FLAME STABILIZATION AND NO$_X$ REDUCTION IN A NON-PREMIXED BURNER WITH SAWTOOTH MIXER

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Abstract

Sawtooth mixing device used in a non-premixed burner is evaluated for flame stabilization and NOx reduction accomplished by the forced mixing of the fuel and air due to the streamwise vortices. Three geometries with blade deflection angles of 0, 20, 40 degrees (SM0, SM20, SM40) are tested. Methane is delivered through the fuel jet pipe and air passes through the co-flow annulus. The flame mode changes (attached flame, lifted flame and extinction) against the fuel flow speed are measured, and the stability diagram is drawn. Moreover, by traversing thermocouple and sampling probe in the flame, the distribution of temperature, NOx and O_2 mole fractions are measured. In the case of SM0, the flame has the least tendency to lift and in the case of SM40 the flame has the least tendency to extinct. With the change in blade angle, flame shape, flame stabilization, the distribution of temperature and NOx mole fractions are changed considerably.

1 Introduction

In recent years, the global environment is increasingly drawn notice of, and the governmental regulation to reduce NOx emission from the dominant combustion sources is more strictly enforced. Lean-Premixed-Prevaporized (LPP) combustion is one of techniques to reduce NOx emissions for industrial gas turbine combustors. Usage of this LPP technique restricts the increase in thermal NOx by making fuel lean condition and good mixing. However, it is actually difficult to make fuel so lean for the aircraft engines because wide-range combustion conditions (for example, rapid acceleration and deceleration) are needed. In addition, this technique has the problem about safety, for example, flashback and blow-off etc. Therefore non-premixed combustion is fundamentally adopted in combustors for the aircraft engines.

Although its mechanism is unexplained and discussion is continuing now [1-3], a present understanding of non-premixed flame stabilization is that partial premixing condition and synergistic interactions of various reaction zones play key role [4]. Also a large number of studies have been made on the static mixers for supersonic combustion so far, but little is known about the static mixers for subsonic combustion system that are used in practical combustors.

The purpose of the present experimental study is to evaluate the flame stabilization accomplished by the forced mixing of the fuel and air due to the streamwise vortices downstream of the Sawtooth Mixer (SM), which also gives rise to the partial premixing zone as the core of flame stabilization. The NOx reduction accomplished by decreased temperature due to the existence of the premixing zone between fuel and air is evaluated in such burners.

Four sets of experiments are conducted to examine the effects of the sawtooth mixer as the mixing device on the flame stabilization and NOx reduction. At first blow off conditions of three sawtooth mixers are examined with change in the fuel-air ratio, fuel velocity and air velocity (air: <5[m/s], fuel: <12[m/s]). Secondly the NOx mole fractions in the flame for three sawtooth mixers are measured. Thirdly the temperatures that are closely related to the generation of NOx are measured. Fourthly the mole fractions of O_2 that is a reactant of NOx formation are measured.

2 Experimental setup

2.1 Co-axial burner and Sawtooth Mixer

Schematic diagrams of co-axial burner and Sawtooth Mixer (SM) are presented in Figs. 1 and 2. Methane is supplied from the center pipe of the burner, surrounded by the air from the annular pipe. To study the influence of SM geometry on the flame stabilization and NOx reduction, three geometries with blade deflection angles of 0 degree (SM0), 20 degrees (SM20) and 40 degrees (SM40) are tested. These angles are chosen in order to take a look at the effects of the separation of flow and the existence of slit of sawtooth mixer. That is to say, 20 degrees is chosen as no separation case, 40 degrees is chosen as the separation case, and 0 degrees is selected because it is considered the effect of the slit may possibly be more important than the blade angle. Hereafter the outward deflecting blade is called ‘OB’, the inward deflecting blade is called ‘IB’ and the location between blades is called ‘slit’. These geometries are shown in Fig. 3 and Table 1.

2.2 Blow off condition measurement

While keeping on constant air flow speed, the fuel flow speed is changed, and the fuel flow speed is measured when flame mode changes. Three characteristic flame modes, i.e., attached flame, lifted flame and extinction, are observed, and the stability diagram [5,6] is plotted as Fig. 5. Here lifted flame is defined as the flame when flame base locates away from the burner rim perfectly. Experiments are conducted for both increasing-fuel and decreasing-fuel velocity cases because of the existence of hysteresis.

