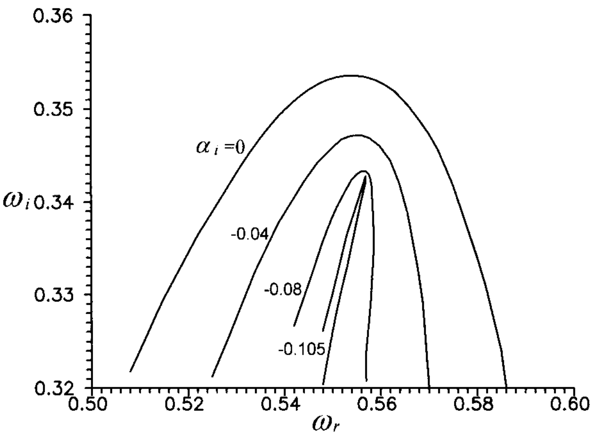


Fig. 3 Unstable branch of α_i contours for a damped bending plate; branch-cut singularity occurs.

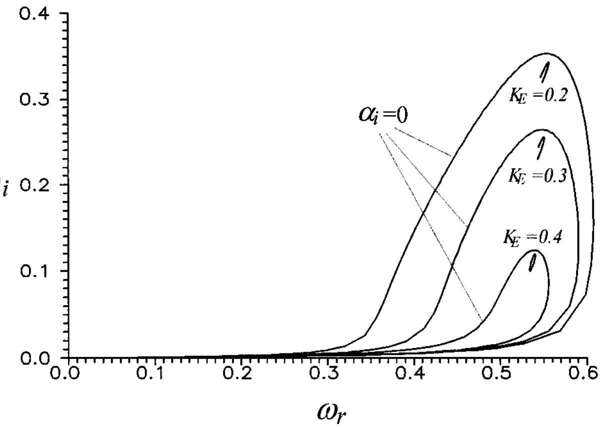


Fig. 4 Unstable branch of α_i contours for a damped bending plate; cusp point moves toward origin as spring stiffness is increased.

by Yeo et al.[6] in the potential flow over a single-layer viscoelastic wall.

On the other hand, no cusp points have been found at the α_i contours for an undamped plate ($d = 0$). All of the $\alpha_i \neq 0$ contours are discontinuous in upper-half plane; ω roots jump to the opposite side of the real axis before the contours form cusps. It, therefore, indicates that a potential flow over an infinitely long undamped bending plate does not admit absolute instability.

A similar situation can also be seen for a membrane ($T \neq 0$, $D = 0$). A potential flow over an undamped membrane admits static temporal instability, whereas a flow over damped membrane admits only an absolute instability mode.

Conclusions

The instability of a uniform potential flow over a plate–spring system is investigated from the time-asymptotic spatio-temporal perspective. The study indicates that uniform potential flow over damped plate–spring system admits only absolute instability modes. Absolute instability sets in as the flow becomes unstable according to normal-mode temporal theory, and the onset of instability for a damped plate (or membrane) is unaffected by the damping level. A potential flow over an undamped plate–spring system does not admit absolute instability.

References

[1]Hansen, R. J., Hunston, D. L., Ni, C. C., and Reischman, M. M., "An Experimental Study of Flow-Generated Waves on a Flexible Surface," *Journal of Sound Vibration*, Vol. 68, No. 2, 1980, pp. 317–334.

[2]Gad-el-Hak, M., Blackwelder, R. F., and Riley, J. J., "On the Interaction of Compliant Coatings with Boundary-Layer Flows," *Journal of Fluid Mechanics*, Vol. 140, 1984, pp. 257–280.

[3]Brazier-Smith, P. R., and Scott, J. F., "Stability of Fluid Flow in the Presence of a Compliant Surface," *Wave Motion*, Vol. 6, No. 3, 1984, pp. 547–562.

[4]Lucey, A. D., and Carpenter, P. W., "A Numerical Simulation of the Interaction of a Compliant Wall and Inviscid Flow," *Journal of Fluid Mechanics*, Vol. 234, 1992, pp. 121–156.

[5]Yeo, K. S., Khoo, B. C., and Zhao, H. Z., "The Absolute Instability of Boundary-Layer Flow Over Viscoelastic Walls," *Theoretical and Computational Fluid Dynamics*, Vol. 8, No. 2, 1996, pp. 237–252.

[6]Yeo, K. S., Khoo, B. C., and Zhao, H. Z., "The Convective and Absolute Instability of Fluid Flow Over Viscoelastic Compliant Layers," *Journal of Sound Vibration*, Vol. 223, No. 3, 1999, pp. 379–398.

