# $NO_x$ and CO emission Characteristics of Two-Stage Model Gas-Turbine Combustor Using $CH_4/NH_3$ Blended Fuel

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## 1 Abstracts

This study investigates the NOx and CO emission characteristics of a two-stage model gas turbine using a methane/ammonia blend fuel. For two-stage combustion, an methane/ammonia blend fuel with a volume ratio of 2:8 was used in the primary zone to change the bulk velocity and the equivalence ratio, while air or methane/air was injected to the secondary combustion zone. The equivalence ratio and velocity of the secondary air and methane/air mixture are fixed to 0.8 and 3 m/s, respectively. For the baseline case, the single-stage premixed flames of methane and ammonia blend fuels are classified into five regimes: brush flame (I), M-shape flame (II), conical flame (III), columnar flame (IV), and yellow flame around the main flame (V). CO emission in the single-stage combustion with a blended fuel of methane/ammonia increased drastically at $\phi_{\mathrm{pri}} \geq 1.0$. The similar trend was observed in the two-stage combustion with methane/air injection in the secondary zone. While for air injection in the secondary combustion zone, CO emission increased drastically at $\phi_{\mathrm{pri}} > 1.3$. For two-stage combustion, air and methane/air injection in the secondary zone rather decreased NO emission, as compared with those for single-stage combustion. For two-stage combustion, the reduction of NO emission with the $CH_4$/air injection in the secondary zone is more effective than that with pure air.

## 2 Introduction

In recent years, global warming has emerged as one of a serious environmental problems. A huge amount of research effort has been put into designing combustors to reduce $CO_2$ emissions in the field of gas turbines and industrial boilers. Ammonia ($NH_3$) and hydrogen ($H_2$) have been drawing attention as an alternative to hydrocarbon fuels. Since the boiling temperature and condensation pressure of ammonia are nearly the same as those of propane, most existing infrastructures for propane can readily be used for ammonia [1,2]. However, there are some improvements in terms of combustion engineering when using ammonia instead of common hydrocarbon fuels. The heat of combustion and the maximum laminar burning velocity of ammonia/air flames are approximately 40 and 20% respectively of those for

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typical hydrocarbon fuel/air flames. The flammability limit of ammonia/air mixture is narrow, and its ignition temperature is high [1,3]. Because of these characteristics, it is difficult to directly apply ammonia combustion to most combustors. Therefore, $CO_2$ emissions are gradually reduced by blending conventional hydrocarbon fuel with moderate amounts of ammonia [4,5]. Methane/ammonia co-firing technology can be effective in terms of flame stability, while reducing high $NO_x$ emissions from ammonia-methane co-combustors is challenging.

The two-stage combustion technique has been found to be effective in reducing $NO_x$ emissions [6,7]. Since there are many control factors such as the height of secondary combustion and secondary combustion conditions (the equivalent ratio and flow rate), it is expected to be quite flexible in reducing $NO_x$ emissions. In addition to single flames (flames based on swirl flow), however, complicated interacting flames (double and triple flames in the secondary zone) can occur. These interacting flames can complicate CO and NOx emission behaviors.

In this study, the flame shape and CO and $NO_x$ emission characteristics were investigated by varying the bulk velocity and the equivalence ratio of the first zone in a two-stage model gas turbine combustor using a mixture of methane and ammonia. Air or methane/air mixture was injected into the secondary zone. The stability regime diagram of the flame is expressed in terms of the equivalence ratio and bulk velocity based on the shapes of the visualized methane/ammonia premixed flames. In addition, the CO and $NO_x$ emission characteristics of the single- and two-stage combustions are investigated.

