Effect of Radiation Reabsorption on Laminar Burning Velocity of Methane Premixed Flame Containing with Steam and Carbon Dioxide*

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Flame properties in the ambience of steam and carbon dioxide are complicated because of the third-body effect and radiation reabsorption. Thus, we performed detailed chemical kinetic calculations that include the effect of radiation reabsorption to clarify the premixed laminar flame speed of such a mixture, being one of the most important properties for controlling combustion. Pressure was varied up to 5.0 MPa to simulate the 1 700°C class combined gas turbine system. The results show a marked increase in laminar burning velocity by considering radiation reabsorption. Laminar burning velocity was increased up to 150% in cases of methane-oxygen and steam or carbon dioxide mixtures. It was found that the preheating of the upstream, unburned mixture caused this increase. The influence of radiation reabsorption was much larger in the case of lower pressures.

Key Words: Gas Turbine, Premixed Combustion, Radiative Gas, Flame, Radiation Reabsorption, Burning Velocity

1. Introduction

Although a high turbine inlet temperature (TIT) improves thermal efficiency in an open combined power generation system, it causes the system to emit a large amount of NOx. Thus, the CH_4/O_2 firing closed gas turbine system with steam recirculation as working fluid[1] or AHAT (Advanced Humid Air Turbine) system have been noted because of its high efficiency and markedly small amount of NOx emission.

There are a large number of reports about the effect of radiation heat losses from burnt high-temperature gas and a number of reports about the effect of radiation reabsorption by the unburnt radiative gas such as steam and CO_2[2],[3]. However, the effects of elevated pressures and temperatures on laminar burning velocity S_u and maximum flame temperature in radiative gas surroundings have not been fully clarified, especially under the steam condition. The aim of this report is to clarify the combustion properties of CH_4/O_2 flames at elevated pressures (up to 5.0 MPa), elevated temperatures (up to 773 K) and CO_2 or steam surroundings (0 vol% to 91 vol%). We calculated laminar burning velocity under many of such conditions to compare the results between adiabatic conditions and radiation reabsorption conditions. The concentrations of radiative third-body species such as CO_2 and steam were widely varied to investigate the effects of radiation properties.

2. Numerical Models

In this study, one-dimensional laminar premixed CH_4/O_2 flames with radiative and nonradiative dilution gases were considered. The mathematical models were packages found in Refs. (4) and (5). The calculation code was based on PREMIX code[6],[7] in CHEMKIN-II[4],[5], and GRI-Mech 3.0[8] was employed as a reaction database. The radiative effects arise through the source term in the energy equation. The discrete ordinate method and statistical narrow band (SNB)[9] were used as the modeling scheme and radiative property, respectively. Spectral properties were decided from a database by Soufiani[10]. The number of bands and the resolution were 367 and 25 cm^{-1}, respectively. The transmissivity was estimated

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for temperatures and wave numbers of 300 K – 2 900 K and 150 cm^{-1} – 9 300 cm^{-1}, respectively. H_2O, CO_2 and CO were considered as radiative gases. CH_4 radiation was not included because the necessary spectral data were not available. Radiation heat flux is shown as follows.

$$\frac{\partial q_{r,x}}{\partial x} = \nabla \cdot q_{r,x} = \int_0^\infty \nabla \cdot q_{r\lambda,x} d\lambda = \int_0^\infty 4\pi a_\lambda (I_{\lambda b} - G_\lambda) d\lambda \tag{1}$$

Here, q_r, a and $I_{\lambda b}$ demote the radiation heat flux, absorption coefficient and spectral blackbody intensity, respectively. G_λ is the spectral average intensity shown as follows.

