Characteristics of Combustion of a Rich-Lean Flame Burner with Controlled Boundary Zone between Rich and Lean Flames

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1 Introduction

The rich-lean combustion mode as shown in Fig. 1 has recently been adopted in burners for domestic hot water generators and room heaters. In the rich-lean combustion mode, the rich and lean flames are arranged such that a lean flame is stabilized by two surrounding rich flames which are more stable than the lean flame. The burner has a quadruple structure that consists of pathways for a lean flame mixture, an air or a fuel-air mixture supplied to the boundary zone, a rich flame mixture and a secondary air-flow. The rich-lean combustion mode is superior in terms of its low emission of NOx because of the very lean burning throughout the whole of the burner and is an excellent combustion technique for application in practical combustors. However, a very complicated combustion field is established in a rich-lean flame burner because the heat and radicals transferred from the rich flame to the lean flame and the flow field are significantly affected by the characteristics of the rich and lean flames. The characteristics of combustion and flame stabilization also depend on the velocity and air ratio of the rich and lean mixtures as well as the structure of the boundary region between the rich and lean flames. A few studies have reported that the behavior of the flame base in the boundary region between the rich and lean flames is very important for flame stabilization in the rich-lean flame burner [1-4] and that a rich-lean flame burner with a controlled boundary zone has superior characteristics of flame stabilization, a high turn-down ratio (TDR) and low emissions of NOx and CO compared with conventional rich-lean flame burners [5-7]. However, the structure of the flame base between the rich and lean flames is very complicated and appears to have a triple flame structure [8,9]. It is very difficult to examine the structure of the flame base between rich and lean flames and to clarify the mechanism leading to reduced emissions of NOx and CO. In this study, the effects of an air or a fuel-air mixture supplied to the boundary region between rich and lean flames on the characteristics of the combustion and emission of NO and CO and flame stabilization are numerically examined in order to develop a new type of rich-lean flame burner with a high TDR and thermal efficiency and low emissions of NOx and CO.

2 Analytical model

Figure 2 gives the analytical model and boundary conditions of planar, two-dimensional rich and lean flames. The calculation was performed over half the area of the burner because of its symmetry with respect to the central axis of the pathway of the lean flame mixture. A Cartesian coordinate system is taken such that x is the principal flow direction, y is the transverse direction and the origin is at the center of the burner inlet plane, while (v_x, v_y) designates the velocities in the (x, y) directions, respectively. Methane and air were used as the fuel and oxidizer, respectively. The air ratio and velocities of the mixture flowing in the pathways of the lean flame, the boundary zone, the rich flame

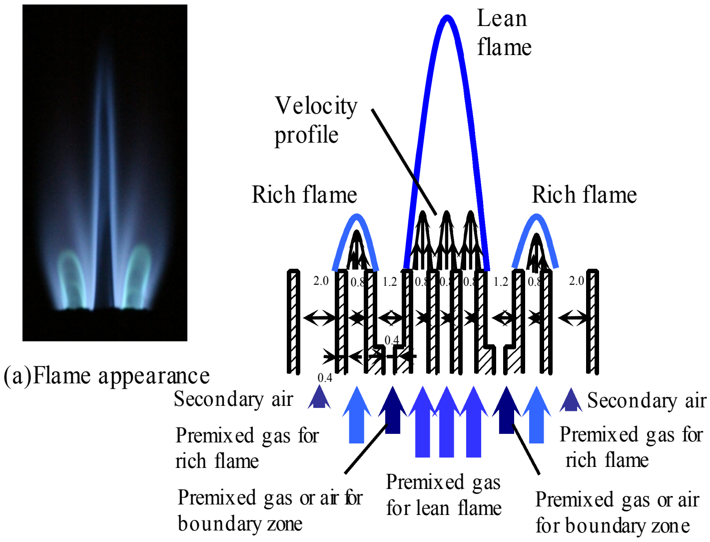


Figure 1. Rich-lean flame burner with controlled boundary zone between rich and lean flames.

