame structure with high temperature, multi phases and complex intermediates is always a big issue for investigating the burning mechanism of pyrotechnic powder[1-5]. In recent years, with the development of scientific instruments, researchers greatly changed the original understanding of the combustion mechanism of pyrotechnics. Thereof, as the most typical case, the burning flame of pyrotechnics has been considered to be a kind of continuous flame as hydrocarbon fuel, divided into internal and external flame structure; it is difficult to distinguish the flame structure due to the influence of hot dust. The newest research shows that the burning flame is the multi-phase structure composing of gases from combustion reaction and discrete burning particles[6], and apparently different from the clear hierarchy structure of combustion flame of hydrocarbon fuel.

Thus, in this paper, a high-speed photographic camera (High-Speed Camera, HSC) was employed to study burning particles in the flame of pyrotechnic and obtained the moving track by analyzing the coordinate position and velocity distribution of burning particles, and then the velocity vector diagram of burning particles was established to comparatively analyze its flame gas flow field.

1 Experiment

A high speed photography system (HG100K, Kodak REDLAKE) equipped with 170 million pixels of CMOS sensor was used to investigate burning particles. It adopts continuous recording mode after triggering, and offers 25 to 100 000 fps frame rate and maximum image resolution of 1 504 × 1 128.

Pyrotechnic powder was used for combustion experiments, whose ingredient includes potassium perchlorate ($KClO_4$, AR, particle size in the range of 80 to 100 mesh, decomposition temperature of 400 ℃), magnesium (Mg, atomized magnesium powder, particle size range of 200 to 325 mesh, melting point of 648.5 ℃, boiling point of 1 090 ℃), and nitro-cotton. 8% of Nitro-cotton solution was prepared by dissolving nitro-cotton with acetone. The potassium perchlorate and magnesium was poured into a certain volume of nitro-cotton solution and mixed uniformly; the mixture after granulating and drying was pressed in a one-way opening iron vessel with inner diameter of 10 mm and height of 20 mm for the experiment.

In the experiment, the pyrotechnic powder column was put in the smoke full of tracer particles; the jet flame of pyrotechnic powder during burning drove smoke flow, and the flame was tested using PIV system shown in Fig.1.

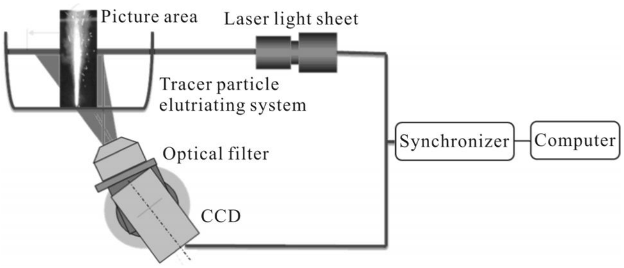

Fig.1 Schematic diagram of the PIV system

The above experimental system consists of an imaging subsystem (including pulsed lasers, light arms, light sheet), image capture subsystem (including CCD camera, light filter, image acquisition board, synchronizer), auxiliary systems (including remote control systems, calibration board and its base), software (including Tecplot flow display software, MATLAB software, etc). Parameters of PIV are as follows: light lens were used, the focal length of spherical mirrors were 500 mm and 1 000 mm and the focal length of cylindrical lens were 15 mm and −25 mm, respectively. The image subsystem is

Power View Plus 4MP 2 k ×2 k pixel self/cross-correlation digital CCD camera with high signal-to-noise ratio, 12 bits output, sampling rate of 15 frames per second, CCD laser protecting array and 50 mm/F1.8 lens. Exposure time was set to 10 microseconds. At the same time, a narrow-band filter with center wavelength of 532 nm and bandwidth for 5 nm was used in order to shield strong light reflection and interference. The double Nd: YAG laser from New Wave Company was selected at high laser energy of 200 mJ/pulse and frequency of 15 Hz which made full use of laser energy and improved signal-to-noise ratio.