$$G_\lambda = \frac{1}{4\pi} \int_{w=4\pi} I_\lambda(w) dw \tag{2}$$

3. Effect of Radiation Reabsorption

To clarify the effect of radiation reabsorption on laminar flame speed S_u, S_u values under adiabatic conditions and SNB conditions for various equivalence ratio ϕ and elevated-pressure cases were compared and are shown in Fig. 1. Radiation reabsorption increases laminar flame speed in all cases. It was considered that radiation reabsorption preheats the upstream premixed gases and increases S_u. Thus, the temperature distributions of adiabatic and SNB conditions are compared and shown in Fig. 2. The SNB model predicts high temperatures of upstream gases brought about by radiation reabsorption, and low temperatures of the downstream gases brought about by radiation heat loss. The elevation of pressure slightly increases flame temperature but suppresses the effect in the SNB model. It was considered that the decrease in optical flame thickness and preheating zone area is brought about by the elevated pressure causes radiation reabsorption. Furthermore, a relatively larger mass flux in cases of elevated pressure may cause a relatively smaller radiative heat flux and less radiation.

4. Effect of CO_2 Dilution

To clarify the effect of CO_2 dilution on the S_u of $CH_4/O_2/CO_2$ flames, CO_2 concentration $X_{CO2}/(X_{CO2} + X_{O2})$ was varied from 0.73 to 0.82 at equilibrium and room temperature conditions. Results are shown in Fig. 3. As increase in CO_2 concentration causes a decrease in S_u in all cases. S_u variation reported by Ruan et al.[2] obtained using the model of Giovangigli[11] is also shown in this figure (marked by x). It has an inflection point at a dilution ratio of 0.8 and is related to the flammability limit caused by radiation heat loss. On the other hand, there are no inflection points under all the pressure conditions considered in this study, although the calculations were a slightly unstable. Under elevated-pressure conditions, a thinner flame causes a decrease in radiation, so the combustion property may approach that of adiabatic conditions as shown in this figure. This may be caused by the increase in radiation reabsorption, which is caused by the relatively short distance between the isothermally conditioned nozzle and the flame.

Under an elevated-pressure condition (1.0 MPa), although the values of S_u are smaller than those of the normal-pressure condition, radiation reabsorption causes an increase in S_u. Ruan suggested that the effects of radiation reabsorption effects on S_u and flammability limits increase at elevated pressures of up to 0.5 MPa. On the other hand, under higher-elevated-pressure conditions (3.0 MPa, 5.0 MPa), the difference between the results of adiabatic conditions and SNB model conditions is very small.

Such an effect of radiation on S_u may be caused by optical flame thickness in a high-pressure environment. A smaller flame thickness causes a smaller radiating vol-