## 3 Experimental setup

The schematic diagram of the two-stage combustor, flow control system, and gas analyzer is shown in Fig. 1. The central part of the nozzle is made of stainless steel with a diameter of 12 mm. Fuel is supplied vertically from 10 holes with a diameter of 0.1 mm (red line in Fig. 1 (a)) in the primary zone. Air is supplied via the swirler section with a diameter of 18 mm. The vane angle of the swirler is 45° and the swirl number is 0.84 [8,9]. The nozzle outlet is tapered with an angle of 23.6° and the nozzle exit diameter is 11 mm. The combustion chamber consists of three sections where two sections are made of two quartz windows and the secondary staging unit is made of ceramic. The diameter of the combustion chamber is 36 mm, and the total length is 380 mm. At a height of 150 mm, methane/air (or air) mixtures are supplied toward the center point via four holes with a diameter of 6.35 mm.

The flow rates in the primary and secondary zones are controlled by mass flow controllers. In the primary zone, the blended fuel of 80% methane and 20% ammonia in volume is used and compressed dry air is used as an oxidizer. The equivalence ratio in the primary zone, $\phi_{\text{pri}}$, varies from 1.4 to the

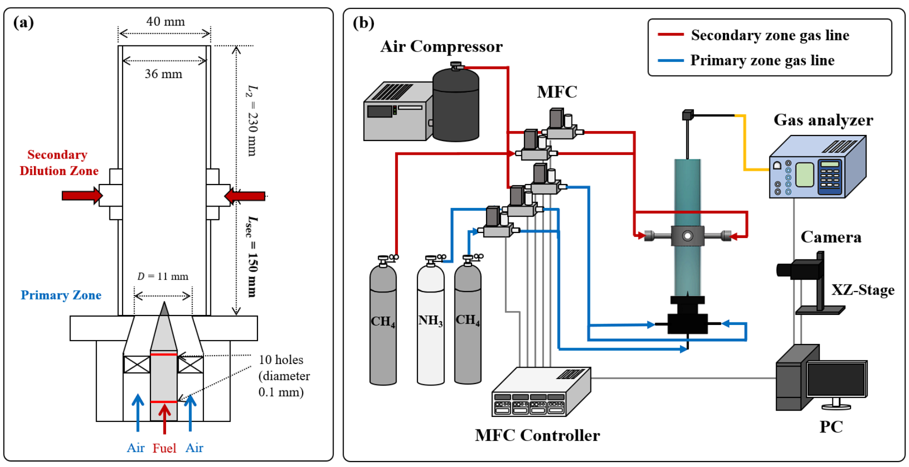


Figure 1: Schematic diagram of two-stage model gas-turbine combustor and experimental setup.

blowout limit, and the bulk flow velocity in the primary zone, $\boldsymbol{U_{pri}}$, is in the range of 4 to 10 m/s. Air or methane/air premixed mixture (the equivalence ratio of 0.8) is supplied with the flow velocity of 3 m/s in the secondary combustion zone.

Direct images of the flames were captured using a digital camcorder at 30 fps. Quantitative emission values of CO, NO, and $NO_2$ are measured at the exit of the combustion chamber and analyzed with a gas analyzer (AFRISO, Maxilyzer NG). The measurement limit of the gas analyzer is 4000 ppm for CO, 5000 ppm for NO, and 200 ppm for $NO_2$, respectively.

# 4 Results and discussion

## 4.1 Flame shape of single- and two-stage combustions

The instantaneous flame images in the single-stage combustion with $X_{NH3} = 0.2$ and $U_{pri}$ = 0.8 m/s are shown in Fig. 2. At $\phi_{pri}$ < 1.0, only a single lean premixed flame is observed. At $\phi_{pri}$ > 1.0, a rich premixed flame exists in the primary zone and a diffusion flame is additionally generated at the combustor exit. Five different flame regimes are identified based on the flame shape. In the range of $\phi_{pri}$ = 0.8 - 1.2, the flame exists brushed without distinction between inner recirculation flame and outer recirculation flame, which is referred to as a brush flame (Regime I). At $\phi_{pri}$ = 0.7, In Regime II, the flame changes to an M-shape flame [8]. At $\phi_{pri}$ = 0.6 and 0.5, it becomes a conical flame (Regime III) and a columnar flame (Regime IV), respectively [8]. At $\phi_{pri}$ > 1.3, a yellow flame is observed around the blue flame (Regime V). The classification of the flame regime is clearly shown in the flame stabilization diagram and can be seen in Fig. 3. The lean blowout limit occurs at $\phi_{pri}$ = 0.45 regardless of $U_{pri}$. Also, the division of the flame regime was more sensitive to the changes in $\phi_{pri}$ than those in $U_{pri}$.

