Focus Reflective Shock Wave Interaction with Flame

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Abstract: An experiment on deformation of flame under the effect of focusing shock wave reflection is performed with the help of multiple-spark camera to understand the flame instability of the deformation process. Methane and oxygen are mixed stoichiometrically to be used in the experiment. Based on Navier-Strokes equations, two-dimensional axisymmetric elementary reactions are numerically simulated. And the simulation results are solved by optical calculation. Shaded pictures by simulation fit well with experimental photos. Focusing reflecton shock waves can affect the flame, which accelerates the deformation of flame and renders violent burning in high-energy flammable gases behind waves. Therefore anticlockwise whirlpool appears. It clusters around the external surface of flame and has a tendency to develop toward the right. Finally, the whirlpool focuses on the right side of the flame, which involves the fresh unfired gases into the whirlpool circle, and consequently the head of mushroom cloud is formed. Meanwhile, when shock wave passes through the flame, the intensity of the shock waves on the axis is strengthened.

Key words: focusing shock wave; focus reflection; flame

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1 Introduction

Interactions between shock wave and flame occur frequently in many combustion processes. Research on this issue is indispensable for academic study and practical application. Previously, Markstein[1] conducted a classical experiment to demonstrate the interactions of a plane incident shock wave and its reflected wave with the flame. The results revealed that whirlpool appeared in the internal section of the flame and the flame tended to distort and deform under the effect of shock wave, rendering the turbulence and dramatical increase rate of combustion. Recently, Thomas, et al[2] have performed a series of experiments concerning the significant flame acceleration induced by stronger shock wave and detonation ignition in $C_2H_4/O_2/N_2$ mixture. Systematic numerical examinations on the pressure wave interaction with a cylindrical flame in a two-dimensional (2D) configuration were conducted by Batley, et al[3] using a one-step chemistry. And the results showed that the vorticity field and deformation of the flame were caused by a baroclinic effect. Khokhlov, et al[4] developed a Navier-Stokes equation solver based on one-step chemistry to discuss the interaction between shock wave and flame with sinusoidal disturbance in front. Based on the detailed elementary reaction, Ju, et al[5] discussed the vortex generation, flame distortion and influences on the flame deformation of shock wave intensity by simulating the interaction of plane shock and cylinder flame. Khokhlov, et al[6-9] simulated the shock-flame interaction, using a high resolution format and an adaptive mesh refinement calculation technique, to examine how the interaction of shock and flame generates turbulence and hot spots. Gang Qiang, et al[10] performed experiments on the interaction

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of shock wave and flame, and simulated the interaction process of shock wave and flame. The flame stability and the mechanism of vortex formation were discussed in line with experimental data and simulation results. Gui, et al[11] studied the effects of a plane incident shock wave and its reflected wave on the flame in methane and air mixture through experiments and simulation. Detonation and deflagration initiation under focusing conditions with different reflector types were experimentally investigated and numerically simulated by Gelfand and Bartenev[12-13]. The focusing shock experiments, as well as numerical simulation were carried out by Dong, et al[14-16]. They found that bow shock waves were formed in different shades of a reflective reflector, and the pressure of the gas dynamics focus caused by focusing and flow field wave structure was complex.

Although most researches focused on the interaction of plane shock wave and flame, less attention were paied to the interactions between focusing shock and flame. In this paper, this topic were investigated through two approaches, i. e. , experiments and numerical simulation. It is well-known that the combustibles with high chemical activities are easy to cause turbulence burst, and even lead to detonation, rendering the indistinguishable characteristics of the flame front. So methane and air mixture are used in this experiment for its relatively low activity. And the experiment results are validated with the help of a multiple-spark camera to find out the flame instability of the deformation process. Also, the second-order accuracy wave propagation algorithm is employed in the simulation, taking advantage of the fitted coordinates corresponding to the parabolic focusing reflective wall, based on the detailed elementary chemistry mechanism. Simulation results show that computational shaded pictures fit well with the photos taken by the camera in the experiment. Besides, this paper wants to demonstrate how the flame deformation occurs under the effect of shock wave reflective focusing. Additionally, the influences of flame on the shock wave intensity are discussed.