[7]Briggs, R. J., *Electron-Stream Interaction with Plamas*, Monograph No. 29, MIT Press. Cambridge, MA, 1964, Chap. 2.

[8]Bers, A., *Handbook of Plasma Physics*, North-Holland, Amsterdam, 1983, Chap. 3.

[9]Kupfer, K., Bers, A., and Ram, A. K., "The Cusp Map in the Complex-Frequency Plane for Absolute Instabilities," *Physics of Fluids*, Vol. 30, No. 10, 1987, pp. 3075–3082.

P. J. Morris
Associate Editor

Effect of Addition of Radicals on Burning Velocity

Kenichi Takita* and Goro Masuya†
Tohoku University, Sendai 980-8579, Japan
Takahiro Sato‡
Hitachi–Zosen Company, Osaka 559-8559, Japan
and
Yiguang Ju§
Tsinghua University,
Beijing 100084, People's Republic of China

Introduction

IT is well known that the addition of radicals to a combustible mixture drastically decreases the ignition delay time and extends the flame holding limit.[1] Therefore, many practical applications, for example, a plasma torch igniter for a scramjet engine[2] or ignition and flame holding by a laser, and enhancement of combustion by a continuous electric discharge,[3] have been developed to enhance ignition and flame stability. Although the effect of the addition of radicals on ignition delay time has been extensively investigated, little attention has been focused on its effect on burning velocity except for the case of flame propagation with oscillation in a closed chamber.[4] From the viewpoint of flame holding, a change in burning velocity by the addition of radicals may possibly play an important role. In this study, the effect of the addition of radicals on burning velocity was investigated using a one-dimensional flame code.

Numerical Method

Burning velocities with the addition of radicals were calculated using the one-dimensional flame code developed by Smooke et al.[5] A reaction model constituted from 15 (O_2, H_2, H_2O, H, HO_2, O, OH, H_2O_2, N_2, N, NO, NO_2, N_2O, NH, and HNO) species and 45 elementary reactions[6–8] was used in the calculations. The code and

Presented as Paper 99-2147 at the 35th Joint Propulsion Conference, Los Angeles, CA, 20–23 June 1999; received 20 April 2000; revision received 20 November 2000; accepted for publication 1 December 2000.

*Assistant Professor, Department of Aeronautics and Space Engineering; takita@cc.mech.tohoku.ac.jp. Member AIAA.

†Professor, Department of Aeronautics and Space Engineering. Senior Member AIAA.

‡Researcher, Department of Environmental System and Technology.

§Professor, Department of Engineering Mechanics.

the reaction model were inspected by Qin et al.,[9] and good agreement with their experimental data of H_2/air flame was obtained for a wide range of equivalence ratios at 0.1 MPa. Radicals were added by force at the inflow boundary, and then their reactions gradually progressed toward the flame surface. Therefore, radicals different from the ones added at the boundary were produced in the preheat zone as secondary products.

Results and Discussion

Figure 1 shows changes in burning velocities with the addition of O radicals to a stoichiometric H_2/air mixture for different inflow temperatures T_0. Basically, an increase in temperature of a mixture causes the burning velocity to increase. When the temperature of the mixture is low, the burning velocity does not change with the addition of O radicals, even with the addition of a volume of 0.1%. This result is in contrast with change in ignition delay time with the addition of radicals. Ignition delay time was reduced by a factor of 2 or more by the addition of a volume of only 0.0001% O radicals.[2] When the temperature of the mixture becomes high, in particular, more than 750 K, the burning velocity increases more than that in the case of no radical addition. Moreover, the increment of the burning velocity depends on the concentrations of radicals. A comparison between the O radicals and H radicals is also shown in Fig. 1. The effect of the addition of H radicals is smaller than that of O radicals for the same ratio of the addition.