Figure 4 shows the flame images when the secondary flow is injected to the combustor at $U_{pri}$ = 8 m/s and $X_{NH3} = 0.2$. Figure 4a shows the flames when the secondary air is injected at $U_{sec}$ = 3 m/s. Images taken from the front (a1), bottom (a2) and top (a3) to observe the flame inside the secondary zone are also included. Overall, there is no difference in the shape of the primary zone flames regardless of the secondary zone flames (see Fig. 2 and Fig. 4a1). In the primary lean premix flame ($\phi_{pri}$ = 0.6, 0.8), no flame exists in the secondary zone. At $\phi_{pri}$ =1.0, 1.2, 1.4, an rich premixed flame was formed in the primary zone, and the remaining fuel from the primary zone reacts with the secondary air to generate a diffuse flame in the secondary zone.

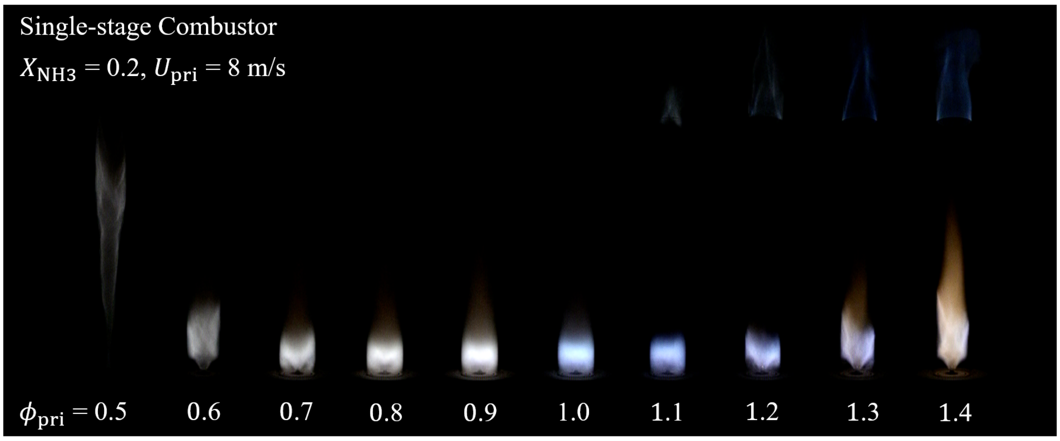


Figure 2: Instantaneous flame images for various primary equivalence ratio $\phi_{pri}$ with $X_{NH3} = 0.2$ and $U_{pri} = 8$ m/s in a single-stage combustor.

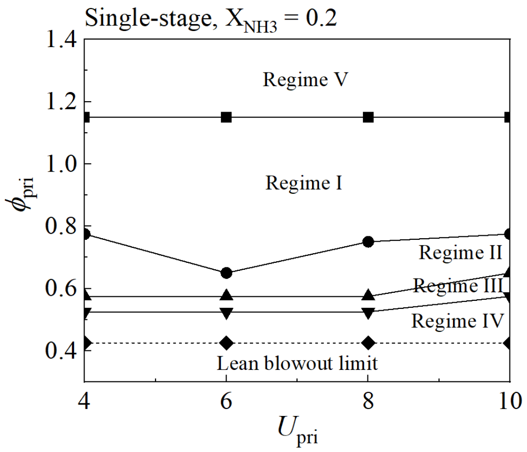


Figure 3: Flame regime diagram in the $U_{\mathrm{pri}} - \phi_{\mathrm{pri}}$ space in a single-stage combustion with $X_{\mathrm{NH3}} = 0.2$.

