Flame Propagation in a Channel with Obstacles

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1 Introduction

The shape of flame front can be changed differently due to the influences of various obstacles placed in the fire scene, and the same with the flame propagation velocity and environmental pressure. Flame propagation can be sustained acceleration in a tube with repeated obstacles and may lead to deflagration to detonation transition (DDT). Previous investigations have performed with single or repeated baffle-type[1,2] and block-type obstacles[3,4] to investigate the effects of obstacles on the propagating flame front and overpressure resulting from the premixed turbulent flame.

In the present work, two kinds of obstacles are used to investigate the effects of different obstacle to the flame front propagation. A high speed shadowgraph system is used to obtain the sequential images showing the interaction process of the obstacles and flame. Numerical simulations with Large Eddy Simulation were also performed to explore the detail information.

2 Experimental set-up

The experimental setup is shown schematically in Fig 1. The rectangular cross-section combustion chamber has the length of 320 mm in length and 58×54mm2 in inner cross-section. A pair of optical glass plates is mounted for permitting high-speed flame visualization. The ignition end (left) of the chamber is closed with a flange, while the open end (right) is sealed with a thin plastic membrane. The obstacle is placed with 180mm distance from the left end of the chamber to the backward-facing surface of the obstacle. The mixture in the combustion chamber is ignited by an electric spark installed at the ignition end. A high-speed shadowgraph imaging system is used to visualize the flame propagations, which is consisted of a light source, a concave mirror and a high speed multi-lens camera.

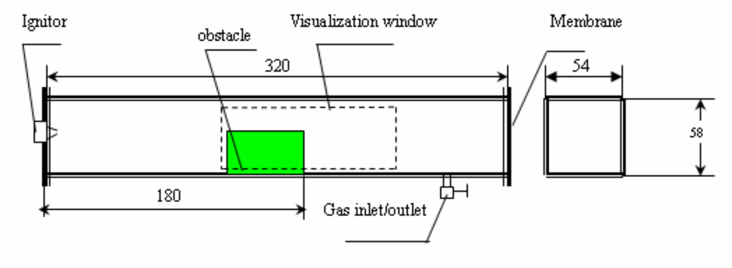
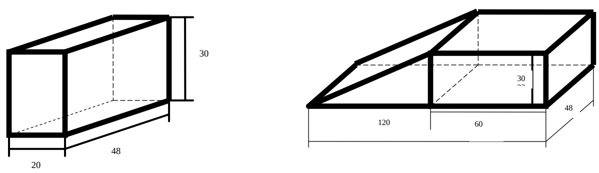


Fig.1. Schematic of the combustion vessel with an obstacle mounted.



a) b)

Fig.2 Two kinds of obstacles

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Two kinds of cylinder obstacles are placed on the bottom of chamber. Their shape and dimension are shown in Fig2. The first one (model A) is a rectangle, and the second one (model B) is a wedge.

3. Mathematical Mode

The Favre filtered LES equations for compressible reactive flow are written as:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j)=0$$

$$\frac{\partial \rho Y_f}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j Y_f)=\frac{\partial}{\partial x_j}D_{eff}\rho\frac{\partial Y_f}{\partial x_j}-\dot{\omega}_f$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j u_i)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\sigma_{ij}$$

$$\frac{\partial \rho E}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j E+p u_j)=\frac{\partial}{\partial x_j}q_j+\frac{\partial}{\partial x_j}(u_i\sigma_{ij})+Q_f\dot{\omega}_f$$

Here $\dot{\omega}$ is reaction rate of fuel. According to the modified Eddy-Break-up closure(EBU)[]

$$\dot{\omega}_f=C_{\rm EBU}\overline{Y_m^{"2}}\rho\frac{\varepsilon_{\rm sgs}}{k_{\rm sgs}}$$

$C_{\rm EBU}$ is a model constant of the order of unity. The $\varepsilon_{\rm sgs}, k_{\rm sgs}$ is turbulence dissipation rate and turbulence kinetic energy in the subgrid turbulent time scale, respectively.

$$k_{\rm sgs}=\left(\frac{\mu_{\rm sgs}}{C_{\rm v}\overline{\Delta}}\right)^2$$

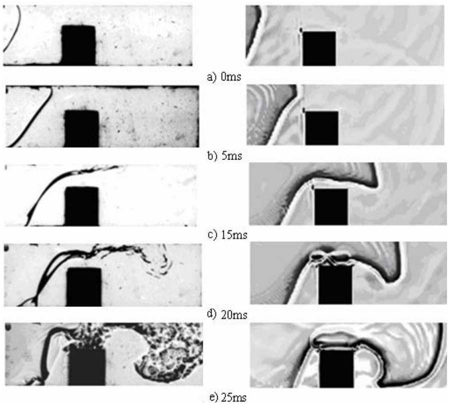
and

$$\frac{\varepsilon_{\rm sgs}}{k_{\rm sgs}}\sim\frac{\sqrt{2k_{\rm sgs}}}{C_{\rm EBU}\overline{\Delta}}$$

Where $\overline{\Delta}$ is the characteristic LES grid size. The coefficients $C_{\rm v}$ is taken as constants and equal to 0.41.The effective viscosity $\mu_{\rm sgs}$ is modeled using constant coefficient Smagorinsky SGS model.