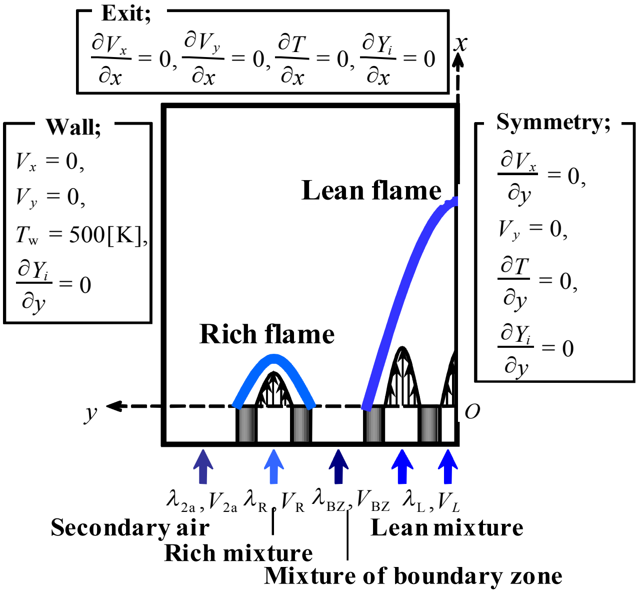
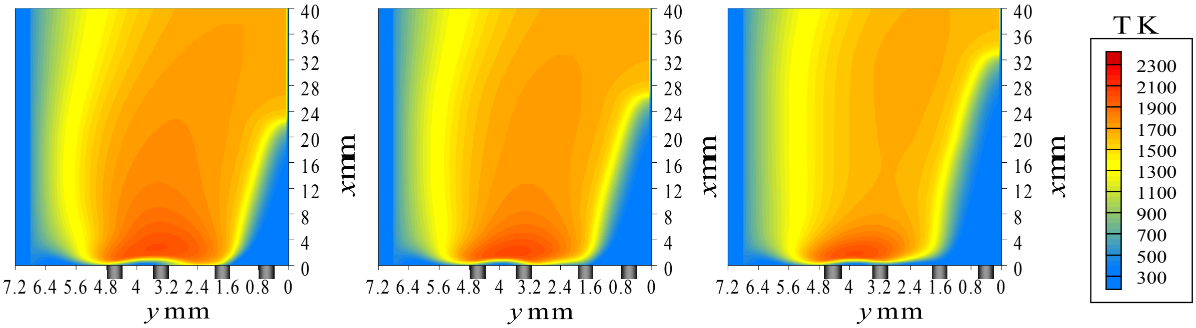


Figure 2. Analytical model and boundary conditions.

and the secondary air-flow are λ_L, λ_{BZ}, λ_R and λ_{2a}, and V_L, V_{BZ}, V_R and V_{2a}, respectively. The velocity profiles at the burner inlet are assumed to be those of a Poiseulle flow. The governing equations in the conventional analysis are used [10, 11]. Transport properties are estimated by applying the simplified transport model [12], and thermodynamic properties are obtained from the CHEMKIN database [13]. For the chemical reactions, GRI-mech3.0 is used to calculate the flame structure [14] .

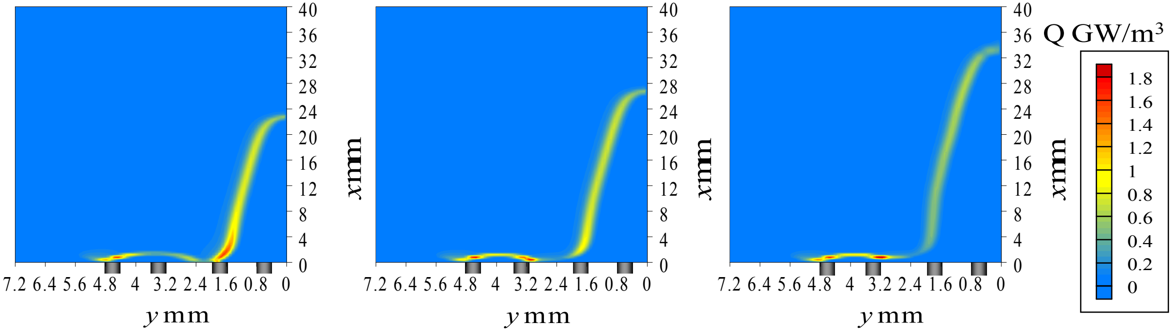
3 Results and Discussion

Figure 3 shows the flame structures of the rich- lean flames with a controlled boundary zone between the rich and lean flames. When air is supplied to the boundary region, the length of the lean flame is increased as shown in the temperature profiles. This is because the mixture at the lean flame is diluted by the air supplied to the boundary zone and the burning velocity of the lean flame is



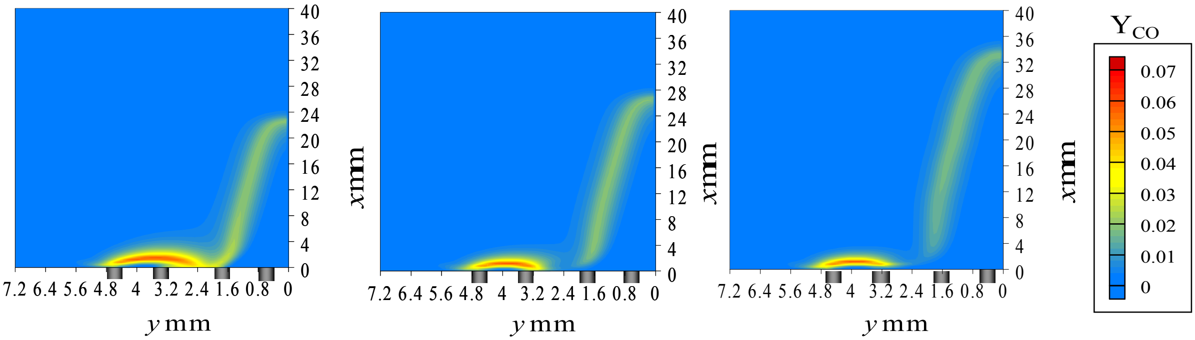
(a) V_{BZ}=0 m/s (b) V_{BZ}=0.2 m/s (c) V_{BZ}=0.4 m/s