The increase in $\phi_{\mathrm{pri}}$ increases the amount of remaining fuel, which makes the shape of the diffusion flame more distinct (see image in Fig. 4a2). In this case, the diffusion flame in the secondary zone is inclined due to the swirling flow induced in the primary zone.

Figure 4b shows instantaneous flame images when methane/air is injected into the secondary zone at $\phi_{\mathrm{sec}}$ = 0.8 and $U_{\mathrm{sec}}$ = 3 m/s. For conditions where $\phi_{\mathrm{pri}}$ < 1.0, lean premixed flames are formed in the primary and secondary zones. Since the distance between the primary and secondary flames is large

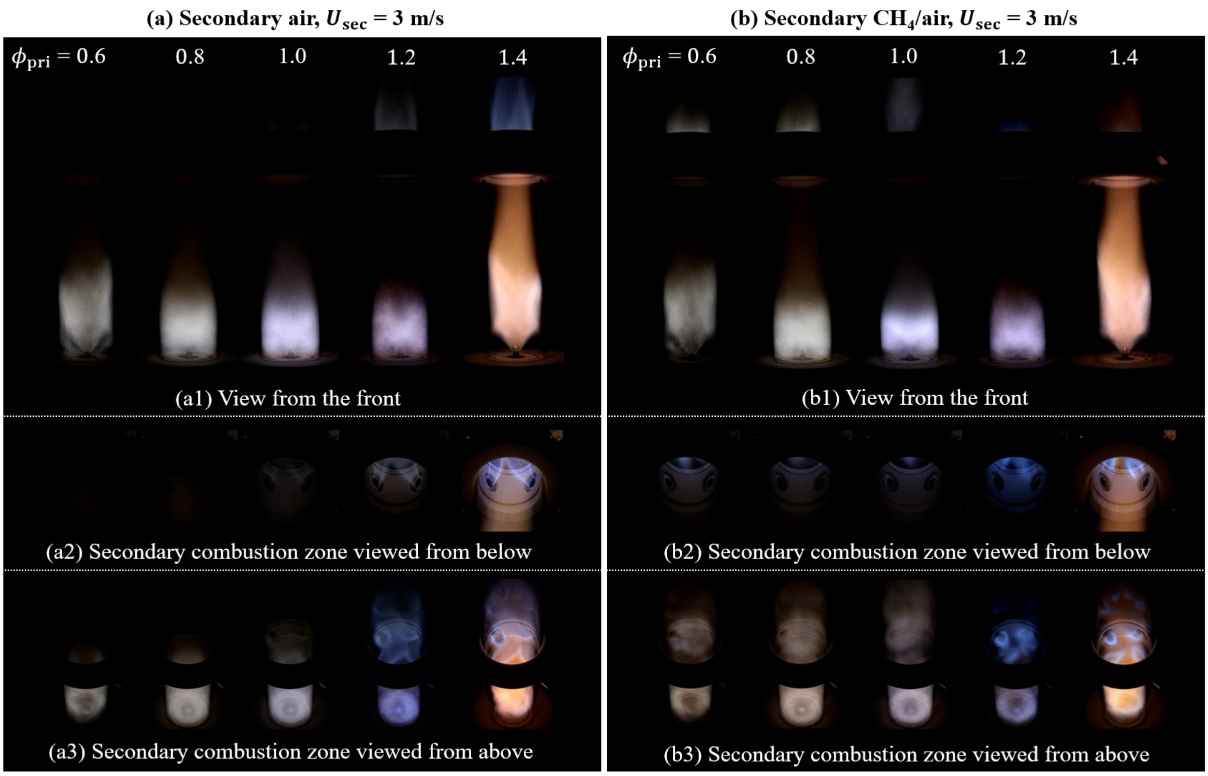


Figure 4: Flame images against $\phi_{\mathrm{pri}}$ for $U_{\mathrm{pri}} = 8$ m/s at $X_{\mathrm{NH3}} = 0.2$ in a two-stage combustion; (a) secondary air injection, $U_{\mathrm{sec}} = 3$ m/s, (b) secondary $CH_4$/air injection, $U_{\mathrm{sec}} = 3$ m/s, $\phi_{\mathrm{sec}} = 0.8$.