Recombination reactions of radicals in the preheat zone of a flame were considered as dominant phenomena to determine the burning velocity with the forced addition of radicals. Therefore, changes in concentrations of radicals in the preheat zone of the flame were investigated for the same three conditions in cases of the addition of O radicals shown in Fig. 1. Figures 2a and 2b show mole fractions of O radicals and H radicals in the preheat zone and the flame region, respectively. The H radicals are produced mainly by the reaction; $O + H_2 \rightarrow H + OH$. The O radicals added to an unburned mixture rapidly decrease toward the flame surface, even in the case that the temperature of the mixture is 800 K. The mole fraction of the O radicals ahead of the flame surface in the case of $C_0 = 0.1\%$ and $T_0 = 500$ K, is almost the same order as in the case of $C_0 = 0.1\%$ and $T_0 = 800$ K, which results in a considerable increase in the burning velocity; however, the burning velocity in the case of $C_0 = 0.1\%$ and $T_0 = 500$ K does not change with the addition of O radicals as shown in Fig. 1. Thus, the concentration of O radicals ahead of the flame surface is not a decisive factor in determination of the burning velocity. On the other hand, the concentration of the H radicals produced by reactions of O radicals in the case of $C_0 = 0.1\%$ and $T_0 = 800$ K is much higher than that in other conditions. In addition, the behaviors of the H radicals, which increase toward the flame surface in the cases of $T_0 = 800$ K, are different from that of the O radicals. Therefore, this result suggests that the dominant factor in determination of the burning velocity is the concentration of H radicals in the preheat zone. However, as shown in Fig. 1, change in the burning velocity resulting from the direct addition of H radical was smaller than that for the addition of O radicals. The total amount of radicals (H, O, OH) or their balance in reactions must be important. The total amount of radicals produced by reactions in the preheat zone in the case of the addition of O radicals is about two times that in the case of the addition of H radicals.

Figure 3 shows a comparison between the addition of N and O radicals for the increase of burning velocity. There is little difference between the N and the O radicals. The reason for this is considered to be that the N radicals react with O_2 and are converted to O radicals in the early stage. In the region of low radical concentration (lower than 0.15%), burning velocities gradually increase with the addition of

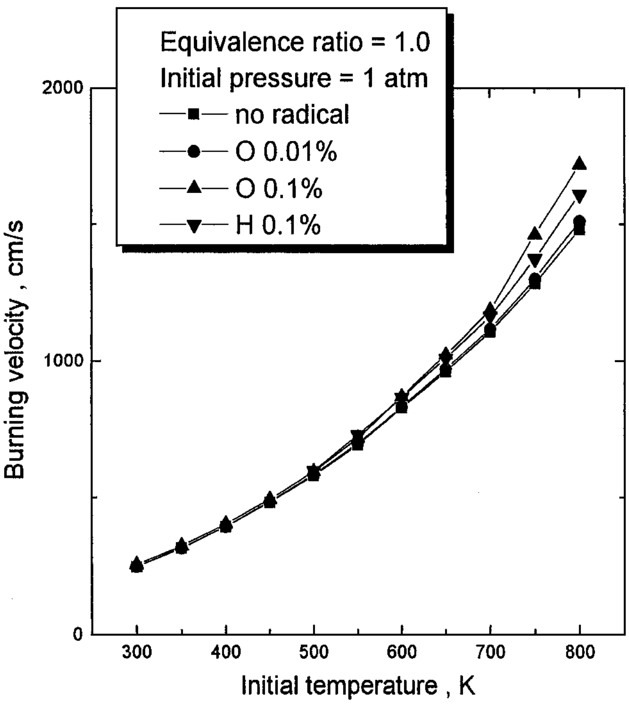
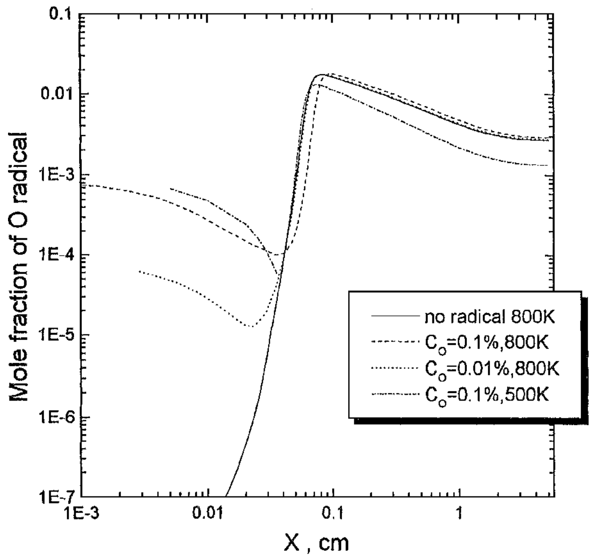
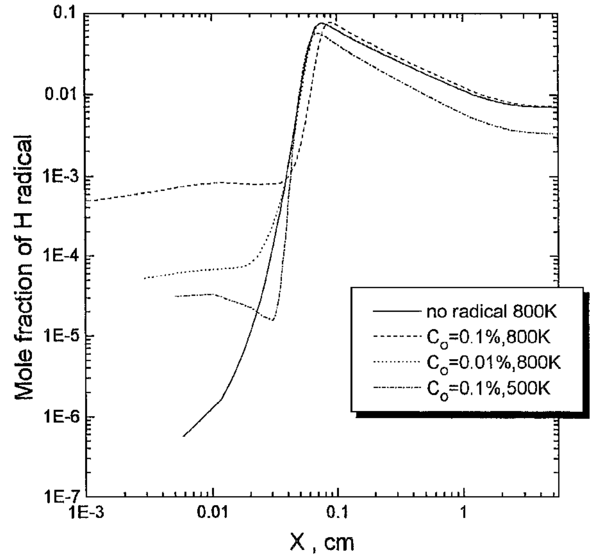