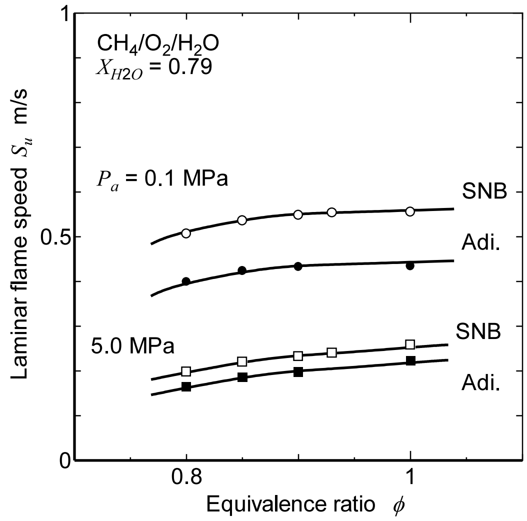

Fig. 1 Effect of radiation reabsorption on laminar flame speed

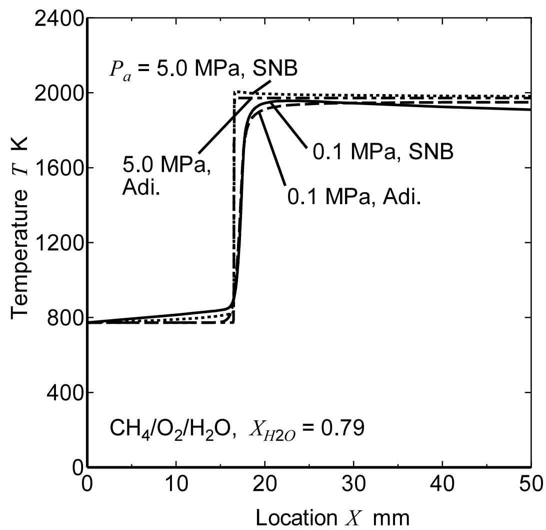

Fig. 2 Effect of radiation reabsorption on temperature distribution

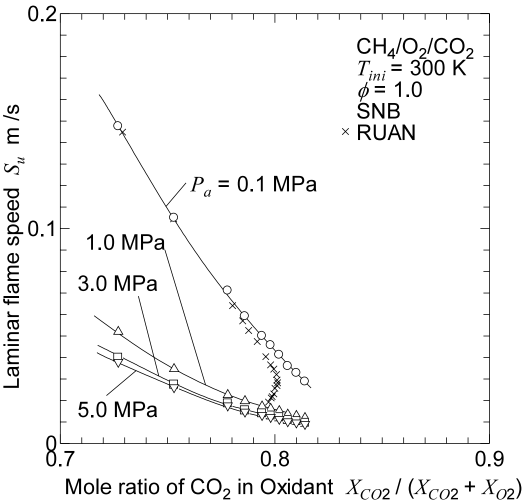

Fig. 3 Effects of CO_2 concentration and ambient pressure on S_u of $CH_4/O_2/CO_2$ flame

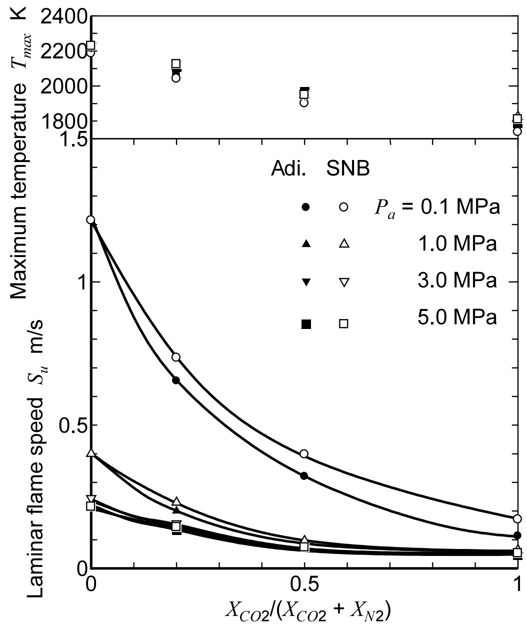

Fig. 4 Effect of radiation reabsorption on S_u of $CH_4/O_2/CO_2$ flame

ume, so the effects of radiation are smaller than that in the normal-pressure case. The compact reacting zone may cause the disappearance of the inflection point of S_u in this study as shown in Fig. 3. It was found that the effect of CO_2 concentration on S_u is strongly affected by the ambient pressure and the radiation model. Thus, more detailed research under conditions in the vicinity of 1.0 MPa should be needed.

5. Effects of Radiation Properties

The effect of CO_2 concentration on the S_u of the stoichiometric $CH_4/O_2/N_2$ flame is calculated by replacing the N_2 of this flame with CO_2 and shown in Fig. 4 as a function of CO_2 dilution ratio.

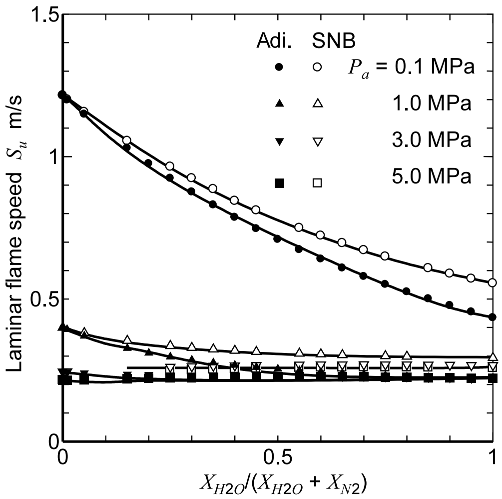

Fig. 5 Effect of radiation reabsorption on S_u of $CH_4/O_2/H_2O$ flame

An increase in CO_2 dilution ratio causes monotonic decreases in S_u and maximum flame temperature in the cases of adiabatic conditions and SNB conditions. The increasing rate of S_u caused by the application of the SNM model was not affected by CO_2 replacement ratio.

