# A Numerical Study on the High-Speed Flame Propagation in a Vortex Tube

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#### Introduction

Recently the phenomenon of high-speed flame propagation along the axis of the vortex tube of premixed gas, "vortex bursting", has been attracting attentions as a mechanism of promoting the intensity of turbulent combustion. So far, many researchers have been studying this phenomenon experimentally, theoretically and numerically, and its governing mechanisms have been cleared up to a considerable extent [1, 2]. However, there is still some ambiguity about how these mechanisms work for each flame condition and for each stage of its propagation, so the next thing to do on this problem should be to investigate the phenomenon more quantitatively and in detail, especially by numerical simulation. Since almost all the numerical studies conducted so far have been dedicated to the analysis of the fluid dynamic effects, they have been based on a simple overall reaction model and on the assumption of unity Lewis number. That is, more detailed features of the flame itself have not been investigated. In this study we simulated the high-speed flame propagating in a premixed gas vortex using a numerical calculation with a full kinetic mechanism, and investigated how the local burning velocity and local flame structure change during the propagation in detail.

### **Numerical Method**

In this study we adopted an unsteady axisymmetric model. At first the whole domain is uniformly filled with a premixed gas of hydrogen and air, and at the time t=0 a straight vortex whose centerline lies on the axis suddenly emerges and a hot spot of 0.35mm x 0.35mm is also given at the origin at the same time. The equivalence ratio is 0.5 and the temperature of the hot spot is 2500K. The initial vortex is assumed to be a Burgers vortex whose rotation velocity w is

$$w(r) = \frac{\Gamma}{2\pi r} \Big[ 1 - \exp\{-r^2/(\sigma_0/2)^2\} \Big],$$

with the representative diameter  $\sigma_0=0.1$  cm and the maximum rotation velocity  $W_0$  is 0, 10 and 20 cm/s. After the ignition by the hot spot the flame starts to propagate in the axial and radial directions while the

vortex is gradually damped by the viscosity. In the numerical 2D code, which was developed by the authors, SIMPLE [3] is used as an algorithm to solve the flow field and QUICK scheme is used in discretizing the convective terms. The thermochemical and the transport properties are calculated with CHEMKIN subroutines. The reaction mechanism by Yetter et al.[4] is used for the combustion of hydrogen and air. The computational domain is 0 < x < 4cm and 0 < r < 4cm.

### **Results and Discussions**

Figure 1 shows the time variation of the flame propagation velocity u in the axial direction. It is seen that when a vortex exists, i.e.  $W_0=10m/s$  or 20m/s, the propagation velocity at first increases largely and then gradually approaches to a constant value, which is so large as 14m/s for  $W_0=10m/s$  and 26cm/s for  $W_0=20m/s$ . These values are surprisingly larger than the laminar burning velocity of 1D flame  $Su_0=51cm/s$  obtained by PREMIX code, so this fact obviously corresponds to the vortex bursting phenomenon. It is noted that for each case the asymptotic value is between the theoretical prediction by Umemura and that of Ishizuka.

Figure 2 shows the time variation of the local burning velocity  $Su_{Local}$  at the leading edge of the flame, i.e. at the flame surface on the axis. Here  $Su_{Local}$  is obtained by subtracting the axial flow velocity at the edge of the preheat zone from the propagation velocity u. We defined the edge of the preheat zone as the point 0.3mm ahead of the inflection point of the temperature distribution normal to the flame surface. It is seen that as a whole the larger the maximum rotation velocity is the larger the local burning velocity is. At the early stage of the propagation  $Su_{Local}$  is considerably large probably by the effect of the high energy from the initial hot spot, and it gradually decreases and approaches asymptotically to some constant value for



Fig. 1 Time variation of the flame propagation velocity u



Fig. 2 Time variation of the local burning velocity at the flame leading edge

each case. It must be noted that the latter values are much larger than 51cm/s. This fact means that there is a factor which increases the local burning velocity itself besides the "fluid dynamic effect" that the flame is pushed by the induced vorticity and the large pressure gradient across the flame.

As a cause to increase  $Su_{Local}$  as shown in Fig. 2, we think of the thermal-diffusive unbalance due to the small Lewis number of the unburned gas. Figure 3 shows the temperature distribution at t=0.7msec for  $W_0$ =10m/s. It is seen that the maximum temperature in this region is about 2100K which is much higher than the equilibrium temperature 1652K, which obviously shows the excess enthalpy accumulated due to the unbalance. Figures 4(a)-(c) show the diffusion mass flux of H<sub>2</sub>, conduction heat flux and the resultant of the two vectors, respectively. Here the diffusion flux is equivalent to the chemical energy flux since it was weighted by the heat of combustion of H<sub>2</sub>. It is clearly seen from these figures that the entering chemical enthalpy flux is much larger than the leaving heat conduction flux throughout the flame surface. Especially, there is a large convergence the former and a large divergence of the latter due to the large curvature of the flame around the leading edge. Furthermore, there also is a considerably large flame stretch at the flame leading edge, which is not shown here, the unbalance mentioned above appears at this region. Figure 5 shows the concentration distributions of H, O and OH. It is noted that there are large amount of these radicals around the leading edge suggesting high activities of chemical reactions, which obviously is a consequence of the large convergence of H<sub>2</sub> flux and high temperature at this region.

## References

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Fig.4 Temperature distribution (t=0.7msec)



Fig.5 Diffusion flux of  $\mathrm{H}_2$  , conduction heat flux and the resultant



Fig.6 Concentration distributions of H, O and OH