Fig. 1 Changes in burning velocities by addition of radicals O and H for different initial temperature of stoichiometric H_2/air mixture.



a) O radicals



b) H radicals

Fig. 2 Changes in mole fractions of radicals in preheat zone of flame for different initial concentration of radicals and temperature.

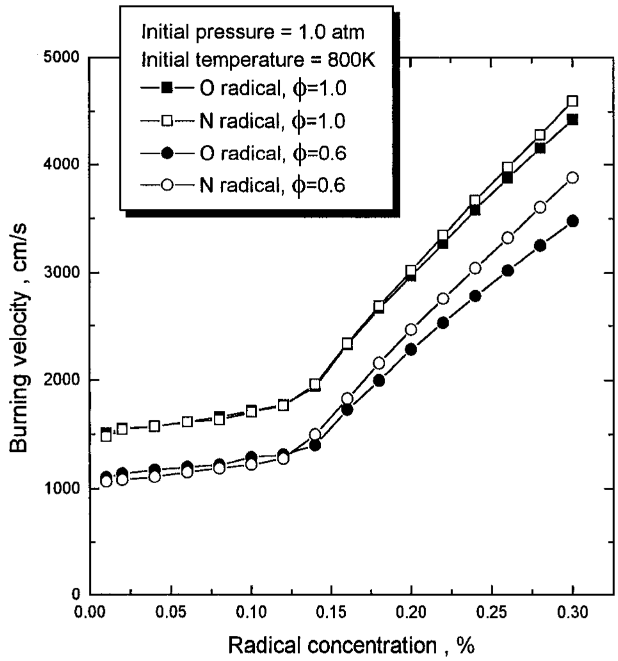


Fig. 3 Dependence of burning velocities on concentration of radicals; $T_0 = 800$ K and $P_0 = 0.1$ MPa.

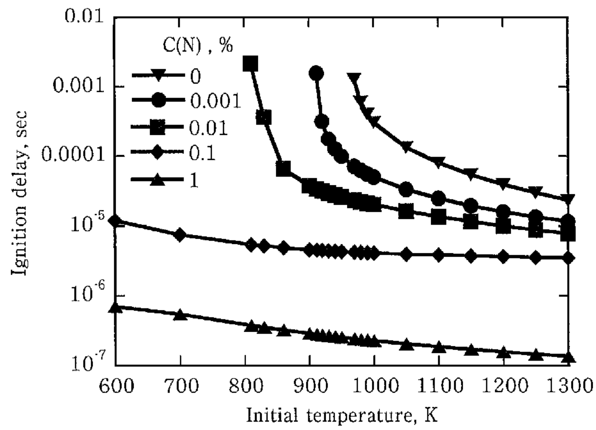


Fig. 4 Dependence of ignition delay time on concentration of radicals for different initial temperature.

radicals. When radical concentration exceeds 0.15%, burning velocities increase steeply with the addition of radicals, and the ratios of this increase are proportional to the radical concentration. This tendency agrees with the experiments of Ohisa et al.[3] They showed that the addition of radicals using a continuous corona electric discharge resulted in an increase of burning velocity and that the increment was proportional to the electric power input that mainly determined the radical concentration. Figure 4 shows the effect of the addition of N radicals on ignition delay of a stoichiometric H_2/air mixture. Note that the ignition limit disappears with the addition of almost the same amount of radicals as the threshhold concentration (about 0.1%) as shown in Fig. 3.

