Active control of coaxial jet flames under different fuel compositions through manipulation of mixing process with miniature jet actuators

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Received: 26 March 2020; Revised: 23 May 2020; Accepted: 12 June 2020

Abstract
The gaseous fuel-air coaxial jet flow and combustion under different fuel compositions are actively controlled through periodic excitation of the initial jet shear layer with arrayed miniature jet actuators equipped on the inner surface of the annular nozzle. In the present study, methane (CH$_4$) is diluted by nitrogen (N$_2$) or carbon dioxide (CO$_2$) with various dilution rates to mimic biogas with different ratios of combustible and non-combustible components. The spatio-temporal development of the controlled jets are examined with phase-locked two-component particle image velocimetry (PIV). Firstly, it is found that the large-scale vortical structures and the associated mixing in the cold coaxial jets are flexibly controlled by changing the injection frequency $f_v$ of the miniature jets even for the different fuel dilution rates, which affect the momentum flux ratio of the coaxial jet. Based on the cold jet experiments, the present control scheme is applied to bluff-body held coaxial jet flames. The flame holding and emission characteristics for the controlled flames are evaluated under different dilution rates. It is demonstrated that the blow-off limits of the controlled flames are significantly extended to higher dilution rate as increase in $f_v$. Moreover, carbon monoxide (CO) emission for different fuel dilution rates can be improved by manipulating the mixing upstream of the flame base. At low dilution rate, CO emission is drastically reduced through the enhanced mixing by the intense vortices, which realize highly-oxygenated combustion. On the other hand, at high dilution rate, low CO emission can be achieved through the local mixing enhancement near the inner shear layer by the weak vortices, which lead to relatively high temperature combustion.

Keywords : Biogas, Coaxial jet flame, Vortex, Mixing, Active control, Miniature jet actuator

1. Introduction

In resolving a global warming problem, biomass has been expected as a potential renewable energy source. In particular, gasified biomass, which is called biogas, attracts growing attention because it can be supplied directly to conventional gas turbines or gas engines. However, biogas is composed of combustible and non-combustible components, so that its heating value is quite low if compared to natural gas or city gas. In addition, even if the same gasification source and method are employed, the ratio of combustible and non-combustible components in biogas could be fluctuated temporarily depending on operating conditions of the gasification plant (Yamasaki et al., 2009). Therefore, it is not straightforward task for biogas to keep flame stability and high combustion efficiency. Since the performance of passive devices such as a swirler is deteriorated at their off-design conditions, active combustion control technique is prospective to maintain an ideal flame under various operating conditions.

It is well known that perturbations in jet shear layer are amplified through Kelvin-Helmholtz and/or column instabilities, resulting in formation of large-scale vortical structures. The evolution of such vortices is extremely sensitive to external excitation of the shear layer. Therefore, bulk forcing with loud speakers has been often employed to alter the jet flow structures and enhance the mixing (Crow and Champagne, 1971; Zaman and Hussain, 1980; Reynolds et al., 2003; Wicker and Eaton, 1994; Chandra et al., 2003). Recently, active control using micro devices such as synthetic jet
Glezer and Amitay, 2002), miniature jet (Ibrahim et al., 2002; Saiki et al., 2016), electro-magnetic flap actuator (Suzuki et al., 2004; Kurimoto et al., 2015; Saiki et al., 2011a) or plasma actuators (Sammy et al., 2007; Benard et al., 2008) have also been carried out to introduce the local disturbances directly into the initial jet shear layer and realize more efficient flow modification.

Since combustion phenomena are strongly dependent on heat, mass and momentum transport, active combustion control through manipulation of shear flows have been pursued intensively (McManus et al., 1993). McManus et al. (1990) examined the effect of acoustic flow excitation on the lean ethylene/air premixed flame in a dump combustor. They showed that flame stability and nitrogen oxide (NO\textsubscript{x}) emission can be improved by changing the development of large-scale vortices in the shear layer. Chao et al. (1996) imposed acoustic forcing on a propane-air premixed lifted flame. They reported that mixing between the mixture and the ambient air upstream of the flame base is enhanced by the induced vortices, and thus NO\textsubscript{x} emission is suppressed without significant increase in CO. Furlong et al. (1998) applied a feedback control system consisting of diode-laser absorption sensors and loud speakers to an ethylene-air diffusion flame. They demonstrated that, by separately forcing fuel and air flows, combustion efficiency is increased through the mixing enhancement. Saiki et al. (2011b) employed micro flap actuators made by Suzuki et al. (2004) for control of methane-air coaxial jet flames. They claimed that flame stability and CO emission are improved under different overall equivalence ratios through flexible manipulation of the vortex intensity and the methane-air mixing process. However, in the previous studies, active control according to different fuel compositions has not been conducted.