2.3 Temperature measurement and NOx and O_2 mole fraction measurement

The temperature field is obtained by using a hand-made Pt-Rh 40:20 thermocouple with a diameter of 100 μm following Fristrom’s text book [7]. The NOx and O_2 mole fraction fields are obtained by the gas sampling. The combustion gases from the flame for the measurement of NOx and O_2 are sampled using a water-hot quarts glass probe with a top diameter of 300 μm. A dry combustion gas via a dehydrator is delivered to the gas analyzer (Shimadzu, NOA-7000). Measurement conditions are fuel velocity of 1.65[m/s], and air velocity of 0.27[m/s] and 0.54[m/s]. However, in the case of SM40, air velocity of 0.54[m/s] is not included because flame is lifted.

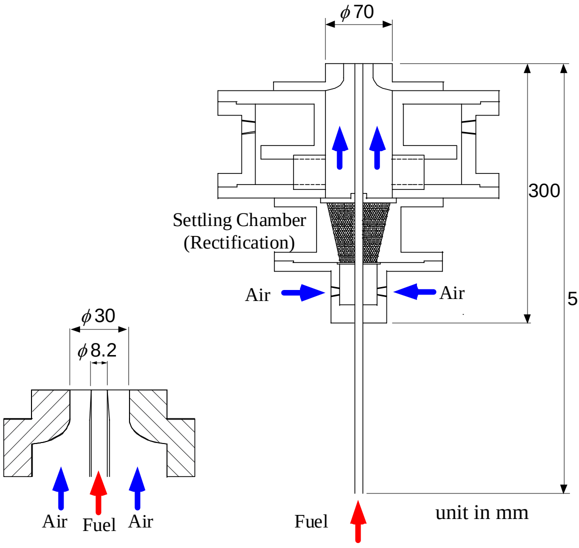


Fig. 1. A Schematic View of Co-axial Burner

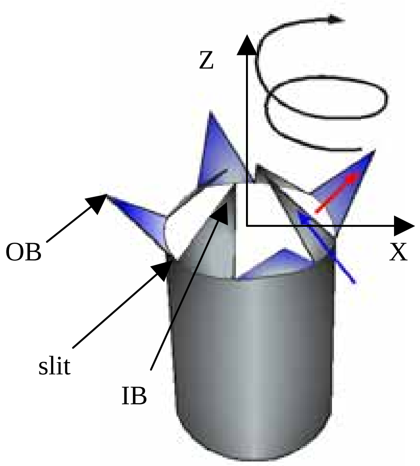


Fig. 2. A Schematic Diagram of Sawtooth Mixer

Table. 1. Design Parameters of Sawtooth Mixers

Name	λ(mm)	h(mm)	l(mm)	α(deg)
SM0	7.85	0	4	0
SM20	7.85	2.91	4	20
SM40	7.85	6.71	4	40

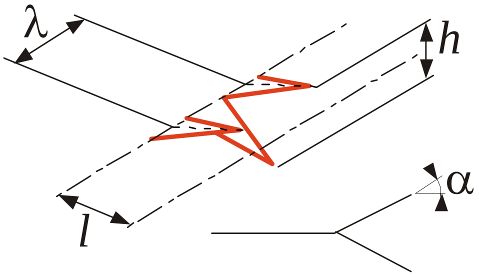


Fig. 3. Design Parameters of Sawtooth Mixers

3 Results and discussion

3.1 Flame stabilization

SM changes the flame shape. The characteristic lifted flame with SM40 is shown in Fig. 4. The flame with SM40 has the structure with four sub flames at OB and main flame at the center due to the high blade angle. Fig. 5 is the stability diagram. The attached-flame and extinction domains become smaller, in the decreasing-fuel-velocity cases than in the increasing-fuel-velocity cases.

