Vol. 46 No. 6 SCIENCE IN CHINA (Series E) December 2003

Turbulence in laminar premixed V-flames

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Received January 2, 2003

Abstract Strong velocity fluctuations had been found in the laminar premixed V-flames. These velocity fluctuations are closely related to the chemical reaction. But the effects of the upstream combustible mixture velocity on the velocity fluctuations inside the flame are quite weak. The probability distribution function (PDF) of the velocity in the centre region of the flame appears "flat top" shaped. By analyzing the experiment results the flame-flow interactions are found to affect the flame not only at large scale in the flow field but also at small scale inside the flame. These effects will give rise to flame generated small scale turbulences.

Keywords: flame-flow interactions, flame generated turbulence, small scale structure inside the flame.

DOI: 10.1360/03ye03

Combustion process coexists with flow in almost all the practical combustion devices. The flame-flow interactions have been one of the most challenging areas in combustion science and technology as well as combustion researches, since they are closely related to the fundamental elements of combustion process, e.g. flame structure, flame propagation, flame stabilization, flame instabilities, soot process and pollutants forming. Turbulence-flame interactions have been widely studied and many important achievements have been gained in literature. However, a detailed physical understanding of turbulence-flame interactions is still lacking due to the complexity of the problem itself.

Karlovitz[1] and his co-workers first proposed the concept of flame generated turbulence in the early 1950s. Later on Eschenroeder[2] theoretically discussed the mechanism of intensifying turbulence due to the chemical reaction. Yoshida and Tsuji[3] measured the axial component of velocity fluctuations in the unconfined flame and found the tendency of intensifying turbulence. Moreau and Boutier[4] also found the intensification of root-mean-square of the axial component of velocity fluctuations in the flame. Bray[5] and his co-workers discussed the mechanisms of flame generated turbulence and predicted that the turbulence might be either intensified or weakened by the buoyancy due to the flame. Driscoll[6–8] and his co-workers recently studied the flame-vortex interactions by using the unique microgravity condition and they found that flame caused the initial vortex to be completely attenuated, but there was a new "flame-generated" vortex opposite in sign to the initial vortex. All these studies focused on the regions ahead and behind the flames without paying attention to the situation inside the flame. The present paper addresses the situation inside the flame and the behavior of the flame-flow interactions inside the flame.

1 Experimental apparatus

All the experiments were conducted in the National Microgravity Laboratory of the Chinese Academy of Sciences. Fig. 1 shows the scheme of the burner and a typical flame image. The inner diameter of the burner is 62 mm. The flame holder is located 20 mm downstream from the burner exit which is a rod 2 mm in diameter. The V-flame stabilizes downstream near the flame holder. The outer and inner diameters of the co-axial flow are 92 and 68 mm, respectively. The methane and air entered the burner near the bottom of the burner separately and then mixed. Fine screens, honeycomb and small steel-ball layers were used to eliminate the large scale eddies. The turbulence generating grid was removed when laminar flame is studied. 99.99% pure methane was used as fuel. The burner was assembled on a coordinate frame movable in x, y and z direction and revolvable on z axis. The minimum distance between two measuring points was 0.07 mm in the z direction. A two-dimensional hot wire anemometry and a one-dimensional laser Dopper velocimetry (LDV) were used to measure the mean velocity and the turbulence intensity. Fig. 2 shows the scheme of LDV system.