The objectives of this study are improvement of jet flame characteristics under different fuel compositions through active control of the fuel-air mixing with the miniature jet actuators developed by Saiki et al. (2016). The fuel and the air fluids are issued from a coaxial nozzle, which is commonly utilized in gas turbine combustors, and the actuators are installed on the inner surface of the annular nozzle. Unlike the synthetic jet (blowing and suction type actuator), the present actuator realizes a blowing type excitation. Therefore, it could be applied even in high temperature environments such as industrial gas turbine combustors. In order to mimic biogas with different ratios of combustible and non-combustible components, CH\textsubscript{4} fuel is diluted by N\textsubscript{2} or CO\textsubscript{2} with various dilution rates. Firstly, the large-scale vortical structures and the associated fuel-air mixing for the controlled jets are examined through phase-locked PIV. Then, the present control scheme is applied to bluff-body held coaxial jet flames. The improvement for the blow-off limits and the CO emission under the different fuel dilution rates are attempted through manipulation of the mixing process upstream of the flame base.

2. Experimental setup for active combustion control

Figure 1 shows a schematic of experimental setup for active control of coaxial jet flames. Details of the coaxial jet rig are described in (Saiki et al., 2016), and only major aspects are outlined here. A central fuel jet is issued from a long stainless tube (outer diameter \(D_i = 10\) mm, thickness \(t = 0.3\) mm). As for the fuel, CH\textsubscript{4} is diluted by N\textsubscript{2} or CO\textsubscript{2} with
various dilution rates of 0–60%. Air is issued from an annular nozzle (inner diameter $D_i = 10$ mm, outer diameter $D_o = 20$ mm, contraction ratio 12). The fuel-air coaxial jets are discharged vertically into a 200 mm-high combustion chamber with $56 \times 56$ mm$^2$ square cross section. The bulk mean velocities of central fuel and annular air jets are respectively $U_{m,i} = 0.67$ m/s and $U_{m,o} = 1.89$ m/s. The Reynolds number of the annular air jet $Re = (U_{m,o}D_o/\nu)$ is 2500, where $\nu$ is kinematic viscosity coefficient of the air. When pure CH$_4$ is used as the fuel, the overall equivalence ratio $\phi$ and the outer to inner momentum flux ratio $M = (\rho_o U_{m,o}^2/\rho_i U_{m,i}^2)$ are $\phi = 1.0$ and $M = 14$, respectively. Here, $\rho$ and $\rho_i$ are mass densities of the central and annular fluids. Hereafter, $x$ and $r$ represent the streamwise and the radial directions, respectively.

The flow structure and the mixing behavior in a coaxial jet are dominated by development of the outer shear layer, when the annular jet is faster than the central one (Rehab et al., 1997). Moreover, if mass density is different between the central and the annular fluids, $M$ becomes a dominant parameter for coaxial jet flow development (Favre-Marinet M. and Camano Schettini E.B., 2001). Therefore, 12 miniature jet actuators ($D_m = 1.0$ mm) are installed on the inner surface of the annular nozzle, and the periodic disturbances are introduced directly into the initial outer shear layer. The miniature jet holes are fabricated as close to the nozzle exit as possible and located at $x = -2.5$ mm. The periodic radial miniature jet injections are achieved by using a rapid response servo-valve (MOOG, J814-0008), and pulsed flowing with the effective duty ratio of 20% is employed to induce the intense vortices (Saiki et al. 2016). Here, the miniature jets are issued when the phase angle $\theta$ with respect to the driving signal for the servo-valve is $0 \sim 0.4\pi$. The 12 miniature jet injections are all synchronized. The Strouhal number $St = fD_o/U_{m,o}$ is defined with the valve-driven frequency $f$, and changed from 0.1 to 1.9. The present Strouhal number corresponds to the ratio of the time scale for the jet flow to that for the periodic control inputs. The mean velocity of the miniature jet $U_{m,i}$ is equal to $U_{m,o}$, where the total air flow rate for the actuators is 4% of that for the annular jet.

