The study of the fluctuations of scalar fields and flames for turbulent counterflow nonpremixed flames

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Introduction

Turbulent nonpremixed flames have a great interest for many researchers, because it plays an important role in the practical combustion systems. However, the process of turbulent nonpremixed combustion is quite complicated. Therefore, it is difficult to understand the properties of turbulent nonpremixed combustion completely. An important theory of flame structure for turbulent nonpremixed flames has been described by Peters [1] as the laminar diffusion flamelet model. According to the concept, the extinction of turbulent nonpremixed flames in the flamelet would occur when the mean scalar dissipation rate, evaluated at the location of the mean stoichiometric mixture fraction, exceeded a critical value, which was equal to the scalar dissipation rate at the extinction of laminar counterflow diffusion flame. And it showed the importance of the measurement of scalar fields for turbulent nonpremixed flame.

Authors have studied about the turbulent nonpremixed flames formed in a counterflow, focusing on the extinction phenomena[2,3]. In particular, in order to visualize the turbulent effect on the macroscopic flame structure(assumed as the diffusion region) and behavior(wrinkling of flames), the laser tomographic technique has been used. From the results, the reasonable agreement between the theoretical prediction of laminar diffusion flamelet model and the analysis of the scalar dissipation rate based on experimentally observed data was obtained. Though a lot of studies have been done for turbulent nonpremixed flames, the understanding of the relationship between flow field and the scalar field of flames is not completed yet. Therefore, in the present study, the investigations of fluctuations of scalar fields and flames for turbulent nonpremixed flames formed in a counterflow will be performed based on the simple measurements of velocity field and laser tomographic technique.

Experimental Setup and Method

The detailed description of experimental setup and method have been reported previously (Kitajima et al, [2]). The experimental apparatus consists of opposed unit nozzle-type two burners, which have the same construction. The upper side burner blows air as the oxidizer-stream, and the bottom side burner blows methane diluted by nitrogen as the fuel-stream. In order to generate the turbulence in flows, perforated, plates can be installed at the exit of converging nozzles in each burner. Straight circular tubes, 24 mm in diameter and 100 mm in length, are set downstream of the perforated plates to develop the turbulence generated by perforated plates. The visualization of flame structures and behavior has been done by laser tomographic technique. Silicon oil droplets (boiling point=300°C) are employed as the particles for Mie scattering. The flow velocity of air-stream and fuel-steram are set equal ($U_o = U_f$). The fuel volume fraction of fuel-stream (Xf) is 50%. The ratio of flow momentum is kept equal ($\rho_{air}\bar{U}_o^2:\rho_{fuel}\bar{U}_f^{\ 2}$ = 1.00 : 0.761□. The distance of the burner exits L is set 16 mm for stable flames and is varied from 10 to 15.82 mm for extinction limits. Initial characteristics of flows for every perforated plate, which are measured 1mm downstream at the center of the air-stream burner exit as the condition of a free stream, are shown in Table 1. At each turbulent flow condition, more than 100pictures are taken with a 35 mm still camera.

Results and Discussion

Figure 1 and 2 show the axial velocity and velocity fluctuation profiles at various initial turbulent conditions along the mean stagnation stream line measured by one-component forward scattered LDV system. From the profiles of the velocity fluctuations, it can be found that the interaction of turbulence between the incident flows in a counterflow is slight. And the turbulent properties of incident flows may be clearly divided by the boundary of each incident flow in a counterflow. It is known that the axial flame location of laminar nonpremixed flame formed in a counterflow is determined by the stoichiometric mixture fraction (Sung et al, [4]). In the present results, the stoichiometric mixture fraction is kept for all the turbulent conditions (Zst = 0.138) and the mean locations of flames and the boundaries of diffusion regions(described in next sentences) at every turbulent condition almost corresponded to the laminar case(Air: P0 Fuel: P0). Therefore, although the existence of turbulence, the mean velocity fields of turbulent counterflow in the present study are similar to the laminar counterflow field, that is known as the typical characteristics of turbulent counterflow field.