(a) Temperature profiles



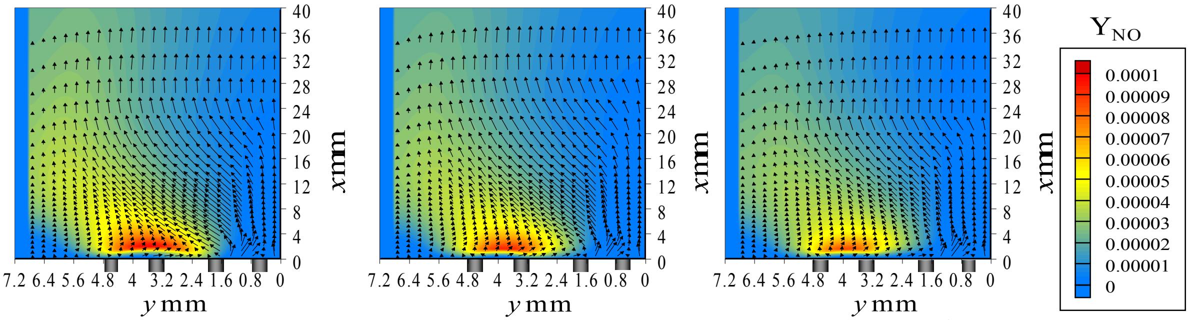
(a) V_{BZ}=0 m/s (b) V_{BZ}=0.2 m/s (c) V_{BZ}=0.4 m/s

(b) Heat release rate profiles



(a) V_{BZ}=0 m/s (b) V_{BZ}=0.2 m/s (c) V_{BZ}=0.4 m/s

(c) CO profiles



(a) V_{BZ}=0 m/s (b) V_{BZ}=0.2 m/s (c) V_{BZ}=0.4 m/s

(d) NO profiles

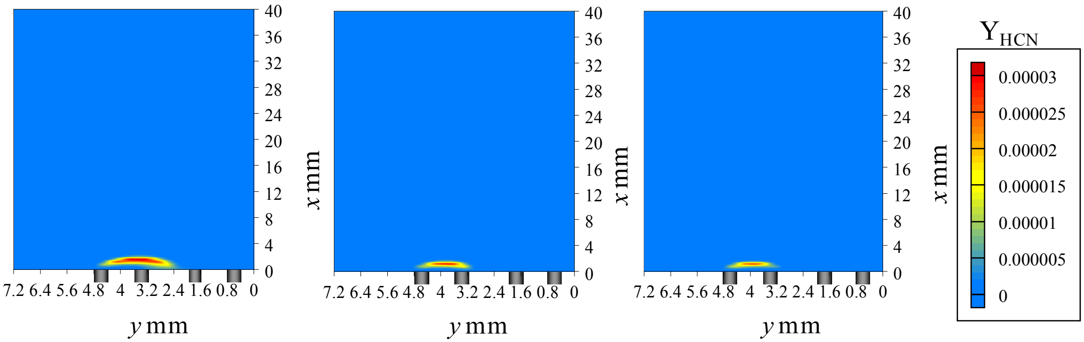
Figure 3. Flame structures of rich-lean flames with controlled boundary zone between rich and lean flames

($\lambda_{BZ}=\infty$(air), λ_L=1.6, V_L=3.4 m/s, λ_R=0.5, V_R=0.5 m/s, $\lambda_{2a}=\infty$(air),V_{2a}=0.23 m/s).

decreased. The area of high temperature from 1900 to 2100 K, which is higher than the adiabatic temperature at the air ratio $\lambda_R = 0.5$ of the rich mixture, expands behind the rich flame. This is because the surplus fuel at a high temperature discharged from the rich flame and the surplus air discharged from the lean flame burn in this area. When air is supplied to the boundary zone, the area of high temperature downstream of the boundary zone is reduced and the temperature of the burned gas in the whole downstream area decreases. This is because the temperature of the lean flame is decreased owing to the increase in the air ratio of the lean flame and the burned gas behind the boundary zone is cooled by the air supplied to the boundary zone.