2 Experimental System

The experimental apparatus used in this paper is shown in Fig. 1, including the shock tube part, optical device, and measurement and control system. And the shock tube part can be divided into three sections: the driver section, driven section and test section. The driver section with high pressure and the driven section with low pressure are 1. 2 m and 8. 2 m long, respectively. They are connected by a flange, whose inner diameter is 38 mm. The test section is closed with a parabolic reflective wall in one side, and its two sides are equipped with igniters inside, as well as glass windows for flow field photographing. In experiments, the test section is filled with stoichiometric mixture of methane/air until the pressure reaches 101 325 Pa. The mixed gas is ignited in the setting time. The driver section is filled with high-pressure gas which breaks the membrane and forms a plane shock wave. After the shock wave entering the test section passes through the flame, it reflects and focuses on reflective wall, and subsequently interacts with the deformed flame.

In the experiments, the compressed-air filled in the high-pressure driver section is produced by air compressor. The air pressure of the driven section is 101 325 Pa. Shock wave, formed in the process of film breaking, moves towards the low-pressure driven section. In order to overcome the magnitude differences between the shock wave movement time and the flame development time, the low-pressure driven section need to be long enough. The experimental section is linked with low-pressure driven section of the shock tube, but they are separated by tissues, therefore combustible gas could not spread into the driven section. On the wall above the entrance of the experimental section, there are two pressure test points P_2, P_3, being 25 mm apart. When the shock wave goes into the experimental section, the pressure sensors at the two test points record the corresponding pressure peaks and passing

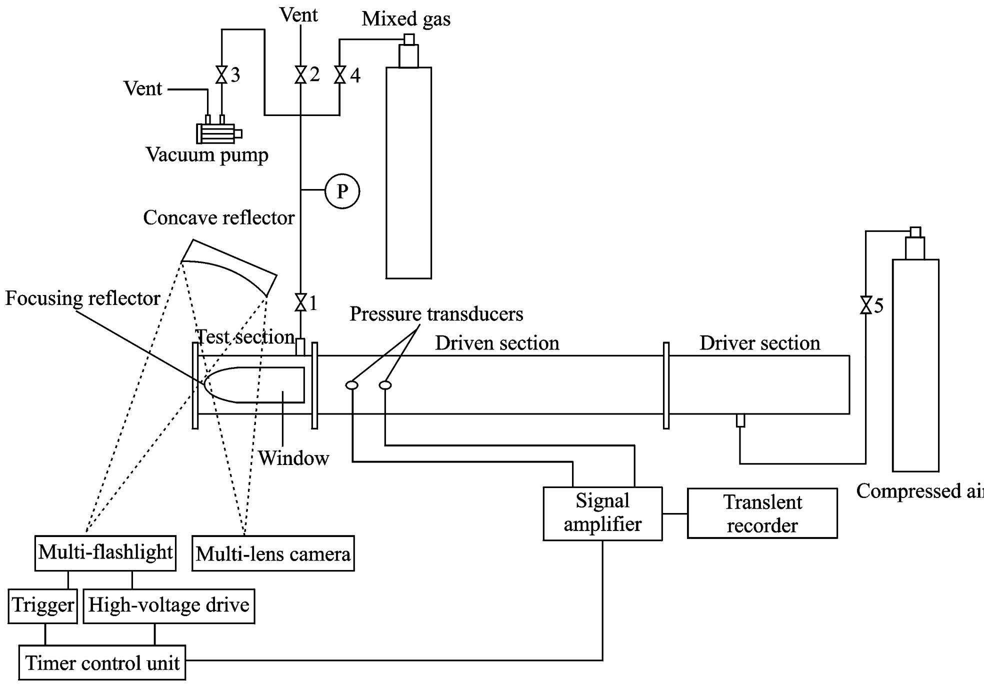

Fig. 1 Experimental device

time, and then one could calculate the strength of the shock wave which enters the experimental section. Before experimentation, one needs to determine the intensity of the shock wave according to the signal from the pressure sensor. Both sides of the experimental section are equipped with 200 mm×45 mm glass windows to capture changes in the flow field owing to the interactions between shock wave and flame.

After the shock wave being generated, the pressure sensor sends an overpressure signal into an electrical signal, which can trigger the controller, and then make the spark light source of the optical device sparkle. The igniter is triggered and the combustible gas is lighted at the same time, ensuring that shock wave interacts with the flame in suitable size. The multiple-spark high-speed camera is used to record the combustion flow field in the window of test section. The optical device is composed of a spark light source, a concave mirror and a multi-lens camera. The light source consists of 16 high-voltage generators, which can control the light on the basis of the preset time sequences by the time schedule controller. After reflection by the concave mirror, the light passes through an unknown flow field. Finally the negative film behind the camera lens is exposed, and shading pictures of the shock-flame interaction at different time are obtained. Pressure measurement system is composed of a pressure sensor, an amplifier and an instantaneous state recorder. Two pressure sensors are assembled at the entrance of the test section to test the strength of the inlet shock wave.