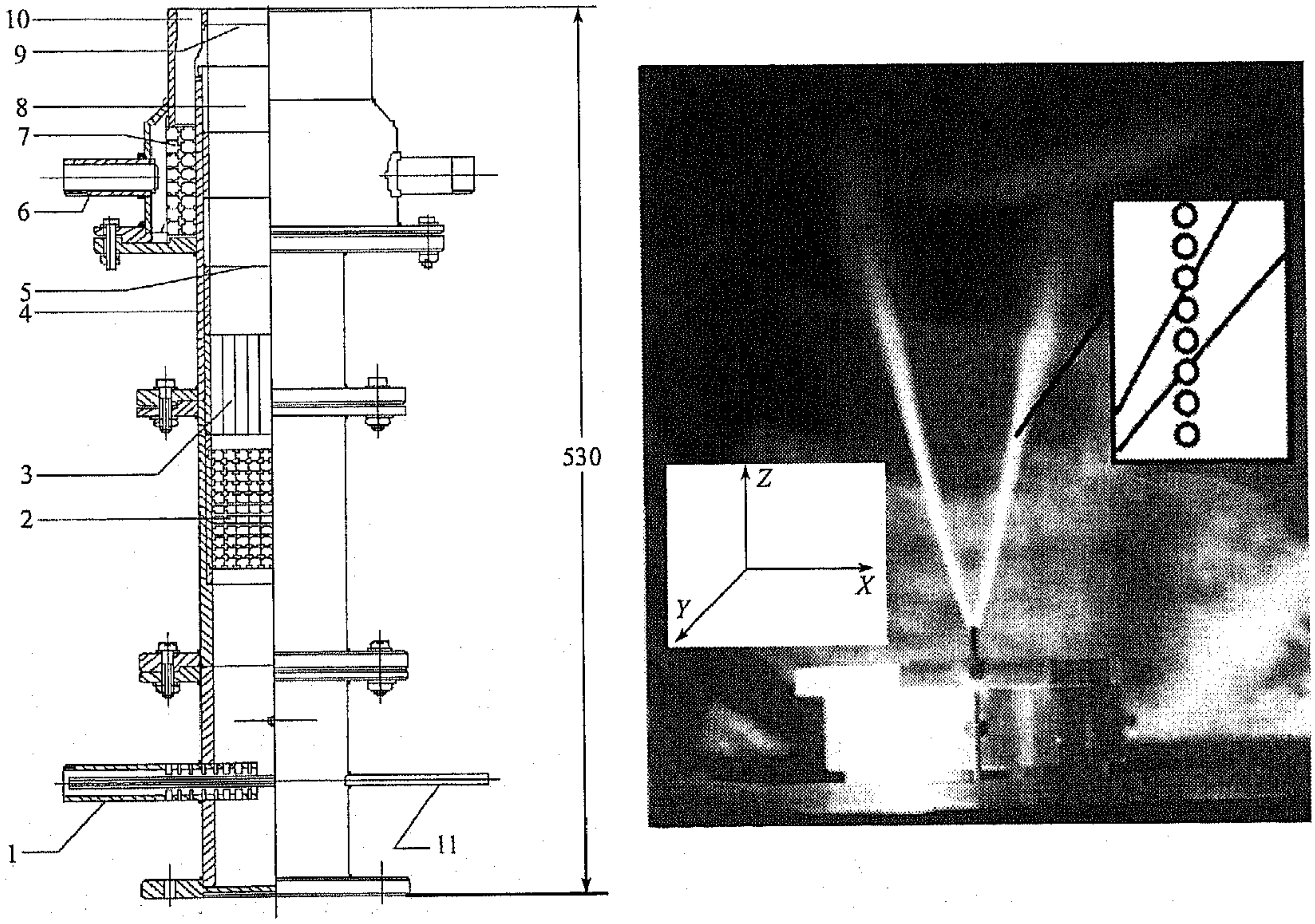

Fig. 1. Scheme of the Burner and a typical flame. 1, Air inlet; 2, steel-ball layer; 3, honeycomb; 4, bush; 5, fine screens; 6, co-axial flow inlet; 7, co-axial uniformer; 8, inner jet; 9, turbulence generating grid; 10, co-axial air flow; 11, fuel inlet.