The experimental system, controlled by a synchronizer, provides accurate control and activation signal simultaneously to obtain image for the experiment. INSIGHT 3GTM software and Tecplot coupling with MATLAB software was utilized for graphical display and analysis.

Experimental procedure is as follows:

(1) The experiments were performed in the dark room.

(2) The distances of the HSC and PIV to the burning flame were adjusted to ensure the flame full field of view through high-speed photographic apparatus and CCD of PIV, and based on the calibration board of PIV parts, the image size of the PIV and high-speed camera were calibrated, shown in Fig.1. The testing results are shown in Fig.2 and Fig.3.

(3) Burn a lot of incense, the smoke of incense was taken as tracer particles. When the smoke filled the combustion tower, experiment started by igniting the pyrotechinc column. Compared with the burning particles, the smoke particles from burning incense were very tiny, so the flow field measured by PIV is only the gases flow field of the flame.

(4) The exposure time was needed to be set according to speed, brightness and other factors of burning particles. With the shortenness of exposure time, the gas flame radiation was filtered out and wake effect of burning particles was eliminated. Experimental results show that when the exposure time is set to 15 μs and the frame rate of high speed photographic camera is set to 500 frames per second; the moving status of burning particles can be tracked, as shown in Fig.3.

(5) It was reported in Ref.[7] that the particle size is mainly concentrated between 100 μm to 400 μm, and when the height of the distance from the nozzle is gradually increased, the number of particles decreases obviously.

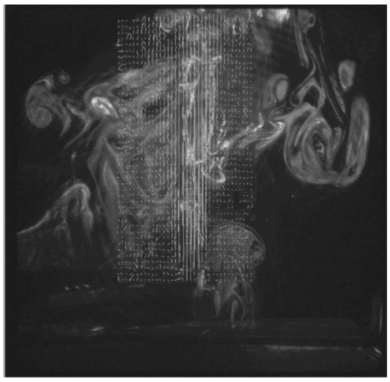

Fig.2 Burning flame images of pyrotechnic powder from PIV

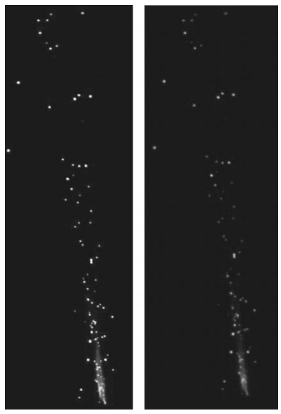

Fig.3 Burning flame images of pyrotechnic powder from high-speed camera

2 Velocity vector of burning particles

2.1 Experimental image analysis

The analysis of experimental graphs is as follows[6,8]:

(1) The highlighted section (process images of continuous spraying) in Fig.3 is burning particles in combustion flame of pyrotechnic powder. Nonluminous particles due to the short exposure time are filtered out. The luminous particles are burning particles.

(2) With the combustion proceeds, these burning particles will move up via jet state; when the rising velocity of burning particles is zero, it starts to decline due to the force of gravity.

(3) The trajectory of each burning particle can be captured by the use of high-speed photographic camera.

2.2 Problem analysis and solution

The First of all, three successive pictures at a time were selected to do binarization processing and picture size calibration, and then obtained the image position of each particle by the gray weighted centroid algorithm [9]. The processing step can be got via Matlab software.

Secondly, in the first graph, each burning particle was marked as P_i and its coordinate position as $P_i(x_i,y_i)$. In the second graph, searching was done in the geometric neighborhoods of coordinate position (the sector plus rectangular area); and traversing was proceeded to burning-particle candidates, shown in Fig.4. Burning-particle candidates which mark variables were not 1 and which areas were the most equal were marked as P_i, and the state of burning particle at next time was P_i'. Furthermore, to set the mark variable of two points, flag, as 1 ensured that they would not be marked again; the current speed of burning particles (pixel / f) were obtained by subtracting two coordinates; the above-mentioned steps were repeated to all the examples in the first picture, as shown in Fig.4.