To compare the radiative properties between CO_2 and H_2O, the effects of H_2O dilution on the S_u of $CH_4/O_2/N_2$ flames were calculated and are shown in Fig. 5. In the cases of low ambient pressures, the results of adiabatic conditions and SNB conditions show a monotonic decrease in S_u with increasing H_2O dilution ratio, and applying the SNB model causes an increase in laminar flame speed, which is the same as the result in Fig. 4. However, the S_u increasing ratio caused by radiation reabsorption increases with H_2O replacement ratio, and it was found that the effect of H_2O replacement ratio on S_u is very small under high-pressure conditions.

6. Comparison between Effects of CO_2 and H_2O

To compare the effects of radiative properties on S_u, the concentrations of CO_2 and H_2O were widely varied. In this calculation, the CH_4 and O_2 concentrations are 7% and 14%, respectively, and the ratio of CO_2 concentration to residual gas concentration $X_{CO2}/(X_{CO2}+X_{H2O})$ is varied from 0% to 100%. Results are shown in Fig. 6. As in Fig. 1, applying the SNB model causes an increase in S_u in all cases, and an increase in CO_2 concentration causes a decrease in S_u. The ratio of S_u obtained using the SNB model to that obtained using the adiabatic model was also calculated to clarify the effect of radiation and is shown in the same figure. It was found that the effect of radiation reabsorption by CO_2 gas is about 20% larger than that of radiation reabsorption by H_2O gas.

To clarify the radiative effects of H_2O on combustion properties, the laminar flame speed S_u and maximum flame temperature of $CH_4/O_2/H_2O$ flames under equilib-