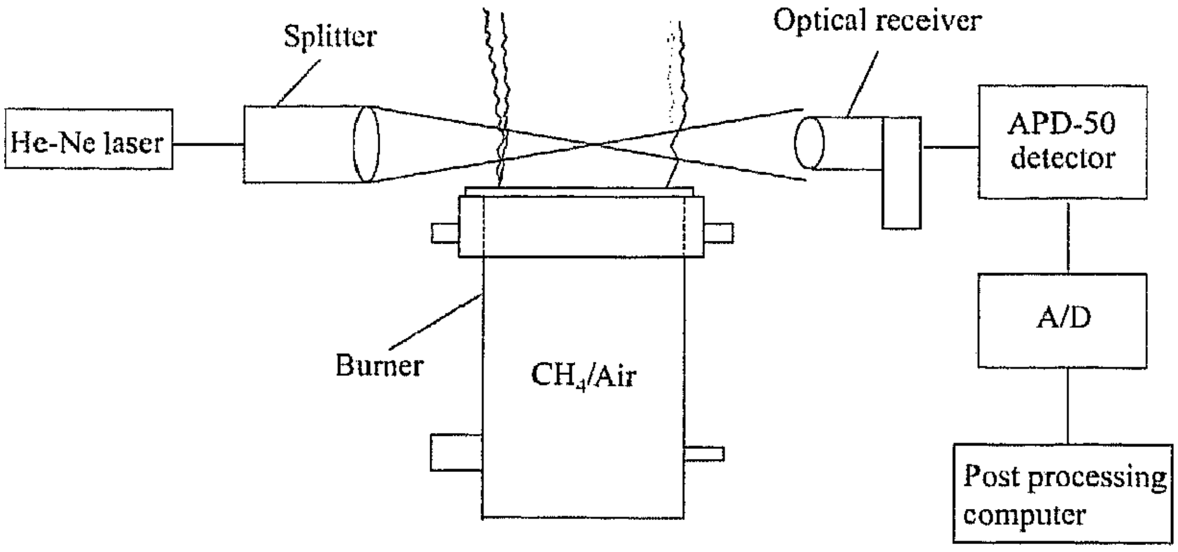

Fig. 2. LDV system.

2 Results and discussion

2.1 Cold flow experiments

Cold flow experiments in the cases with and without flame holder were measured by using hot wire anemometry at the flow rate m = 19 kg/h and mean velocity at the exit of the burner $\bar{U}$ =1.35 m/s. The measurements were conducted in a plane perpendicular to the flame holder at distances 0D, 1D, 2D (D is the inner diameter of the burner = 62 mm) from the exit of the burner. The distance between two horizontal neighboring measuring points is 2.5 mm. The mean velocity and turbulence intensity of these two cases are presented in figs. 3 and 4, respectively.

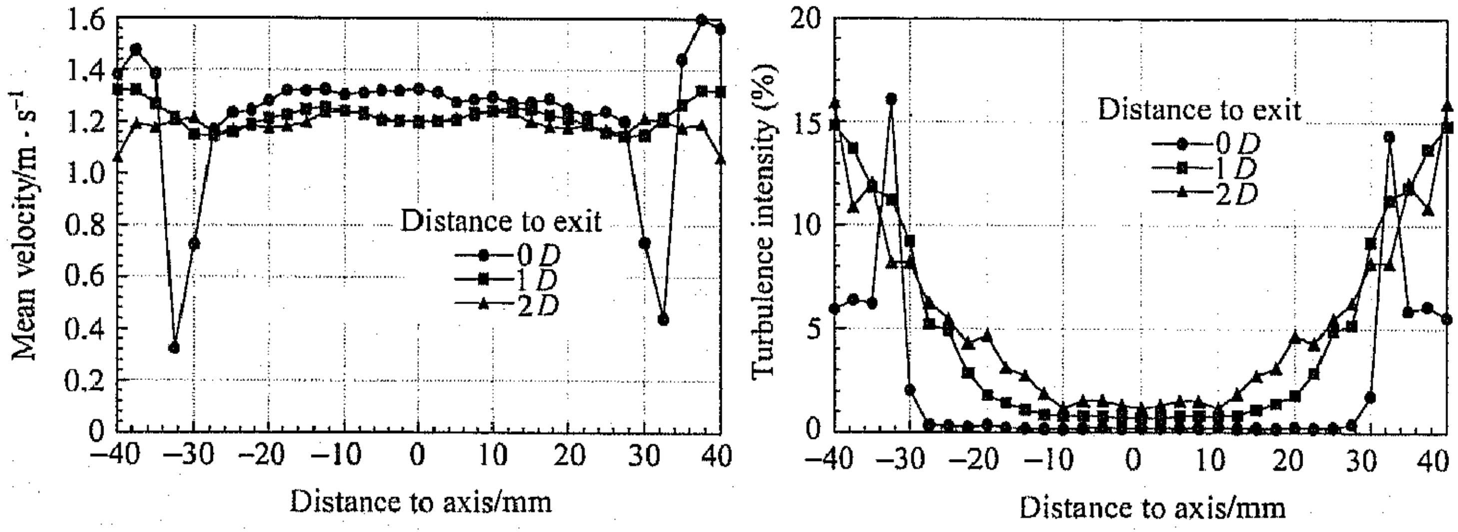

Fig. 3. The mean velocity and turbulence intensity distributions of the flow field (without flame holder).