Figure 5 shows the dependence of the burning velocity on the equivalence ratio of the mixture. Burning velocities in the cases of the addition of N radicals increase by almost the same ratio for the whole range of the equivalence ratio as that for the addition of O radicals. In Fig. 5, the predominant radical changes at near stoichiometry of the H_2/air mixture, though its difference is slight. Moreover, the equivalence ratio where the maximum burning velocity is observed shifts to the rich side only for the case of O radicals. These differences between the N and O radicals are caused by reactions of NO produced by the reaction $N + O_2 \rightarrow O + NO$.

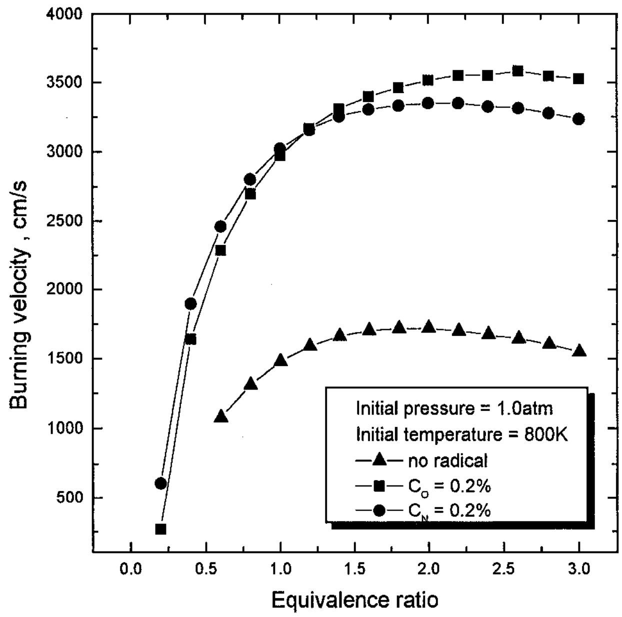


Fig. 5 Dependence of burning velocities on equivalence ratio of H_2/air mixture; $T_0 = 800$ K and $P_0 = 0.1$ MPa.

Conclusions

An increase in burning velocity due to the addition of radicals occurred only under conditions of high temperature (more than 750 K) and high radical concentration (more than about 0.1%), which agrees with the concentration for radical run away in nondimensional analysis. The ratio of the increase in the burning velocity by the addition of radicals was proportional to the radical concentration. In addition, the effect of the addition of N radicals on the burning velocity was almost the same as that of the addition of O radicals. This tendency agreed with the previous analysis[2] on ignition delay time.

References

[1]Harison, A. J., and Weinberg, F. J., "Flame Stabilization by Plasma Jets," *Proceedings of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. A321, 1971, p. 95.

[2]Takita, K., Uemoto, T., Sato, T., Ju, Y., Masuya, G., and Ohwaki, K., "Ignition Characteristics of Plasma Torch for Hydrogen Jet in Airstream," *Journal of Propulsion and Power*, Vol. 16, No. 2, 2000, pp. 227–233.

[3]Ohisa, H., Shirokami, H., and Tachibana, T., "Effect of Radicals on Flame Propagation," *36th Japanese Symposium on Combustion*, 1998, pp. 365–367 (in Japanese).

[4]Wiriyawit, S., and Dabora, E. K., "Modeling the Chemical Effects of Plasma Ignition in One-Dimensional Chamber," *Proceedings of Twentieth Symposium, (International) Combustion*, Combustion Inst., Pittsburgh, PA, 1984, pp. 179–186.

[5]Smooke, M. D., "Solution of Burner-Stabilized Premixed Laminar Flames by Boundary Value Methods," *Journal of Computational Physics*, Vol. 48, 1982, pp. 72–105.

[6]Stahl, G., and Warnatz, J., "Numerical Investigation of Time-Dependent Properties and Extinction of Strained Methane- and Propane-Air Flamelets," *Combustion and Flame*, Vol. 85, 1991, pp. 285–299.

[7]Miller, J. A., and Bowman, C. T., "Mechanism and Modeling of Nitrogen Chemistry in Combustion," *Progress in Energy and Combustion Science*, Vol. 15, 1989, pp. 287–338.

[8]Sanders, J. P. H., "Nonequibrium and Differential Diffusion Effects in Turbulent Hydrogen Diffusion Flames," *Journal of Thermophysics and Heat Transfer*, Vol. 11, No. 3, 1997, pp. 384–390.

[9]Qin, X., Kobayashi, H., and Niioka, T., "Laminar Burning Velocity of Hydrogen–Air Premixed Flames at Elevated Pressure," *Experimental Thermal and Fluid Science*, Vol. 21, 2000, pp. 58–63.

S. K. Aggarwal
Associate Editor