Figure 3 shows the schematic of measurement method of axial location of the air side boundary of diffusion region Y_o, that of fuel side boundary Y_f, and the flame location of Y_{flame}. The detailed description of the definition of assumed diffusion regions visualized by laser tomography was reported in previous work [2]. In the physical space, Y_o and Y_f indicates the isothermal line of 300□C. And it is considered that the fluctuations of Y_o and Y_f are caused by the fluctuations of temperature (one of the scalar property) field. Therefore, the fluctuations of Y_o, Y_f, and Y_{flame} are measured in the present study. Figure 4 and 5 show the probability distribution of observed axial locations of Y_o, Y_f, and Y_{flame} along the mean stagnation stream line for the same experimental conditions as shown in Fig. 1 and 2 respectively. It is found that the distributions of probability of Y_o, Y_f, and Y_{flame} are almost similar, and the distributions are not biased around the mean location for every condition. It can be considered that the fluctuations of temperature field agree well with the fluctuations of nonpremixed flames. Authors previously reported that the distances between Y_o and Y_f (it is assumed as the width of the diffusion region, I) were slightly influenced by flow turbulence. However, the quantitative value of RMS fluctuation of I is much smaller than that of Y_o, Y_f, and Y_{flame} and the significance of effects of the fluctuation of I on the extinction was not observed. On the other hand, the fluctuations of flames estimated by RMS value of the Y_{flame} showed a significance for extinction with the analysis of the scalar dissipation rates [4]. The importance of consideration of macroscopic behavior such as the fluctuations of the flow boundary along the mean stagnation streamline for the counterglow nonpremixed flames have been discussed in detail by Sardi [5], which was based on the displacement of the mean mixture fraction traverse of nonreactive opposed jet flow.

From considerations mentioned above, it is concluded that the fluctuations of temperature field agree well with the fluctuations of nonpremixed flame, at least for the present experimental condition such as the turbulent counterflow nonpremixed flame.

Acknowledgment

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References

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[4] Sung, C. J., Kistler, J. S., Nishioka, M., and Law, C. K., Combust. Flame, 105:pp.189-201, 1996.

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Table 1 Initial flow conditions at the burner exit

	Hole diameter (mm)	Hole distance (mm)	$\bar{U}$ (m/s)	u' (m/s)	u' / $\bar{U}$	ϑ_t (ms)	l (mm)
P0	-	-		0.02	0.017	-	-
P1	7.0	9.0	1.1	0.07	0.070	9.7	9.7
P2	6.0	8.0		0.08	0.081	3.6	3.6