In order to investigate the vortical structures and the associated mixing process, phase-locked two component PIV using the driving signal for the actuators is employed. Silica particles with 1.2 $\mu$m-diameter are seeded into the central and annular fluids. A double-pulsed YAG laser (Continuum, CLP10PIV) is used as the light source and the laser sheet size is set to $80 \times 48$ mm$^2$. The laser pulses is set to $60 \times 48$ mm$^2$ with 50% overlap. The measurement area is set to $60 \times 48$ mm$^2$ with 50% overlap. The measurement area is to $60 \times 48$ mm$^2$ with 50% overlap. The physical dimension of the interrogation area is $1.5 \times 1.5$ mm$^2$. The uncertainty intervals estimated at 95% coverage for the instantaneous velocity $u = 1.89$ m/s is $\text{RSS}_{95\%} = 0.13$ m/s.

In the combustion experiments, a ring-type bluff-body (outer diameter 14 mm, inner diameter 8 mm, thickness 1.0 mm) is installed to hold the coaxial jet flames. The bluff-body is placed at $x/D_o = 1.5$, where the mixing property is drastically changed with different $St_i$ as shown in Sec. 3. The flame holding and CO emission characteristics for the natural and controlled flames are examined. The blow-off limit is identified by increasing the dilution rates of central CH$_4$ with fixed $U_{m,i}$. Here, the flame is judged stable when the flame is held at least for 1 min. In order to measure the CO emission, the exhaust gas is sampled with a stainless probe having the inner diameter of 10 mm at $x/D_o = 25$. The sampled gas is introduced into a drain pod and an exhaust gas analyzer (Hodaka, HT2700). The amount of CO emission is evaluated with 15%O$_2$ conversion to eliminate the dilution effect. The temperature for the natural and controlled flames are also evaluated with a 100 $\mu$m-diameter R-type thermocouple, which is coated with silica to avoid catalytic reaction of the platinum. The ensemble-averaged temperatures are obtained based on the 1000 instantaneous data. Note that the radiation effect on the thermocouple measurement is not compensated here.

3. Cold coaxial jet control

3.1 Effect of Strouhal number $St_i$

Firstly, the effects of $St_i$ on the evolution of large-scale vortical structures and the mixing process are discussed briefly for the cold CH$_4$-air coaxial jet. Details of the effects of $St_i$ can be found in (Saiki et al., 2016). Figure 2 shows instantaneous and time-averaged visualization images of the natural jet. Here, the silica particles are seeded into the central CH$_4$ and annular air fluids separately. The large-scale vortex rings are induced in the inner and outer shear layers at $x/D_o \sim 1.0$ due to the column instability and the mixing of CH$_4$ and air is progressed slowly. Figure 3 represents phase-averaged images ($\theta = 0.9\pi$) of the controlled jets at $St_i = 0.3, 1.1, 1.5$ and 1.9. In the nozzle-near field, both shear layers are rolled-up into vortex rings in phase with the periodic miniature jet injections. In particular, the inner vortices play an
important role for the transport of fuel/air fluids. At St_v = 0.3, the distance between the vortex and the next-phase vortex is large due to low St_v, so that the intermittence passage of the CH_4 is observed (A in Fig. 3a) and the CH_4 concentration is fluctuated largely. On the other hand, when St_v ≥ 1.1, the vortices are shed densely and this promotes the mixing. In addition, it is seen that the potential core length of the central jet is significantly changed with different St_v and the mixing

Fig. 2 Visualization images for natural jet: (a) instantaneous images, and (b) time-averaged images.

Fig. 3 Phase-averaged visualization images (θ = 0.9π) of controlled jets with different St_v: (a) St_v = 0.3, (b) St_v = 1.1, (c) St_v = 1.5, and (d) St_v = 1.9.