3 Numerical Simulation Methods

In the body fit coordinate, the 2D axisymmetric reactive Navier-Stokes equations are as follows

$$\frac{\partial Q}{\partial t}+\frac{\partial(\overline{F}+\overline{F}_D)}{\partial \xi}+\frac{\partial(\overline{G}+\overline{G}_D)}{\partial \eta}+W=S \quad (1)$$

Second-order accuracy of wave propagation algorithm[12] is adapted to calculate the viscous fluxes $\overline{F}$ and $\overline{G}$ in Eq. (1). Second-order central difference format is used to compute the sticky fluxes $\overline{F}$ and $\overline{G}$. Authors utilize the second-order Runge-Kutta methods to solve the axisymmetrical source terms. Chemical reactions can be described as a set of differential equations about the components of Y, and computed by implicit Gear methods. There are 14 components and 19 elementary reactions in the reactions between methane and air[14].

As shown in Fig. 2, the simulation area is 20 cm×2.5 cm and the grid number is 500×150. The shape of the left margin matches the equation $y^2=2.5x$. The lower boundary is symmetrical, and others are all non-slip boundaries. The initial radius of the flame is 1 cm, and the distance between the center and left margin is 5 cm. Assume that 60% of the fuel is consumed at the initial time. The isolating membrane is 5 cm away from the right end boundary. Air is in the right side of the drive section. The initial pressure is 101 325 Pa and the temperature is 300 K. The mixture of methane/air is in the left driven section with the initial pressure of 101 345 Pa, temperature of 300 K, and stoichiometric ratio of 1. The Mach number of shock wave is 1.1.

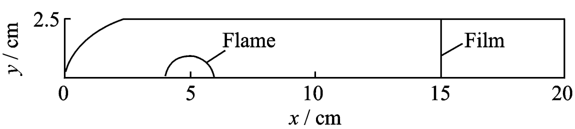

Fig. 2 Section of simulation

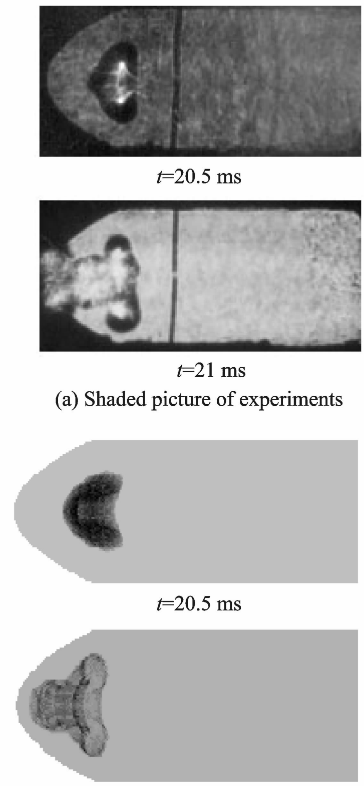

Fig. 3 Shaded picture of flame variation under the effect of focusing shock wave

4 Results and Discussion

The shaded picture of deformed flame under the shock wave effect is shown in Fig. 3. As seen clearly in Fig. 3, Fig. 3(a) agree well with Fig. 3(b) qualitatively when the incident shock Mach equals 1.1. After the interaction between the deformed flame and the focusing reflective shock wave, the fire burning velocity on one side of wall is accelerated and the flame transforms into the shape of mushroom clouds, as shown in Fig. 3(b).

A time sequence of pressure contour plots and OH mass fraction shadow are shown in Fig. 4 when the focus shock wave reflecting on the paraboloid interacts with the flame. The shock wave changes into the paraboloid cavity gradually after interacting with the flame if the cross-section of the combustor is parabolic. At the initial stage, the incident angle of the shock wave is large, so Mach reflection occurs at the wall, as shown in Fig. 4(a). The reflected wave in the form of transverse wave converges to the axis, gradually approaching the outer front of the flame. Compared with the planar reflection, before the reflected shock wave interacts with the flame, the shape of reflection wall has little effect on the flame changes (Fig. 4(b)). As the incident shock wave spreading to the left, the incident angle becomes smaller progressively, and Mach reflection thus changse to be reflected regularly. The lateral wave starts to interact with the flame from the outside of flame, blocking the radical transmission of the flame, so the flame is extruded in the direction of axis by shock wave. Deformation of the transmitted wave begins, and intensity attenuates as well, as shown in Fig. 4(c). Fig. 4(d) shows that the lateral wave focuses in the axis, and further evolves into Mach reflection, while the incident wave gradually disappears. Focus of the shock wave may lead to the ignition of combustible media (Fig. 4(e)). Subsequently, the Mach stem inside the flame interacts with the flame, acting just as the plane reflection