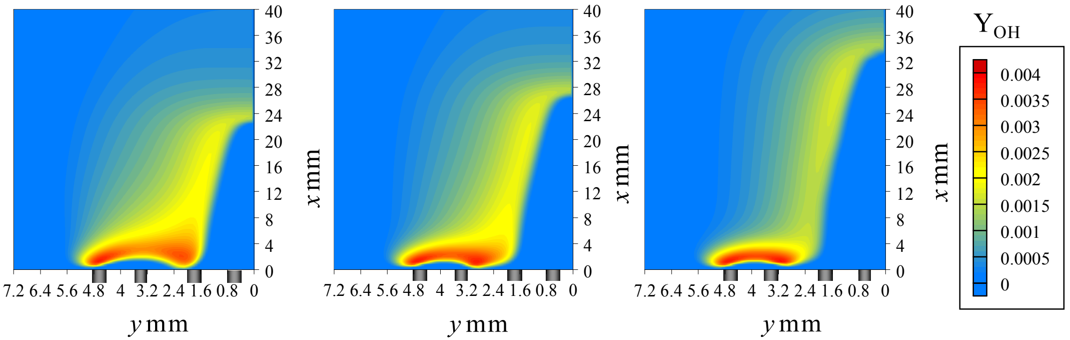
The flame base of the rich flame is not anchored at the burner rim as shown in the heat release rate profiles and is incorporated with the flame base of the lean flame. An area with a high heat release rate appears in the flame base of the lean flame, which strengthens the flame base for blow-off of the flame. When air is supplied to the boundary zone, the flame bases of the lean and rich flames are anchored at each rim of the burner inlet and a heat release rate with a flat profile, which was observed in a previous experimental study [5], appears at the exit of the boundary zone. The flame becomes more stable upon establishing a flat profile for its heat release rate, However, the heat release rate is reduced at the flame base of the lean flame when the air velocity is increased (V_{BZ} = 0.4 m/s) and the flame becomes less stable. This means that there is an optimum velocity of the air supplied to the boundary zone, which was measured in the experimental study [5].

When air is supplied to the boundary zone, the area at the rich flame with a high concentration of CO is reduced owing to the relaxation of incomplete combustion at the rich flame and the promotion of CO oxidation behind the rich flame as shown in the CO concentration profiles. A high concentration of NO consisting of prompt NO and thermal NO appears at the rich flame as shown in the NO concentration profiles. The concentration of NO in the lean flame is low. This means that a small amount of thermal NO is produced by the Zeldovich mechanism at the lean flame. Therefore, it is important to optimize the burning ratio of the rich and lean flames and the air ratio of the rich flame



(a) V_{BZ}=0 m/s (b) V_{BZ}=0.2 m/s (c) V_{BZ}=0.4 m/s

(a) HCN profiles



(a) V_{BZ}=0 m/s (b) V_{BZ}=0.2 m/s (c) V_{BZ}=0.4 m/s

(b) OH profiles

Figure 4. Concentration profiles of HCN and OH.

to reduce NO emission from the rich-lean flame burner. When air is supplied to the boundary zone, the area with a high concentration of NO is reduced. This is because the amount of prompt NO is reduced owing to the increase in the air ratio at the rich flame, and that of thermal NO is also decreased as a result of the decrease in the area with a high temperature downstream of the rich flame.

Figure 4-(a) shows profiles of HCN concentration, which strongly affects the production of prompt NO. A high concentration of HCN appears at the rich flame, thus, the production reaction of prompt NO occurs through the intermediates of HCN, NH and N produced by the reactions $CH + N_2 = HCN + N$ and $CH_2 + N_2 = HCN + NH$ [15]. On the other hand, an area with a high concentration of OH appears at the outer part of the rich flame and behind the lean flame as shown in Fig. 4-(b). In this area, thermal NO is produced by the Zeldovich's mechanism [16]. The area with a high concentration of OH is reduced when air is supplied.

4 Conclusions

The effects of an air or a fuel-air mixture supplied to the boundary zone on the characteristics of the combustion and emissions of NO and CO were numerically investigated.

(1) When air is supplied to the boundary zone, the formation of prompt NO is reduced owing to the marked decrease in HCN concentration at the rich flame due to diluting the rich mixture with the air. The formation of thermal NO is also decreased by a decrease in the temperature of the burned gas due to the air supplied to the boundary. The oxidation reaction of CO is promoted by the air supplied to the boundary zone and the area of high CO concentration is reduced. The characteristics of NO and CO emissions for the rich-lean flame burner with the controlled boundary zone are superior to those for the conventional rich-lean flame burner.

(2) The NO concentration exhausted from the burner is significantly affected by the amount of NO produced at the rich flame. It is important to optimize the burning ratio of the rich and lean flames and the air ratio of the rich flame to reduce NO emission from the rich-lean flame burner.

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