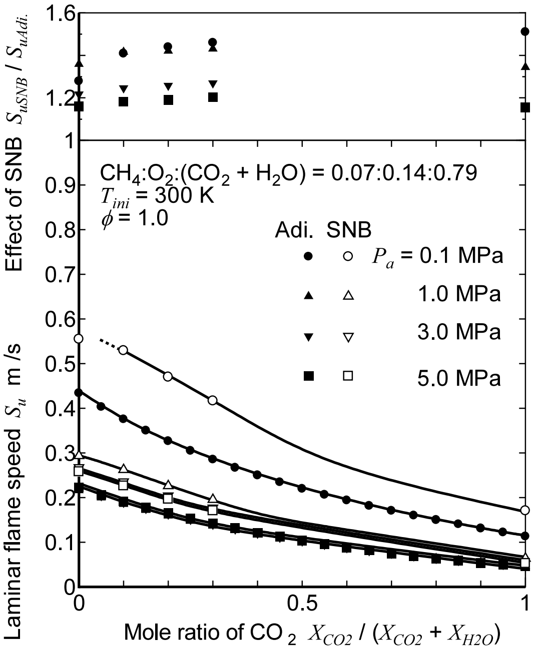

Fig. 6 Effect of third-body composition on S_u

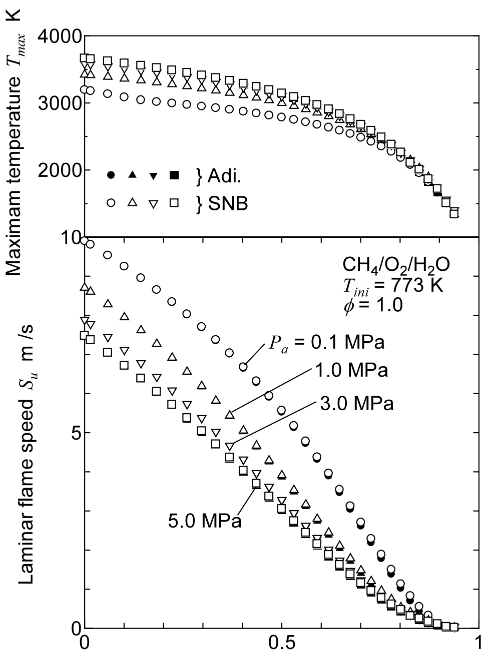

Fig. 7 Effect of H_2O concentration on S_u

rium conditions were calculated and are shown in Fig. 7 as a function of the mole fraction of H_2O, X_{H2O}. X_{H2O} is varied from 0 to 0.91. The radiation effects appear under high-H_2O-concentration conditions (over 0.7). In such cases, laminar flame speed and maximum flame temperature are higher than those under adiabatic conditions. The preheating phenomena in the upstream region are caused by the radiation reabsorption of the radiative species in the premixed gas.

Under high-H_2O-concentration conditions (over

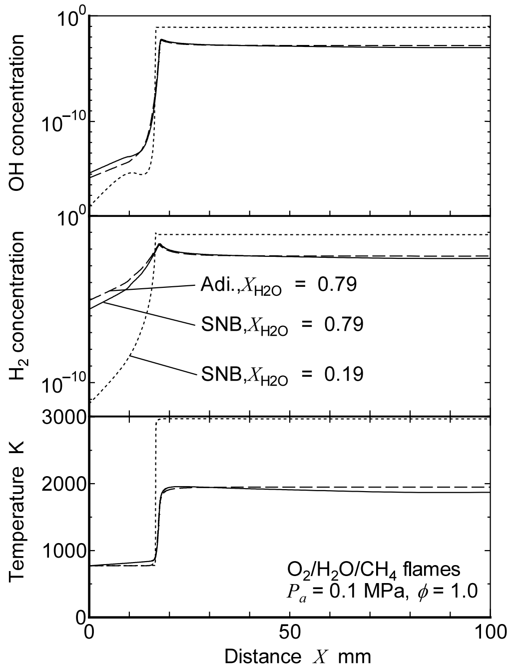

Fig. 8 Effect of H_2O concentration on flame structure

0.85), laminar flame speed (less than 0.1 m/s) and maximum flame temperature (less than 1 000 K) took very low values. These results should be useful in clarifying the extinction mechanism of humidity combustors, flame control in microgravity experiments and other phenomena.

Another important effect of the preheating of upstream gas with H_2O is the steam reformation reaction from H_2O/CH_4 to CO/H_2. Figure 8 shows the concentration distribution of intermediate species for flames of various H_2O concentrations and an adiabatic flame. Not so specific effects of radiation were observed. In the cases of high H_2O concentrations under low-laminar-flame-speed conditions, H_2 has a markedly high concentration in the upstream region of the flame and contributes to stabilizing the flame.

7. Conclusions

The effects of radiation on premixed gas flames were studied using a detailed emission reabsorption model for H_2O, CO and CO_2. The results can be summarized as follows:

(1) Radiation reabsorption can increase laminar flame speed considerably, and the effects of radiation strongly depend on pressure and radiation properties.

(2) Consideration of radiation reabsorption is necessary to calculate the laminar flame speed of flames with radiative gases such as H_2O and CO_2 at slightly elevated pressures (less than 3.0 MPa). However, the effect of radiation is not so large in cases of highly elevated pressures (> 3.0 MPa), because of the thinner radiative zone.

(3) Radiation reabsorption affects the upstream unburnt mixture, so the distance between the flame reacting zone and the wall, such as a fuel nozzle or a combustor wall, greatly influences the flame properties. Thus, the effects of radiation should be considered in designing the combustor for gas turbine systems with high-concentration radiative gases.

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