In the case of SM0, the flame is most stable at the burner rim compared with other SMs, that is, the flame has the least tendency to lift. This phenomenon is considered to be observed because the colder wall, which extracts heat, is small, the strain velocity is small and fuel and air are mixed well at the slit in the case of SM0. When fuel velocity is small enough, the flame is observed between blades.

In the case of SM40, the flame has the least tendency to extinct. The lifted flame is observed at higher air velocity (4～5[m/s]). In addition, the lift-off height is low compared with other SMs. This observation suggests enhanced turbulent mixing downstream by largely deflected SM40. Moreover in the cases of SM20 and SM40, characteristics of stabilization are changed by change in the fuel velocity (U_f) and air velocity (U_a).

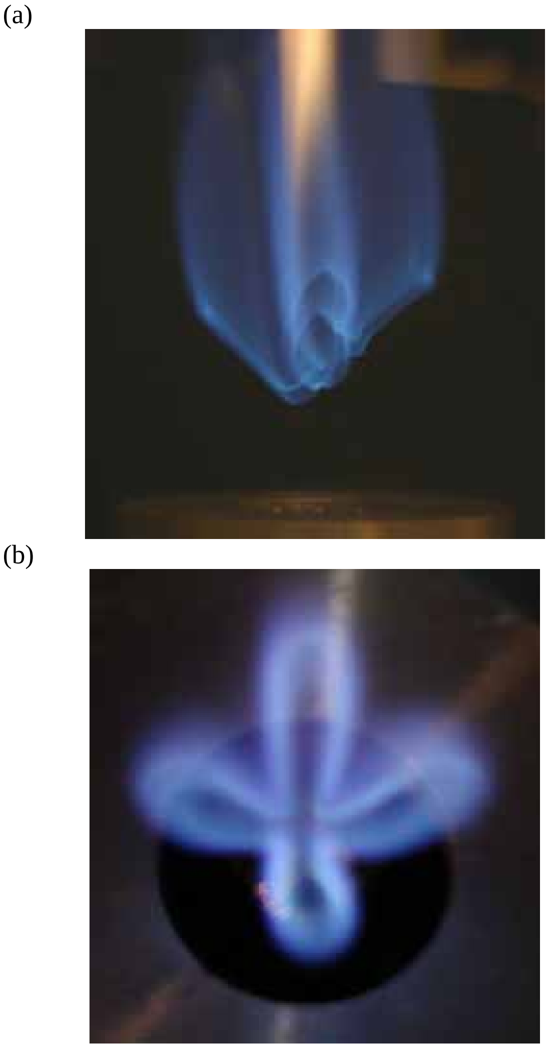


Fig. 4. Direct Photograph of Characteristic Flames with SM40 ((a) side view, (b) top view)

3.2 Temperature measurement

Figure. 6 shows the variation of maximum temperature in the axial cross-section, and Fig. 8 shows the temperature contours for the case of no SM and SM40. In Fig. 8, the high temperature zone over 1600[K] is indicated because NOx emission increases considerably over 1700[K].

When the air velocity is increased from 0.27[m/s] to 0.54[m/s], the temperature remains high at the flame base in the case of SM0, whereas it is reduced in the case of other SMs. This is due to mixing caused by small vortex at the slit. By this mixing the chemical reaction is enhanced at the burner orifice. It is considered this mixing at the slit has an effect to the flame stabilization as well.