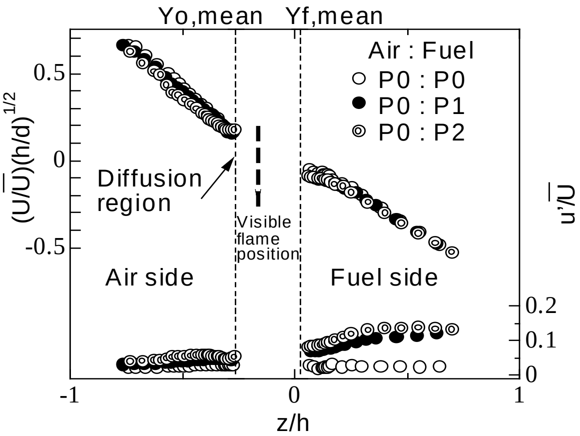


Figure 1 Nondimensional velocity field with nonpremixed flames

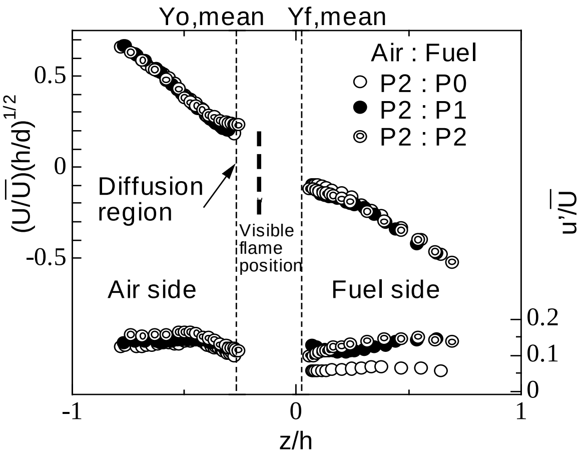


Figure 2 Nondimensional velocity field with nonpremixed flames

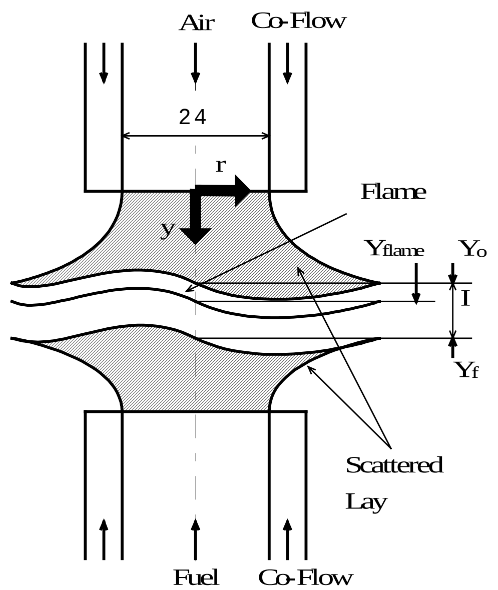
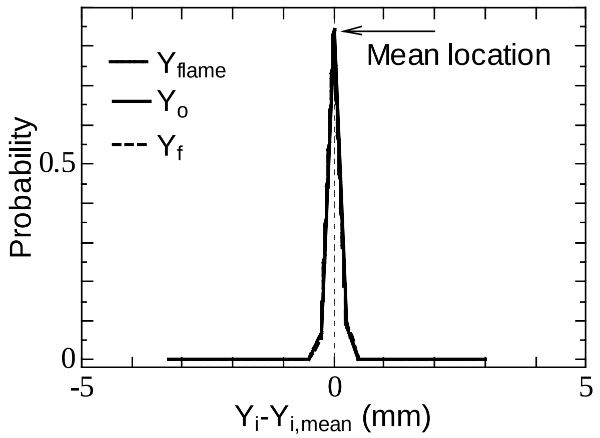
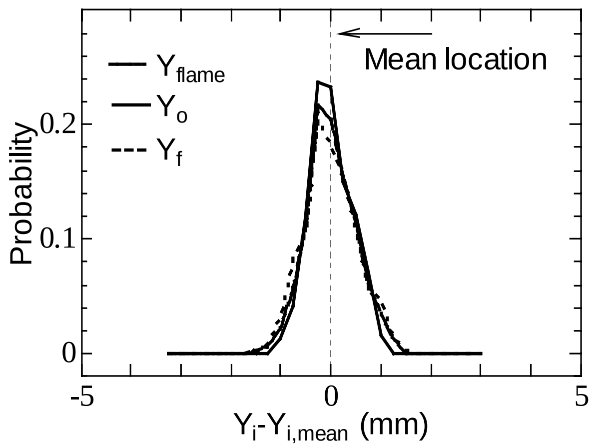