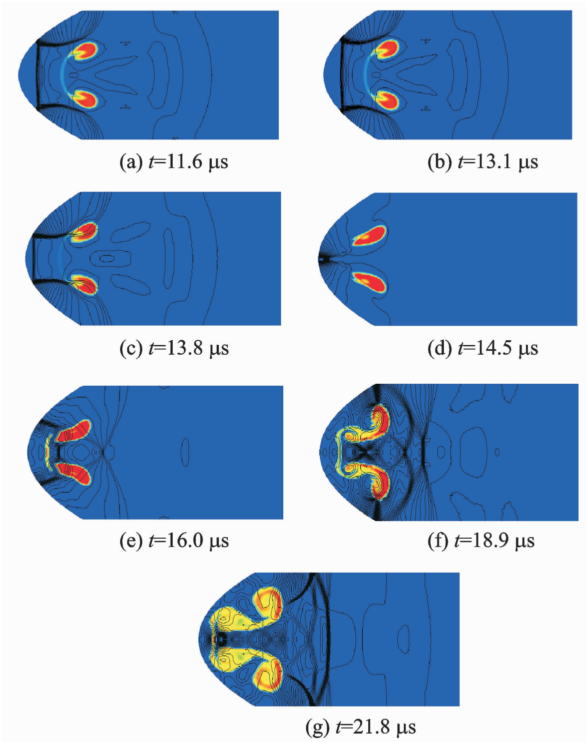

Fig. 4 Time sequence of pressure contour plots and OH mass fraction shadow when shock wave focusing interacting with flame

shock wave interacts with the flame. The interior of the left side of tubular flame is stretched to the left and then combines with the focus ignition flame gradually, forming the stem of the mushroom cloud. The vorticity direction of the right side changes under the reflective shock wave, therefore, the vortex ring combustion zone rapidly expands to the wall, forming a head of the mushroom cloud, as shown in Figs. 4(f,g). The Mach stem evolves to oblique shock wave driven by the penetration shock wave inside the flame. One end reflects on the inner surface of the flame, and oblique shock wave is engendered and converges to the axis; the other end collides and reflects in the axis, and then interacts with the flame again and reflects. The multiple reflection of shock wave on the inner surface of flame and the axis forms a complex shock wave train in the inner gases of flame. A plane shock wave propagation eventually originates in the right, along with the guide shock wave leaving the flame and chasing the shock wave train.

Fig. 5 shows the vorticity distribution of the flow field when the focus shock wave interacts with the flame. Taken the upper half of symmetrical plane for example, the propagation direction of the reflective shock wave and the incident shock wave are in the opposite direction, and the flame thus engenders whorl which rotates counterclockwise under the effect of reflective wave. The whorl concentrates in the outer surface of the flame and gradually developes to the right side, and finally concentrates in the right side of flame. Fresh unburnt gas is involved in the vortex ring of the combustion zone and the head of mushroom is formed.

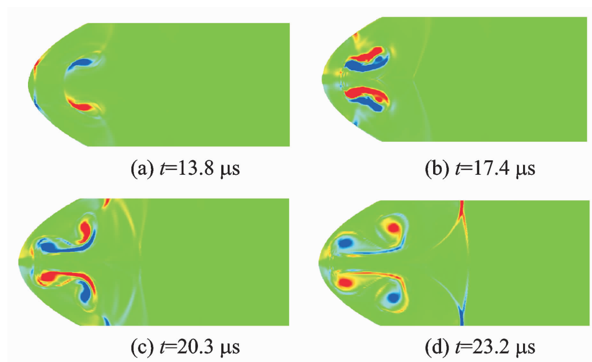

Fig. 5 Vorticity distribution of flow field at different times when shock wave focusing interacting with flame

5 Conclusions

(1) The interactions between focusing shock wave and flame are investigated. The systemic shaded pictures of the incident shock wave focusing and reflecting on the parabolic reflector walls, with the help of the multiple-spark camera, clearly describe the flow bed development. Besides, the process is also simulated by the numerical method. The simulation results agree well with experimental ones.

(2) The results show that the flame deformation and the turbulence guide intense combustion under the effect of incident shock wave, and the combustion becomes more violent under the influence of reflected shock wave, and eventually developes into the mushroom cloud. Meanwhile, when the shock wave passes through the flames, intensity of the shock wave on the axis is strengthened.

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