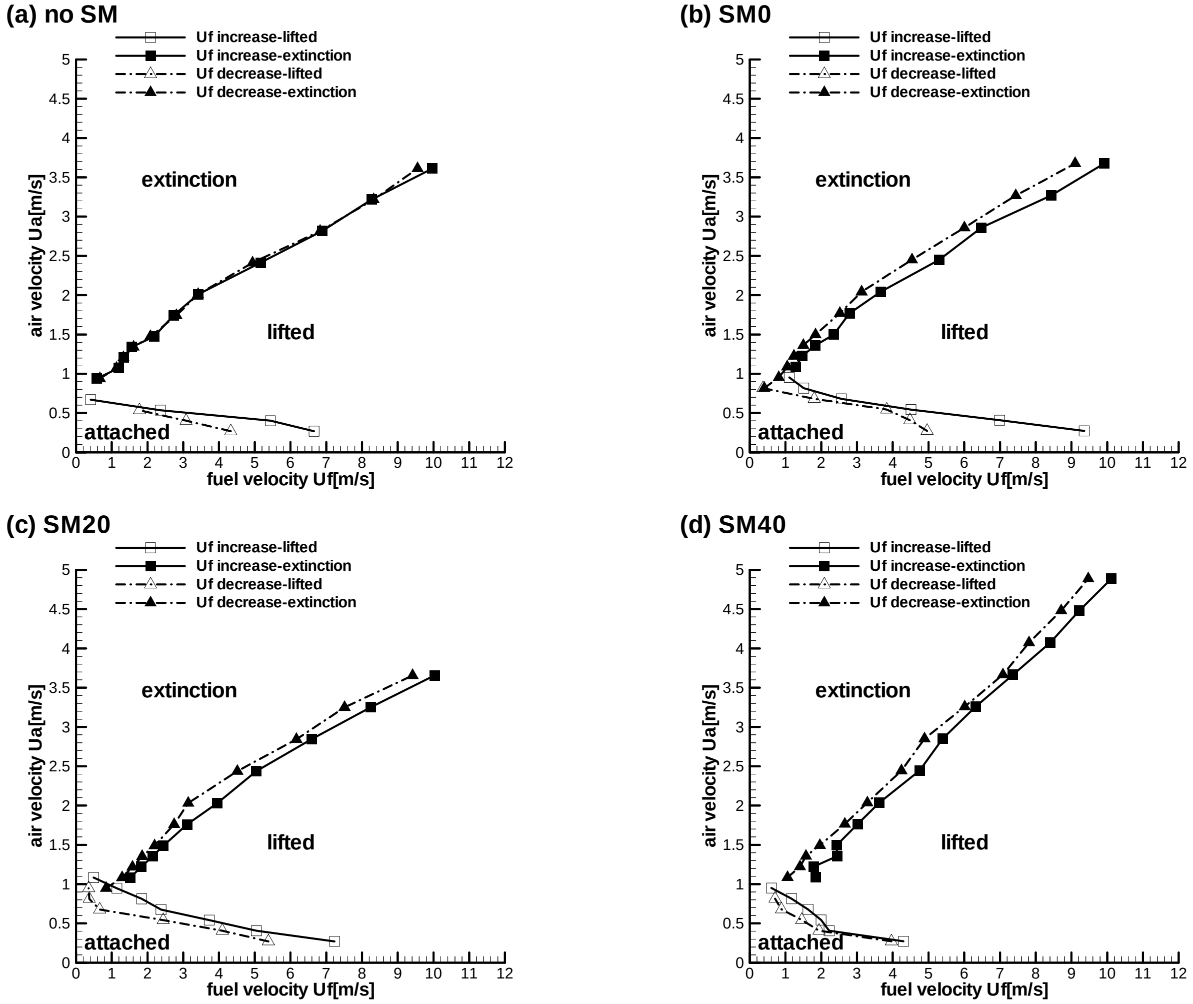


Fig. 5. Stability Diagrams

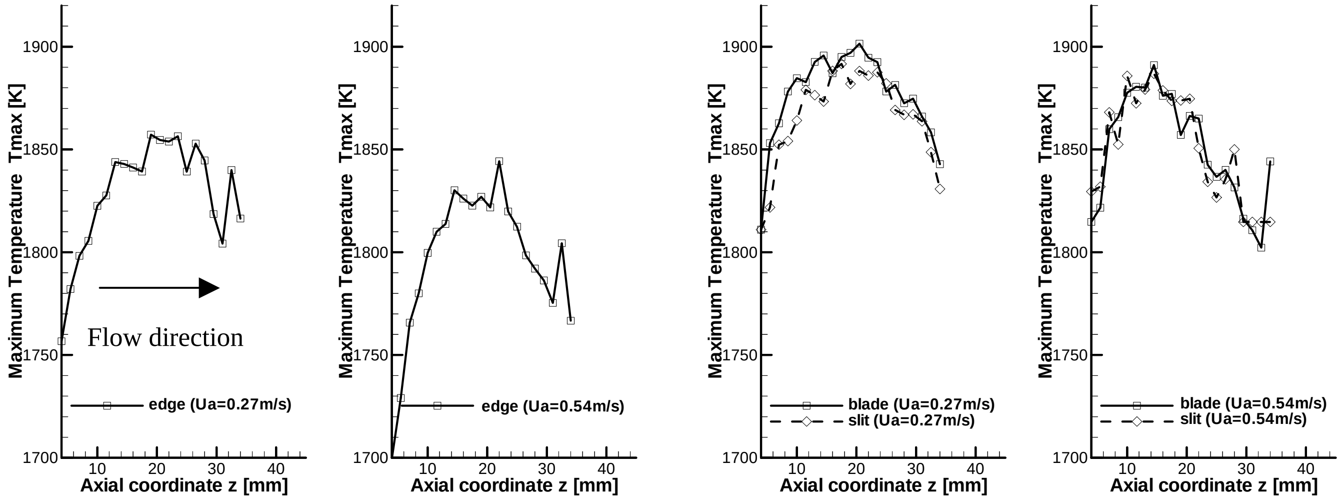
In the cases of SM20 and SM40, the highest temperature is observed just downstream of IB and lowest temperature is observed just downstream of OB. Also, at OB the flame becomes thick to the side of air flow. This is due to difference in the local combustion conditions, that is, at IB slightly fuel-rich combustion occurs because air flow is entrained to fuel flow, and at OB, on the contrary, fuel-lean combustion occurs because fuel flow penetrates into the air flow. Moreover, the other reasons for the existence of high temperature region at IB are the effect of radiation from characteristic flame structure, and the existence of flame around the center flame. In the case of SM40, temperature fluctuates considerably at the downstream regions. This is due probably to turbulent flow generated by SM40.

In the case of SM40 the region where the temperature is higher than 600[K] is widest of all cases. This is probably due to the change in flame structure by SM40, that is, the flame becomes thick at OB and thin at IB. Moreover it is considered that combustion is promoted by radiation from characteristic flame structure.

3.3 NOx mole fraction measurement

Figure. 7 shows the variation of maximum NOx mole fraction in the cross-section, and Fig. 8 shows NOx mole fraction contours for the cases of no SM and SM40. Measured NOx mole fraction isn’t corrected by O_2 mole fraction because O_2 mole fraction largely changes in the flame.

In all cases, when air velocity is increased from 0.27[m/s] to 0.54[m/s], NOx mole fraction decreases at the flame base. This is due to the