The velocity distribution is quite flat along the measuring cross-section in the case without flame holder. The turbulence intensity of about 0.3% is the lowest level along the 0D cross-section. Then it increases slowly with the increasing distance from the exit of the burner. The turbulence intensity is less than 2% in the flat region along the 2D cross-section.

In the case with flame holder, the distribution of the mean velocity and the turbulence intensity is also quite flat along the 0D cross-section at the exit of the burner since it is located upstream of the flame holder. But the distribution of the mean velocity and the turbulence intensity appears a peak along the 1D and 2D cross-section due to the effects of the flame holder. In order to get laminar case, the region 1D downstream from the exit of the burner and 10—20 mm horizontally from the center of the burner is chosen in the study of the flame-flow interactions where the turbulence intensity is less than 1%.

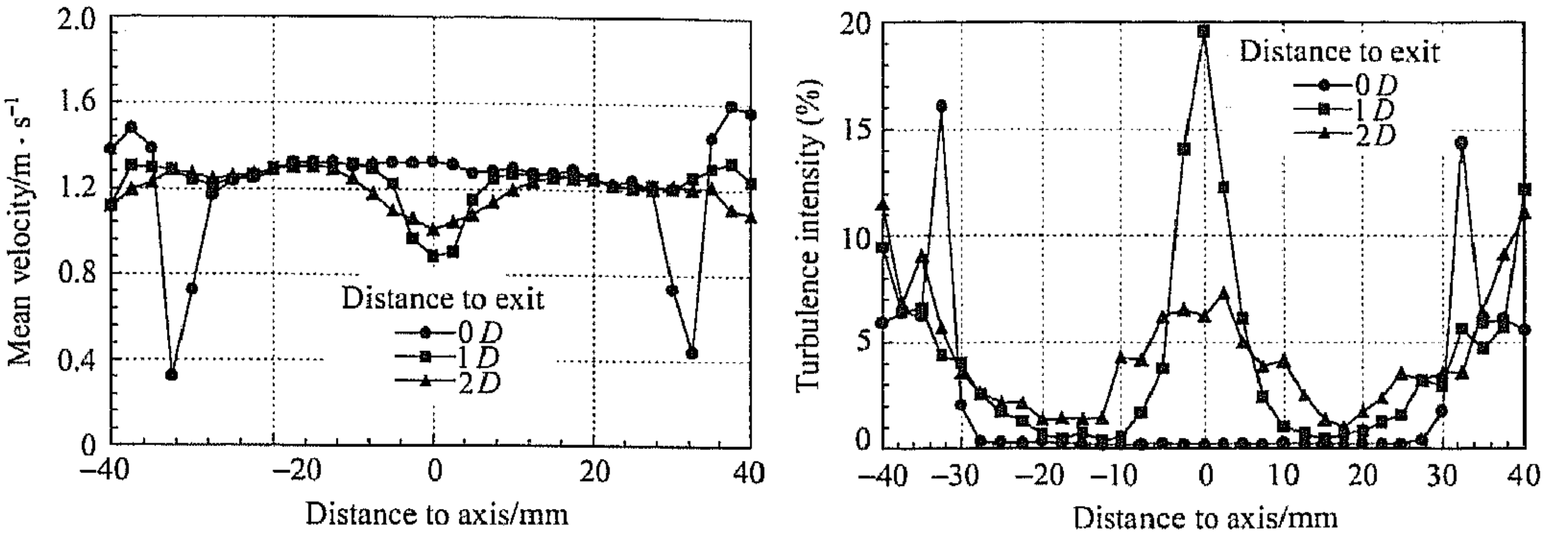

Fig. 4. The mean velocity and turbulence intensity distributions of the flow field (with flame holder).