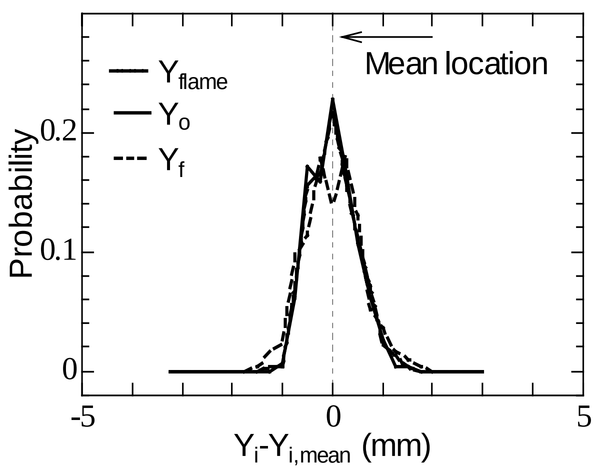
Figure 3 Schematic of the measurement of diffusion region



(a) Air:P0 Fuel:P0

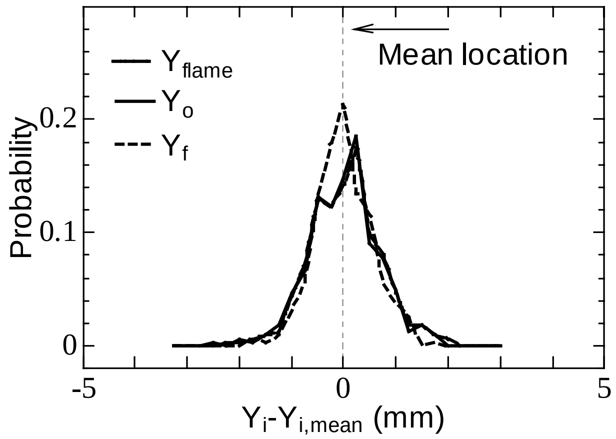


(b) Air:P0 Fuel:P1

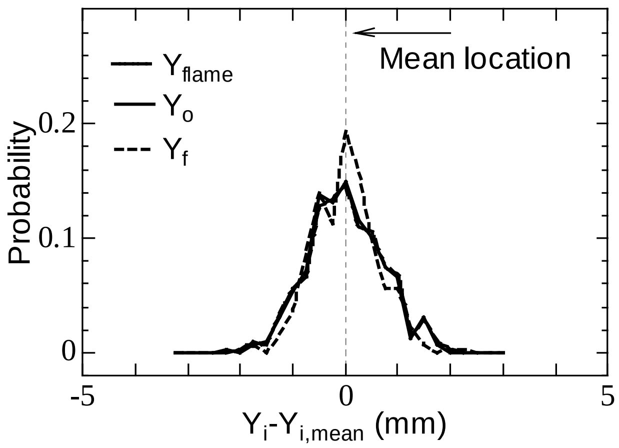


(c) Air:P0 Fuel:P2

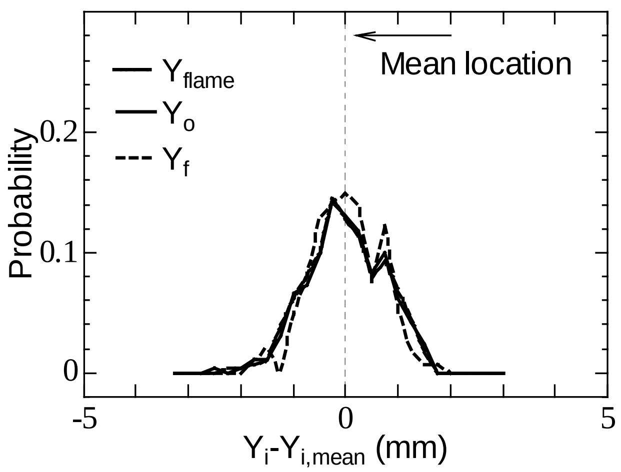
Figure 4 Probability distribution of Y_o, Y_f, and Y_{flame}



(a) Air:P2 Fuel:P0



(b) Air:P2 Fuel:P1



(c) Air:P2 Fuel:P2

Figure 5 Probability distribution of Y_o, Y_f, and Y_{flame}