(a) no SM (b) SM0

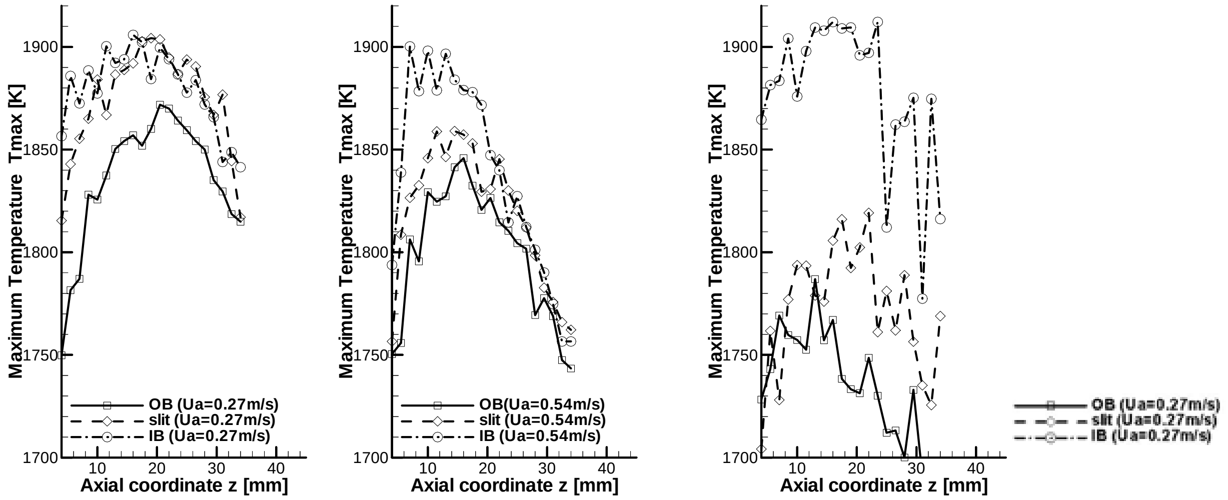

(c) SM20 (d) SM40

Fig. 6. Maximum Temperature in the Axial Direction

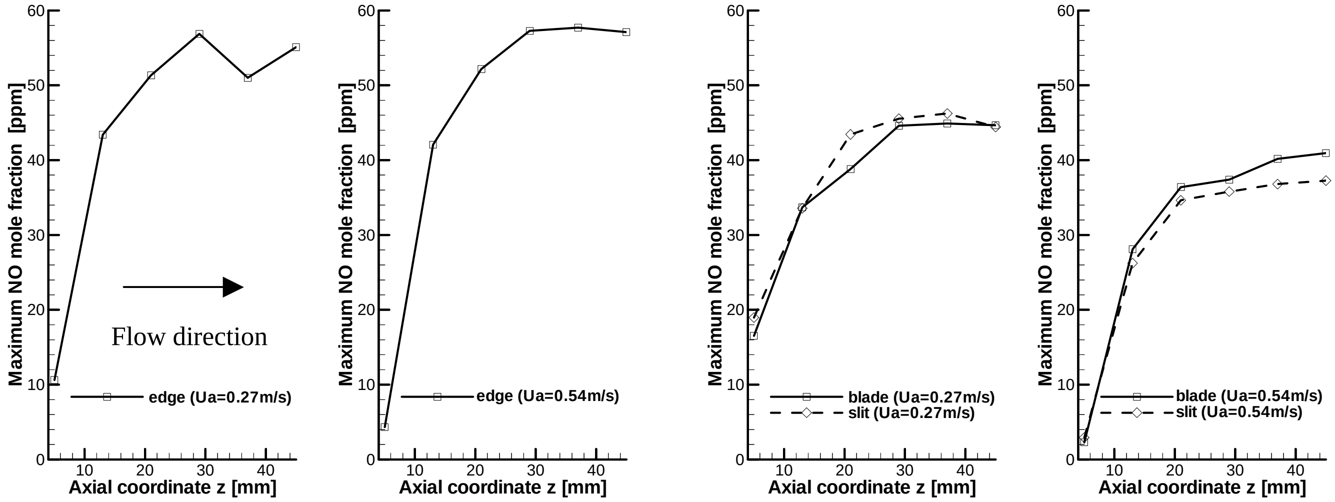
decrease of Zeldovich NO by the temperature decrease at the flame base as is shown in Fig. 6. In the case of SM0, although, temperature at the flame base does not change so much, NOx mole fraction decreases, because fuel and air are mixed well at the slit. In the case of no SM, maximum NOx mole fraction is almost same, except for the flame base when air velocity is increased, but in the case of SM20, maximum NOx mole fraction is decreased. This decrease of NOx mole fraction is considered to be attributed to the increase of entrainment of air flow, in addition to the decrease of Zeldovich NO by the temperature decrease.

In the case of SM40, highest NOx mole fractions are observed at OB and lowest NOx mole fractions are observed at IB. This reversal correspondence between the NOx fraction and temperature at IB is considered to occur because O_2 that plays an important role in NOx production exists sufficiently at OB and O_2 exists in small fraction at IB. Moreover the NOx mole fraction tends to decrease as one goes downstream for the case of SM40. This is due probably to (1) the enhanced entrainment by the presence of SM40, which causes the inverse pressure gradient in this middle stream region followed by the inward (toward the axis) air flow at the downstream and (2) the reduced Zeldovich NO by the temperature decrease downstream.