4. Results and Discussion

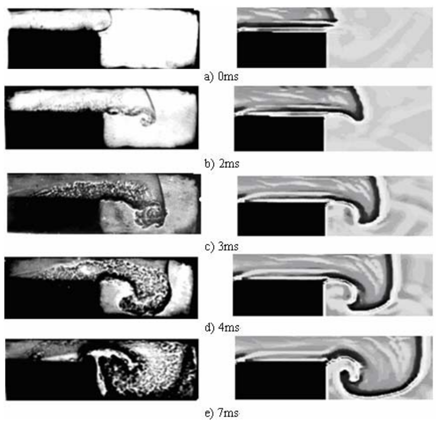
Sequences of high-speed experimental shadowgraphs of flame front passing through model A obstacle are presented in Fig.3I, and the corresponding calculated shadowgraph results are shown in Fig.3II .



I) Measurement II) Calculation

Fig.3 Flame front pass over the rectangle.

From Fig.3, a smooth flame front propagates from left to right. At first, the flame is smooth, however, when it near the rectangle, it loses the planar shape due to the effect of flame-induced unburned gas (Fig.3a-b). Then, the flame passes through the narrow channel between the top surface of rectangle and the upper wall of the chamber. With a sudden area change, the flame front is elongated and accelerated in the contracted flow. The flame front turbulence appears on the leading and lower parts of the flame front (Fig.3c). After that, the flame is entangled by a large vortex behind the obstacle, and the leading flame is drawn towards the back and spreads quickly in all directions to form a fire ball. On the other hand, in the narrow channel, the compressed waves, which produced by deformed flame in the unburnt gas, reflects on the wall and travel through the combustion zone. These processes significantly result in the instability of the flame, the flame front on the top of the rectangle loses its shape and is attached to the top surface of the obstacle. Meanwhile, the intensity of turbulence increases very rapidly (Fig.3d-e).

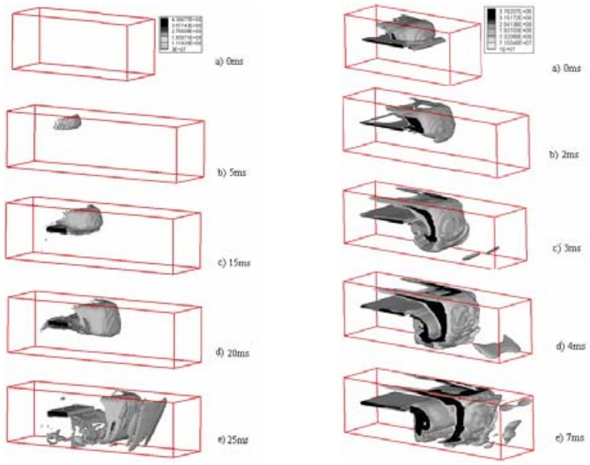


I) Measurement II) Calculation

Fig.4 Flame front pass over the wedge.

When a wedge is used as the obstacle, the channel between the obstacle and the upper wall of the chamber is longer and narrower than in Fig.3. Typical series of shadow photographs of both expeirmental and the calculated results are shown in Fig.4.

As shown in Fig.4a, an accelerating smooth flame front just emits from the channel, and only a few of traces of turbulence appears near the tip surface of the obstacle. Under the effects different instabilites, the turbulence grows, and it can be observed from Fig.4b that the vortical structures appear on the lower part of flame front parallel to the bottom surface of the chamber. Then, these vortices break up into small cells which in turn make turbulence perceivable(Fig.4c). The leading flame front is rolled up under the action of the the vortex. Meanwhile, its tip protrudes toward both the back front of the wedge and the direction of open end of chamber. At last, the flame front foldes itself penetrating into the narrow channel (Fig. 4e).



I) The rectangle II) The wedge

Fig.5 3D turbulent kinetic energy graphs of flame front pass over both the rectangle and wedge obstacles.

It shows clearly that the turbulence-induced mechanism corresponding to the top surface of the obstacle is dominant. In order to further discussing this phenomenon, the contour distributions of turbulence energy when the flame front passes over both rectangle and wedge are shown in the Fig.5I and 5II, respectively. It can be proved the strong turbulence is appeared near the top surface of the both obstacles (black zone in the Fig. 5). it also can be find that the turbulent kinetic energy on the flame front enhanced gradually as flame propagating forward. Thus, the positive feedback effect of the turbulent unburned gas and flame propagation is generated and displayed (Fig.5I a-e and Fig.5II a-e).

conclusion

Both of our experimental and numerical results show that flame can be accelerated when it passes over the rectangle and wedge obstacles located on the bottom of duct. The turbulence-induced mechanism corresponding to the top surface of the obstacle is dominant. After the flame front passes through the narrow channel between the top surface of obstacle and the upper wall of the chamber, the flame is drawn in by a large vortex behind the obstacle. Then, the positive feedback coupling between the turbulent unburned gas and flame is generated.

Acknowledgements

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