Large-scale search starts at the beginning, and the mathematical expression of judging criteria at this area is as follows:

$$(\sqrt{(x-x_i)^2+(y-y_i)^2}<r_0 \cap \arctan(\left|\frac{y-y_i}{x-x_i}\right|)<k)<\cup$$
$$|x-x_i|\, x_l \cap X_i \cdot |y-y_i|<y_i \qquad (1)$$

Then the velocity vectors of all subsequent burning particles were calculated using previous results as conditions, and the algorithm is as follows: the end of velocity vector calculated using the burning particle as benchmark is the forecasted position of burning particle at subsequent time. All particles in the area of predicted position were elected as candidates of burning particles.

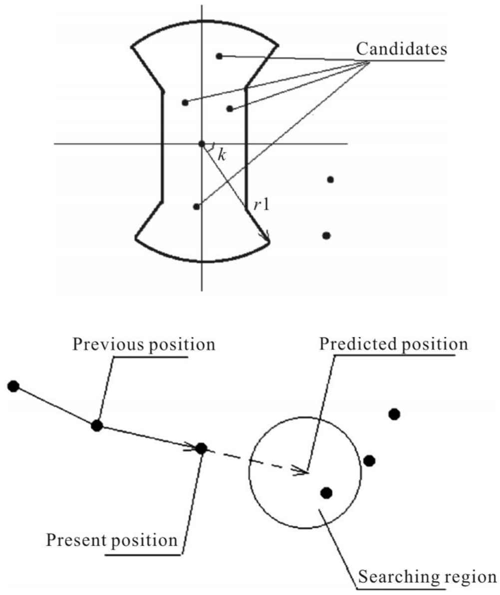

Fig.4 Calibration and trajectory extraction of burning particles

Its mathematical expression for circular neighborhood is $\sqrt{(x+u_0\Delta t-x_0)^2+(y+v_0\Delta t-y_0)^2}<r_1$ in Fig.4. u_0 and v_0 are calculated velocities of cross-ordinate; Δt is the time interval between two images. Thus, the velocity vector can be obtained, as shown in Fig.5.

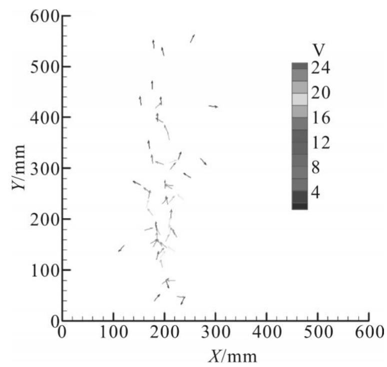

Fig.5 Velocity vector diagram of burning particles in the flame of pyrotechnic powder

3 Analysis and discussion

In fact, the continuity of the image is related to many factors, e.g., exposure time (vision residence time), brightness of gas flame. A large number of burning particles existing in the burning flame is inevitable for the pyrotechnic material made of powder materials.

Although the results obtained by the use of PIV method have the impact on burning particles, namely, that scattered light formed by laser light shining on the burning particles is also received by PIV camera, it also affects the gas flow field. For image processing and burning particle tracking, the images are proceeded in reverse order, and calculation is proceeded from the top down. Since the calculation starts in the scattering region with a low number of burning particles, the calculation for burning particles is more accurate; conducting calculation to high density of flame central region using calculated result in low density of region as the initial value can effectively reduce the deviation of calculation in the high-density area.

Experimental results indicate that the flame gas flow field of pyrotechnic powder measured by PIV shows good continuity shown in Fig.6, different from the flow field of burning particles obtained from trajectory judgment of particles.

The highest velocity of burning particles is up to 24 m/s, as shown in Fig.5; the distribution region of the high-speed burning particle is located at the region between the outlet and position of 400 mm, while the maximum velocity of gas flame flow field of pyrotechnic powder ranges from 13 to 14 m/s, which velocity distributes at the region between the outlet and position of 300 mm, as shown in Fig.6.