Next, three SMs cases are compared with

(a) no SM

(b) SM0



(c) SM20

(d) SM40

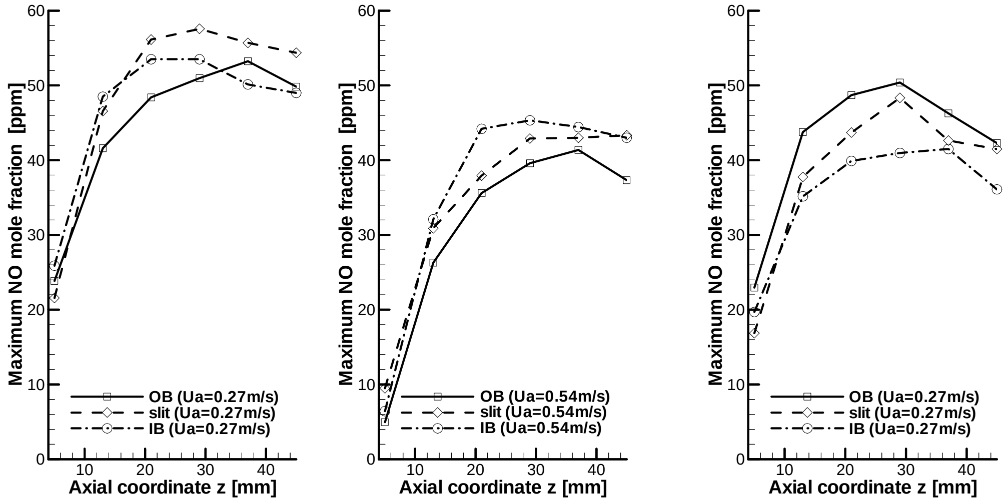
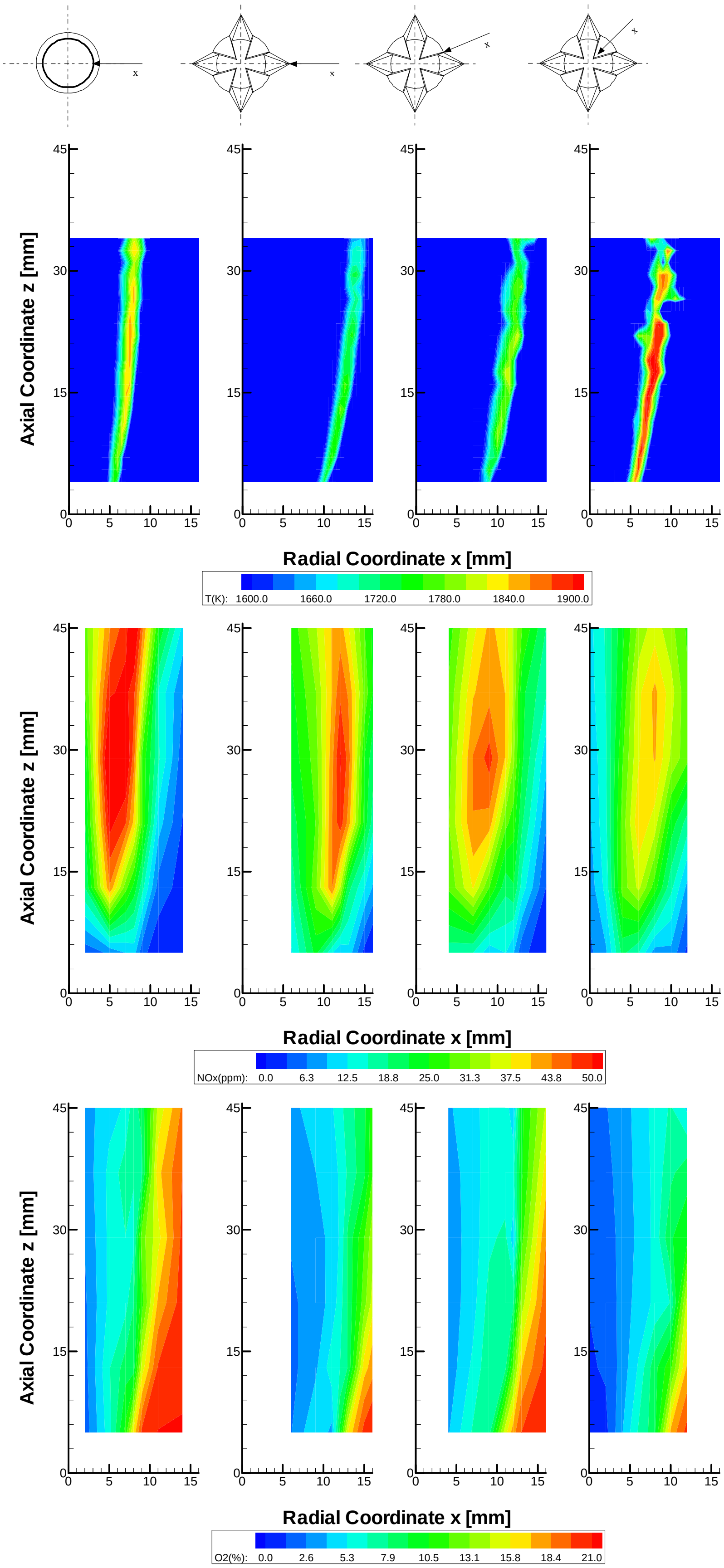