2.2 Laminar flame experiments

A one-dimensional laser Doppler velocimetry was used to measure the mean velocity and turbulence intensity from the upstream far away from the flame, and then crossed the flame into the downstream combustion products region. The distance between the two neighboring measuring points in the z direction was 0.14 mm. So approximately 15 measuring data could be obtained inside the flame.

Experimental results were obtained by setting the mean velocity of combustible mixture at the exit of burner at 1.35 m/s while the equivalence ratio increased from 0.66 to 0.86. (fig. 5). Fig. 5 shows some interesting points:

(i) The turbulence intensities inside the flame are obviously higher than the intensities in upstream combustible mixtures and downstream combustion products.

(ii) The turbulence intensity in upstream combustible mixture is approximately equal to the intensity in corresponding downstream combustion product.

(iii) The turbulence intensity inside the flame increases remarkably with the equivalence ratio. The maximum turbulence intensity is approximately 19% in the present study.

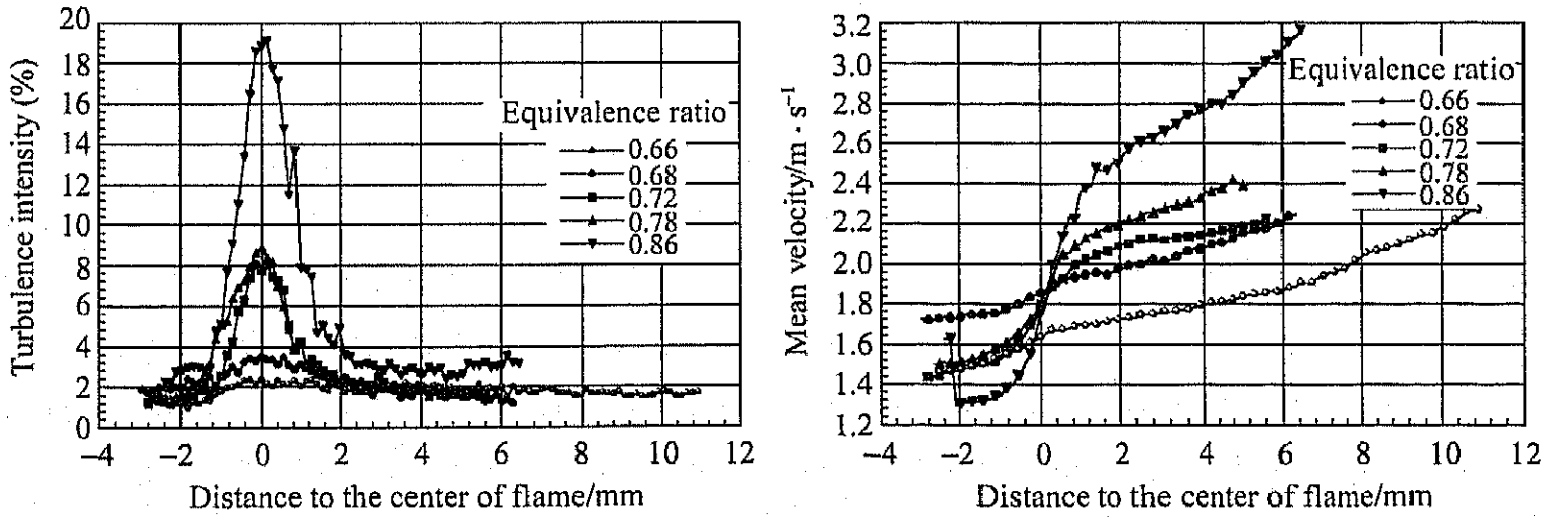

Fig. 5. The turbulence intensity and mean velocity distributions at different equivalence ratios ($\bar{U}$ =1.35 m/s).

These experimental results are worth noting. There are many factors that might lead to these results. Flame wrinkle is one of the factors. At a fixed point the velocity at the point is either the velocity of upstream combustible mixture, or the velocity of downstream combustion product when the flame crosses the point. This velocity variation makes a part contribution to the velocity fluctuations of the present measurement results. The second factor is flame flicker induced by different kinds of flame instabilities. This motion of flame also makes a part contribution to the measured velocity fluctuations. The third factor is that when the vortex generated behind the flame holder propagates along the flame front, the flame front will be wavy. It also makes a part contribution to the measured velocity fluctuations.