Fig. 4 Phase-averaged velocity fields (θ = 0.9π) and corresponding contours of Q for controlled jets with different St_v: (a) St_v = 0.3, (b) St_v = 1.1, (c) St_v = 1.5, and (d) St_v = 1.9.
property at $x/D_o \sim 1.5$ depends on $St_v$ strongly.

Fig. 5 Phase-averaged visualization images ($\theta = 0.9\pi$) of controlled jets with $St_v = 1.1$ at different $M$: (a) $CH_4$-air jet ($M = 14$), (b) $N_2$-air jet ($M = 8$), and (c) $CO_2$-air jet ($M = 5$).

Fig. 6 Phase-averaged velocity fields ($\theta = 0.1\pi \sim 1.7\pi$) and corresponding contours of $Q$ for the controlled jets with $St_v = 1.1$ at different $M$: (a) $CH_4$-air jet ($M = 14$), (b) $N_2$-air jet ($M = 8$), and (c) $CO_2$-air jet ($M = 5$).
Figure 4 shows the phase-averaged velocity fields \((\theta = 0.9\pi)\) for the controlled jets with \(St_v = 0.3, 1.1, 1.5\) and 1.9. Note that the convection velocity of the vortex rings \(U_c (=0.6U_{m,o})\) is subtracted from the velocity vector fields in order to visualize the vortical motion (Adrian et al., 2000). The corresponding contours for the second invariant of the deformation tensor \(Q\) \((<0)\) are also shown in Fig. 4. Here, the \(Q\) is calculated as follows.

\[
Q = \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} \quad (i, j = 1, 2)
\]

(1)

It is clearly seen that, when \(St_v \geq 1.1\), the vortices are induced densely in the streamwise direction. The diameters of vortices at \(St_v = 1.1, 1.5\) and 1.9 are around \(0.45D_o, 0.35D_o\) and \(0.25D_o\), respectively. The vortices become smaller at higher \(St_v\) because the total amount of the air injected by the actuators in one control period is decreased as increase in \(St_v\). Therefore, the present scheme allows us to control the transport range of the inner and outer fluids by adjusting \(St_v\).

As shown in Fig. 4, the induced vortices are most developed at \(x/D_o \sim 0.75\) and broken down in the further downstream. Then, it has been confirmed in our previous study (Saiki et al., 2016) that the turbulent intensity is much increased, indicating the enhanced mixing. Therefore, in the combustion experiments described in Sec. 4, the effects of the bluff-body, which is located at \(x/D_o = 1.5\), on the induced vortical structures is considered to be small.

### 3.2 Effect of momentum flux ratio \(M\)

The flow development in coaxial jets are dependent on the momentum flux ratio \(M = \rho_oU_{m,o}^2/\rho_iU_{m,i}^2\) (Favre-Marinet M. and Camano Schettini E.B., 2001). Therefore, the induced vortical structures could be affected by the inner fuel composition. In order to examine the effects of \(M\) on the controlled jet structures, pure \(N_2\) and \(CO_2\) are employed as the inner fluid. Here, the velocity ratio \((=U_{m,o}/U_{m,i})\) is kept constant, where \(M\) are respectively 14, 8 and 5 for the \(CH_4\)-air, \(N_2\)-air and \(CO_2\)-air coaxial jets. Figure 5 shows the phase-averaged visualization images \((\theta = 0.9\pi)\) for the controlled \(CH_4\)-air, \(N_2\)-air and \(CO_2\)-air coaxial jets with \(St_v = 1.1\). A series of phase-averaged velocity fields \((\theta = 0.1\pi \sim 1.9\pi)\) and the corresponding contours of \(Q\) \((<0)\) are also shown in Fig. 6. The vortex diameter at \(M = 14, 8\) and 5 are respectively...
around 0.45 \(D_o\), 0.4 \(D_o\) and 0.35 \(D_o\), indicating that the vortex intensity is decreased as decrease in \(M\). This is because that the momentum gradient in the inner shear layer becomes weaker with decrease in \(M\) and the evolutions of the control input in the initial jet shear layer is suppressed. However, the induced vortices are large and intense enough to bring outer air to the jet center axis and pinch off the inner fuel even at \(M < 14\). Figure 7 represents the radial distributions of phase-averaged streamwise velocity (0 = 0.1\(\pi\) to 1.9\(\pi\)) at \(x/D_o = 0.75\). The periodic velocity fluctuation is caused by the induced vortices convecting downstream. The periodic fluctuation near the center axis (\(r/D_o = 0\)) becomes smaller with decrease in \(M\). For more detailed comparison, the streamwise variations of vortex intensity \(I_v\) in the inner shear layer for different \(M\) are shown in Fig. 8. In the present study, \(I_v\) is calculated as the integration of \(Q\) as follows.