Fig. 7. Maximum NOx Mole Fraction in the Axial Direction

no SM case about maximum NOx mole fraction. In the case of SM0, maximum NOx mole fraction decreases about 10[ppm]. In the case of SM20, maximum NOx mole fraction is almost same when air velocity is 0.27[m/s], but it decreases about 10[ppm] when air velocity is 0.54[m/s]. In the case of SM40, maximum NOx mole fraction decreases about 5[ppm]. By using SM as mixing device, totally maximum NOx mole fraction decreases, but it increases at flame base. This is due to the promoted chemical reaction at flame base by the effect of SMs.

3.4 O_2 mole fraction measurement

Figure. 8 shows O_2 mole fraction contours for the cases of no SM and SM40. In all cases, the zone where O_2 mole fraction largely changes almost corresponds to the high temperature zone. In the cases of SM20 and SM40, highest and lowest O_2 mole fractions are observed at OB and IB, respectively. This tendency is obvious in the case of SM40, i.e., at z = 5[mm] and x = 10[mm], O_2 mole fraction is about 18[%] at IB and about 5[%] at OB. This is because at the upstream, the air flow is entrained to the fuel flow at IB and the fuel flow penetrates into the air flow at OB. O_2 mole fraction changes in the axial direction considerably, in the cases of SM20 and SM40. This result is considered to be the evidence of the enhanced inward (toward the axis) air flow downstream.



(a) (b) (c) (d)

Fig. 8. Temperature, NOx and O_2 mole fraction contours for U_f=1.65[m/s], U_a=0.27[m/s] ((a) no SM, (b) SM40-OB, (c) SM40-slit, (d) SM40-IB)

4 Conclusion

In this research, three sawtooth mixing devices were used in a methane non-premixed burner. The influence of the sawtooth mixer geometry on flame structure and the NOx production characteristics has been studied by four experiments. The main conclusions obtained are as follows:

- SM0 has an effect to prevent flame from lifting. As far as the NOx mole fraction is concerned, the size of high mole fraction zone where the NOx mole fraction is over 40[ppm] is smallest compared with other cases, but NOx tends to increase as one goes downstream. Even if air velocity is increased from 0.27[m/s] to 0.54[m/s], the high temperature zone remains to locate at the flame base. SM0 considerably promotes mixing at the flame base well.
- SM20 does not have much effect on flame stabilization. When air velocity is increased from 0.27[m/s] to 0.54[m/s], the maximum NOx mole fraction decreases by about 10[ppm], and the high NOx mole fraction zone becomes smaller in size.
- Although SM40 has an effect to promote flame from lifting, SM40 has an effect to prevent flame from blowing off. In the case of SM40, turbulent mixing is promoted. The maximum NOx mole fraction decreases about 5[ppm] compared with the case of no SM, and the middle mole fraction zone where the NOx mole fraction is about 25[ppm] increases in size. O_2 mole fraction changes in vertical direction apparently.
- The small blade angle is effective to stabilize flame at the burner rim, and the turbulent mixing downstream of it has the favorable effect on blowing off.

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