If the measured velocity fluctuations consist of flame wrinkle, flame flicker and flame waviness only, we cannot well explain the experimental results obtained in the present study, because in that case the probability distribution function (PDF) of the velocity should be bimodal. Fig. 6 shows that the PDF of the velocity is not bimodal shaped in the center region of the flame but "flat top" shaped. Although the PDF at the places corresponding to the velocity of upstream combustible mixture and combustion products is relatively high, it represents the effects of flame wrinkle, flame flicker and flame waviness only. The velocities between the velocity of upstream combustible mixture and the velocity of downstream combustion products have a great contribution to the PDF, indicating that besides the three factors mentioned above there must be some other factors. By analyzing the experimental results carefully it is believed that the flame-flow interactions affect the flame not only at large scale in the flow field (i.e. flame wrinkle, flame flicker and flame waviness) but also at small scale inside the flame.

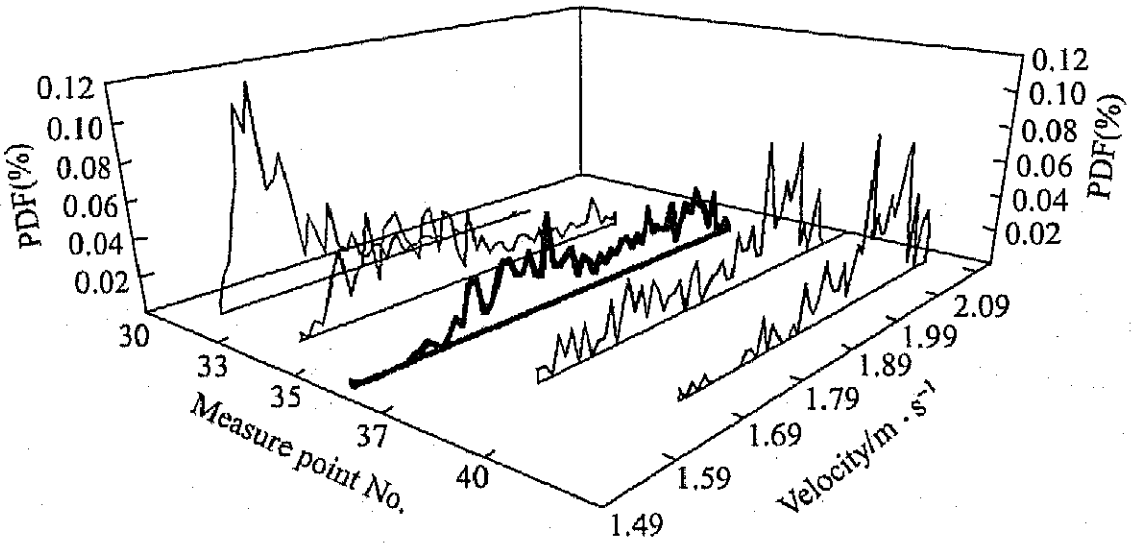

Fig. 6. The PDF of velocity inside the flame ($\bar{U}$ =1.35 m/s, Φ=0.72).

Chemical reaction is a rate process. It has a certain band of characteristic time scale and length scale. Flow (turbulence) is also a rate process. It also has a certain band of characteristic time scale and length scale. When these two rate processes get coupled, part of the energy released in chemical reaction will change into turbulence kinetic energy to enhance the turbulence intensity. These small scale flame-flow interactions will form small scale vortices inside the flame. This is the flame generated turbulence. These small scale vortices (turbulence) will influence the flame characteristics in small scale inside the flame. In the presence of the small scale vortices inside the flame, it consists of the center part of the PDF. Fig. 5 shows that the turbulence intensity inside the flame increases remarkably with an increase in equivalence ratio, indicating that the chemical reaction plays a very important role. When the equivalence ratio keeps constant $\Phi=0.75$, the combustible mixture mean velocity at the exit of the burner varies from 1.0 to 1.6 m/s, and the turbulence intensity increases very little (fig. 7), suggesting that the effects of the upstream combustible mixture velocity on the turbulence intensity inside the flame are quite weak. Meanwhile, the strong turbulence intensity exists only inside the flame. When the flow enters the downstream combustion product region the turbulence intensity attenuates rapidly and returns to the level of the upstream combustible mixture, implying that the turbulence intensity inside the flame is induced by the small scale eddies. These small scale eddies attenuate rapidly in the high temperature combustion product region due to the high viscosity. Since the mean velocity of combustion products is higher than the velocity of upstream combustible mixture although their turbulence intensity is approximately the same level, the root-mean-square of velocity fluctuations of combustion products is higher than that of upstream combustible mixture (fig. 8). These results confirmed our belief clearly that flame-flow interactions generate small scale vortices (i.e. flame generated turbulence) inside the flame even for the laminar premixed V-flames.

