# Effect of Local Flame Stretch at the Tip of the Flame Propagating in a Vortex

Makihito Nishioka and Tohru Hokazono

Department of Engineering Mechanics and Energy, University of Tsukuba Tsukuba, Ibaraki 305-8573, Japan

Corresponding author, M. Nishioka: mnisioka@kz.tsukuba.ac.jp

## Introduction

The phenomenon of high-speed flame propagation along the axis of vortex tube of premixed gas has long been attracting attentions as one of the key flame elements of turbulent premixed combustion or a hint on a new concept of combustion method [1-3]. Theoretically, the mechanism is explained in terms of the large driving force around the flame tip on the axis caused by the interaction between the large density change through the flame zone and the radial pressure drop by the rotating flow. Recently, Nishioka and Ogura simulated the flame propagation in a vortex of lean hydrogen-air premixed gas numerically with detailed chemistry, and showed that there exists a large flame stretch at the flame tip on the axis, which increases the local flame temperature and the local burning velocity around the tip due to the unbalance between thermal and chemical enthalpy [4]. In this case, the flame stretch at the tip is composed of the term of the flame curvature as well as that of the flow divergence, so this flame is a good target in investigating the contribution of flame curvature on flame stretch. In this study, to make the effect of Lewis number clearer, lean methane-air flame was simulated and the result was compared to the hydrogen-air case [4]. The time variation of the local flame stretch rate at the flame tip was examined to investigate the relation between the instantaneous local stretch and the local flame extinction.

#### **Numerical Method**

The model used in this study is basically the same as the one in the previous study [4]. At first the whole domain is uniformly filled with methane-air premixed gas, and at t=0 a straight vortex suddenly emerges with a hot spot on the center of its axis. This initial vortex is assumed to have a Burgers vortex distribution whose rotation velocity w is given as follows.

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

In this study, the representative diameter  $\sigma_0$  is 0.1cm and the maximum rotation velocity  $W_0$  is 0m/s, 10m/s and 20m/s. The initial hot spot has the maximum temperature 2500K and its radius (HWHM) is 0.6mm. The equivalence ratio of the premixed gas is 0.7. After the ignition by the hot spot the flame starts to propagate in the axial and the radial directions. In the numerical 2D code, thermochemical and transport properties are calculated with CHEMKIN subroutines. As a reaction mechanism, a C1-chemistry extracted from GRI-mech3.0 [5] was adopted.

### **Results and Discussions**

Figures 1 and 2 show the time variations of the flame tip position in the case of methane-air flame, and the local burning velocity at the flame tip, respectively. There remains the effect of the initial high temperature spot on the burning velocity just after the ignition. It is noted that the local flame extinction occurs as it propagates along the axis in the case of  $W_0=20$ m/s, which can be recognized as an extinction by the zero burning velocity in Fig. 2. On the other hand, as long as the flame is alive, the local burning velocity does not differ largely between  $W_0=0$ m/s and 10m/s in the steadily propagating period.

Figures 3(a) and 3(b) respectively show the instantaneous distributions of temperature and H atom concentration at t=0.8ms in the case of  $W_0$ =10m/s. Contrary to the hydrogen-air flame [4], the highest temperature point remains at the origin and none of the temperature rise or H atom concentration increase is observed around the tip. This difference is explained by the fact that in the case of lean methane-air flame the thermal-diffusive unbalance is absent, since the Lewis number is almost unity. It is noted that the flame shape is largely stretched in the axial direction, showing that the axial propagation is much faster than the radial propagation. This is because the acceleration in the axial direction by the fluid dynamic mechanism works similarly as the hydrogen-air flame while the radial propagation is done only in the methane-air laminar burning velocity that is much lower than the hydrogen-air flame.



Fig. 1 Propagation of the flame tip on the axis.



Figure 4 shows the time variation of the local flame stretch rate at the tip. Here, flame stretch rate is defined by [6]

$$\kappa = -\mathbf{n}\mathbf{n} : \left(\nabla \mathbf{V}_{fluid}\right) + \nabla \cdot \mathbf{V}_{fluid} + \left(\nabla \cdot \mathbf{n}\right) \left\{ \left(\mathbf{v} - \mathbf{V}_{fluid}\right) \cdot \mathbf{n} \right\},\tag{2}$$

where **n** is the unit vector normal to the flame surface,  $\mathbf{V}_{\text{fluid}}$  is the local flow velocity, and **v** is the local flame propagation velocity. The last term in the right side corresponds to the effect of curvature, and is also plotted in the figure so as to make the contribution of the curvature clear. In the cases of W<sub>0</sub>=0m/s and 10m/s, it is seen that the flame stretch rate at the tip monotonically decreases with time except the initial short period just after the ignition, and the curvature term also decreases with time mainly because of the decrease of its coefficient  $(\mathbf{v} - \mathbf{V}_{fluid}) \cdot \mathbf{n}$ , i.e. the local burning velocity shown in Fig. 2. For W<sub>0</sub>=10m/s,



Fig. 3 Distributions of (a) temperature and (b) H mole fraction ( $W_0=10$ m/s, t=0.8ms).



Fig. 4 Time variations of the flame stretch rate at the flame tip and its curvature term.

except the initial short ignition period the contribution of the curvature term is much smaller than the other terms that correspond to the effect of flow expansion across the flame zone. On the other hand, the time varying behavior of the flame stretch is much different for  $W_0=20$ m/s. That is, the stretch rate after t=0.1msec is almost the same as  $W_0=10$ m/s, which is much smaller than the one expected from the results of  $W_0=0$ m/s and 10m/s. It is interesting to note that the flame extinction occurs suddenly as the flame stretch decreases. At first we expected that the flame stretch at the tip increase as the flame propagates and extinction occur when it reaches a critical value, but this result shows an opposite behavior, which suggests that there exists some strong unsteady effect in causing an extinction of this kind of unsteadily propagating flame.

#### References

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