\[
I_v = \iint -Q dA / U_{m\cdot o}^2
\]

(2)

where \(A\) is the vortex area, of which \(Q\) have negative values. The vortex intensity reaches a maximum at \(x/D_o \approx 0.75\) before the break down, and the maximum values of \(I_v\) for \(M = 14, 8\) and 5 are respectively 145, 137 and 124. Although \(I_v\) becomes lower as decrease in \(M\), the discrepancy in the streamwise distribution of \(I_v\) between \(M = 14\) and 8 is relatively small. In the present exhaust gas measurements, the dilution rate is up to 40%, where \(M\) is larger than 8. Therefore, the control effects on the CO emission shown in later are almost arranged by using \(St_v\).

4. Coaxial jet flame control under different dilution rates

4.1 Blow-off limit

Based on the cold jet experiments, the coaxial jet flames are actively controlled with manipulation of the mixing

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**Fig. 8** Streamwise variations of vortex intensity \(I_v\) in inner shear layer for \(M = 14, 8\) and 5 at \(St_v = 1.1\).

**Fig. 9** Direct photos for natural and controlled flames: (a) dilution rate of 10% with \(N_2\), and (b) dilution rate of 40% with \(N_2\).
process upstream of the flame base. Figure 9a shows raw images of the natural and controlled flames with St\(_v\) = 1.1 and 1.9. Here, the CH\(_4\) is diluted by N\(_2\) with the dilution rate of 10%. In the natural flame and the controlled flame with St\(_v\) = 1.9, a luminous light emission is frequently observed. As shown in Fig. 3d, the mixing is progressed locally near the inner shear layer at St\(_v\) = 1.9. Therefore, at low dilution rate, CH\(_4\)-rich mixture is formed near the jet center axis and supplied to the flame base, resulting in incomplete combustion. On the other hand, in the controlled flame with St\(_v\) = 1.1, blue chemiluminescence emission is observed, showing complete combustion through the mixing enhancement with the densely-shed intense vortices as mentioned above. Fig. 9b shows raw images of the controlled flames with St\(_v\) = 1.1 and 1.9 at the dilution rate of 40%. Note that the natural flame cannot be sustained at the dilution rate of 40% as shown in later. In contrast, at St\(_v\) = 1.1 and 1.9, the stable blue flame can be held successfully.

Figure 10 shows the blow-off limits with respect to the N\(_2\) or CO\(_2\) dilution rate for the natural flames and the controlled flames under different St\(_v\). Note that the data of the natural flame are plotted at St\(_v\) = 0. The blow-off limit is almost unchanged by the kind of the dilution gas tested and is about 27.5% for the natural flame. On the other hand, the blow-off limit for the controlled flame is significantly extended to higher dilution rate with increase in St\(_v\). At St\(_v\) = 1.1 and 1.9, they are around 40% and 55%, respectively. Since the local mixing enhancement is achieved by densely-shed weak vortices at St\(_v\) > 1.1, the flammable mixture can be made near the jet center axis even if the overall equivalence ratio is lower than the flammable limit.

4.2 CO emission

The CO emissions from the natural and the controlled flames are evaluated under different dilution rates. Figure 11 shows the control effects on the CO emission at the dilution rates of 10%, 30% and 40%. The emission level for the CO\(_2\) dilution condition is slightly higher than that for the N\(_2\) dilution condition. This is due to the fact that specific heat of CO\(_2\) is larger than that of N\(_2\), resulting in lower temperature for the CO\(_2\) dilution flames. At the dilution rate of 10%, CO emission from the controlled flame with St\(_v\) = 1.1, where the mixing is mostly enhanced by the intense vortices, is drastically reduced by up to 24% of that from the natural flame (A in Fig. 11). On the other hand, the optimum St\(_v\) number becomes higher with increase in the dilution rate. For the dilution rate of 30% and 40%, CO emission is significantly suppressed at St\(_v\) ~ 1.5 and St\(_v\) ~ 1.9, respectively, if compared to St\(_v\) = 1.1 (B and C in Fig. 11). This is probably because that, as the amount of the combustible component in the fuel is decreased, higher St\(_v\) with weaker vortices becomes effective to supply stoichiometric mixture to the flame base.