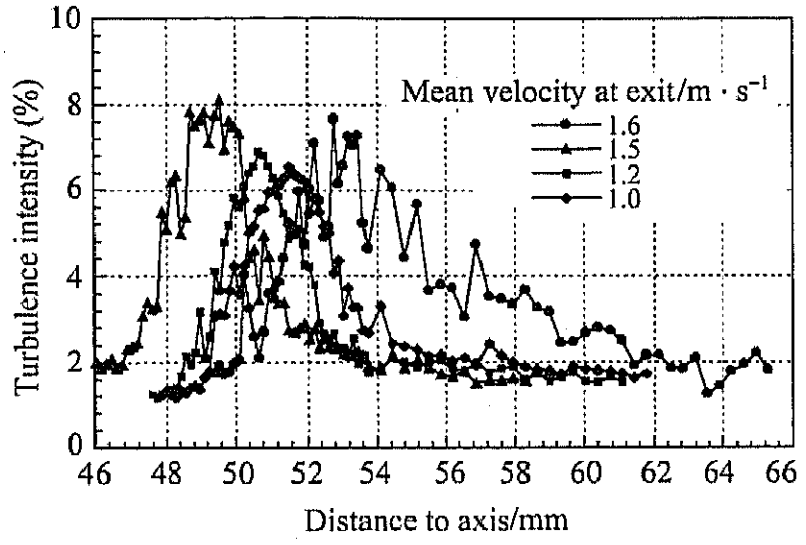

Fig. 7 The turbulence intensity distribution at different exit mean velocities (Φ=0.75).

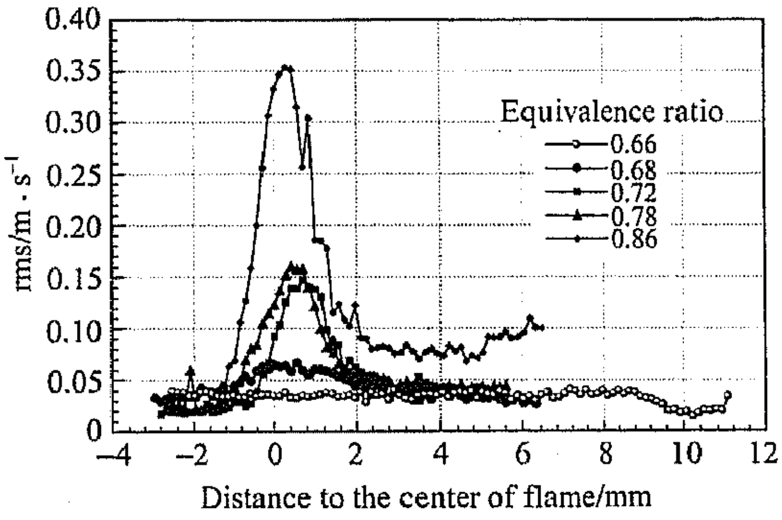

Fig. 8 The rms of velocity fluctuations distributions at different equivalence ratios ($\bar{U}$ =1.35 m/s).

3 Conclusions

Strong velocity fluctuations exist inside the laminar premixed flame (i.e. flame generated turbulence). These velocity fluctuations are closely related to the equivalence ratio (chemical reaction). The effects of the upstream combustible mixture velocity on the velocity fluctuations inside the flame are quite weak. The probability distribution function (PDF) of the velocity is "flat top" shaped in the center region of the flame. By analyzing the experiment results it is believed that the flame-flow interactions affect the flame not only at large scale in the flow field (flame wrinkle, flame flicker and flame waviness), but also at small scale inside the flame. These effects will result in the flame generated small scale turbulence.

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