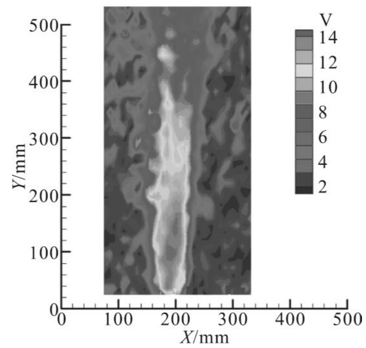

Fig.6 Flame flow field of pyrotechnic powder from PIV analyzing system

Figure 5 and Fig.6 cannot indicate that the flow field velocity of burning particle is faster than that of the gas flame flow field, but the high-speed region of burning particles lags behind the gas flame flow field. This is because the pyrotechnic powder is energetic composite materials; some burning particles are not pure materials, but composite materials containing the oxidizing and combustible agents, thus the high speed cracking phenomenon appears in flames, as shown in Fig.7. The analysis of 500 frames per second indicates that the children popping out of burning particles should have higher velocity than burning particles.

It can be found from the velocity vector diagram of burning particles that: (1) the maximum velocity of burning particles is located at the central region of the flame, not the outlet position; (2) with the ascent of particles, the moving velocity is significantly reduced.

The number analysis of burning particles shows that: (1) burning particles are most concentrated in the central region of the flame, and account for the largest proportion of the number; (2) with the rising process of burning particles, the number of burning particles is gradually reduced; (3) the rise of burning particles are concentrated in the cone range at the core of a flame axis; burning particles hardly appear outside this range.

In addition, the calculation error is related to the interval of the velocity partition, the errors are different for different velocity range. This error percentage is the percentage of the velocity difference and the average velocity of the velocity range. For example, the error is $(14-13)/[(13+14)/2]\times 100\%=7.4\%$ for velocity range of 13−14 m/s.

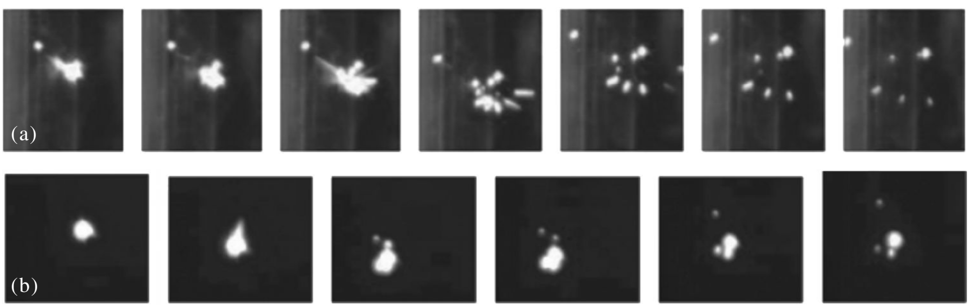

Fig.7 Images for cracking course of the burning particles in flame

4 Conclusions

In this paper, based on HSC, the velocity vector diagram of burning particles in the combustion flame of pyrotechnic powder was obtained, and the gas flame flow field was tested via PIV technology.

Furthermore, it is concluded that:

(1) Trajectories of burning particles can be completely obtained by processing the data in reverse (reversely tracking particles away from the jet nozzle);

(2) Results show that the velocity of burning particles quickly decaying with the increase of height after leaving the jet nozzle does not happen as foresees, while burning particles remain accelerated in a certain zone after being ejected.

(3) Whatever the gas flame flow field, or burning particle flow field, the nozzle position is not the highest velocity region.

(4) Burning particles still have higher velocity and inertia after being rejected due to continuing combustion reaction and bigger mass, which makes high-speed region of burning particles lag behind that of gas flame flow field in which burning articles are located.

After studying and analyzing a few successive pictures at one moment as well as results of the PIV test, it is concluded that both HSC and PIV can do full course capture of data and images, thus this research method can analyze the flow field change from ignition to extinguish.

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