To give an insight into the structure of the controlled flames, the radial distributions of the mean flame temperature at St\(_v\) = 1.1 and 1.9 are shown in Fig. 12. Here, the fuel is diluted by N\(_2\) with the dilution rate of 10% and 40%. The streamwise positions of the temperature measurement are x/D\(_a\) = 1.75 and 3.25 for the dilution rate of 10%, while they are x/D\(_a\) = 1.75 and 2.25 for the dilution rate of 40%. The maximum temperatures are recorded at x/D\(_a\) = 3.25 and 2.25 for the dilution rates of 10% and 40%, respectively. The temperature near the flame base at r/D\(_a\) ~ 0.5 are low because the upstream mixture flow is divided by the ring-type bluff-body. For St\(_v\) =1.1, the radial temperature distributions are

![Fig. 10 Blow-off limits with respect to N\(_2\) or CO\(_2\) dilution rate for natural and controlled flames with different St\(_v\).](image-url)
relatively uniform, indicating that premixed-like combustion is achieved through the mixing enhancement with the intense vortices. Since the combustion reaction occurs in the highly-oxygenated field at St\_v = 1.1, CO emission is significantly suppressed for the low dilution rate condition. On the other hand, the temperature distributions at St\_v = 1.9

Fig. 11 CO emissions for natural and controlled flames under different dilution rates: (a) dilution rate of 10%, (b) dilution rate of 30%, and (c) dilution rate of 40%.
have a peak value (A and B in Fig. 12), showing that diffusion or partially-premixed combustion occurs through the local mixing enhancement with the weak vortices. Therefore, at $St_v = 1.9$, high temperature combustion is realized and CO emission can be reduced for the high dilution rate condition.

5. Conclusions

In the present study, gaseous fuel-air coaxial jet mixing and combustion under different ratios of combustible and non-combustible components in fuel gas are actively controlled through manipulation of the initial jet shear layer with miniature jet actuators. In order to change the fuel compositions, CH$_4$ is diluted by N$_2$ with dilution rates of 10% and 40%: (a) dilution rate of 10%, and (b) dilution rate of 40%.

Fig. 12 Radial distributions of mean flame temperature for controlled flames with $St_v = 1.1$ and 1.9. Here, CH$_4$ is diluted by N$_2$ with dilution rates of 10% and 40%: (a) dilution rate of 10%, and (b) dilution rate of 40%.

The following conclusions can be derived:

1. The large-scale vortices are induced in the shear layers by the periodic miniature jet injections. The vortex intensity is decreased with increase in the Strouhal number $St_v$, which is defined by the miniature jet injection frequency, and
thus the mixing is flexibly controlled by changing $St_v$. As increase in the fuel dilution rate, the outer to inner momentum flux ratio $M$ of the coaxial jet is decreased. The vortex intensity is decreased when $M$ is changed from 14 to 5. However, its variation is relatively small within the range of $M = 8$–14. Therefore, the control effect can be arranged by $St_v$ in the present combustion experiments, where $M$ is larger than 8.

2. The blow-off limit of the bluff-body held coaxial jet flame can be drastically extended to higher dilution rates with increase in $St_v$. This is because that, at higher $St_v$, the mixing is enhanced more locally near the inner shear layer with weaker vortices.

3. It is demonstrated that the CO emissions from the coaxial jet flames operated under different dilution rates can be improved by adjusting $St_v$. At low dilution rate, the CO emission is significantly reduced through the mixing enhancement by the intense vortices with $St_v = 1.1$, which realize highly-oxygenated combustion. In contrast, at high dilution rate, the local mixing enhancement near the inner shear layer by the weak vortices with $St_v >> 1.1$, which lead to high temperature combustion, becomes effective to suppress the CO emission.

Acknowledgements

The present work was partly supported by Grant-in-Aid for Young Scientists (B) (No. 23760184) by JSPS, Japan.

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