enough, the interaction may be very weak. Under the condition of $\phi_{\rm pri} > 1.2$, the secondary zone flames become blue. Although not clearly identified yet, conceptually the primary rich premixed flame and the secondary lean premixed flame strongly interact to form a triple flame. The interaction strength of these primary and secondary flames is expected to affect flame stability and CO and $NO_x$ emissions. The results also imply that the interaction strength can be modulated by changing the distance between the primary and secondary zones. The flame stability and CO/$NO_x$ emission characteristics by the distance between the primary and secondary zones will be extensively investigated in the future.

## 4.2 CO and NOx emissions in single- and two-stage combustions

Figure 5 show the emissions of CO, NO, and $NO_2$ against $\phi_{\rm pri}$ in the single- and two-stage combustions. In the single-stage combustion, $X_{\rm NH3} = 0$ (0.2) represents the pure methane (80% $CH_4$ + 20% $NH_3$) injection. In Fig. 5, the indication of air ($CH_4$/air) in the second stage combustion means the case of injecting air ($CH_4$/air) into the secondary zone. The emissions of CO, NO, and $NO_2$ are converted into those under 15% $O_2$ condition as in the previous studies [8,9]. In Fig. 5a, CO emissions from the single-stage combustion increases rapidly at $\phi_{\rm pri} > 0.9$ and exceeds its measurement limit at $\phi_{\rm pri} > 1.1$. Under the condition that secondary air was injected into the secondary zone at $U_{\rm sec}$ = 3 m/s, the CO measurement limit was extended to $\phi_{\rm pri}$ = 1.4. The CO emission in the two-stage combustion with the secondary methane/air injection at $\phi_{\rm sec}$ = 0.8 and $U_{\rm sec}$ = 3 m/s becomes similar to those in the single-stage combustions. Even though further investigation is required to fully understand them, this result demonstrates that CO emissions can be adjusted by controlling the composition in the secondary zone.

Figures 5b and 5c show the emissions of NO and $NO_2$ against $\phi_{\rm pri}$. NO emission exhibits its maximum of 12 ppm at $\phi_{\rm pri}$ = 1.2 in the single-stage combustion with pure methane ($X_{\rm NH3} = 0$). However, NO emission increases up to 1500 ppm in the single-stage combustion with 20% $NH_3$, while significantly decreasing at $\phi_{\rm pri} > 1.2$. The NO emission of the two-stage combustion with the secondary air injection exhibits slightly lower (much higher) value at $\phi_{\rm pri} \leq (>) 1.2$ than single-stage combustion. NO emissions from two-stage combustion with the secondary methane/air injection have lower values at all $\phi_{\rm pri}$ (except the case of $\phi_{\rm pri}$ = 1.3) than those in the single-stage combustion. Meanwhile, $NO_2$ emissions for the two-stage combustion with the secondary methane/air injection have similar trends as those from NO emission. However, the $NO_2$ emissions with the secondary air injection have slightly higher (lower) values for $\phi_{\rm pri} \geq (<)$ 1.2 than single-stage combustion, which is opposite to NO results.

Consequently, a two-stage combustion technique with the secondary air or methane/air injection has a potential to significantly reduce NO and $NO_2$ emissions. More research is required to fully understand the characteristics of CO, NO, and $NO_2$ emissions from primary and secondary flame interactions.

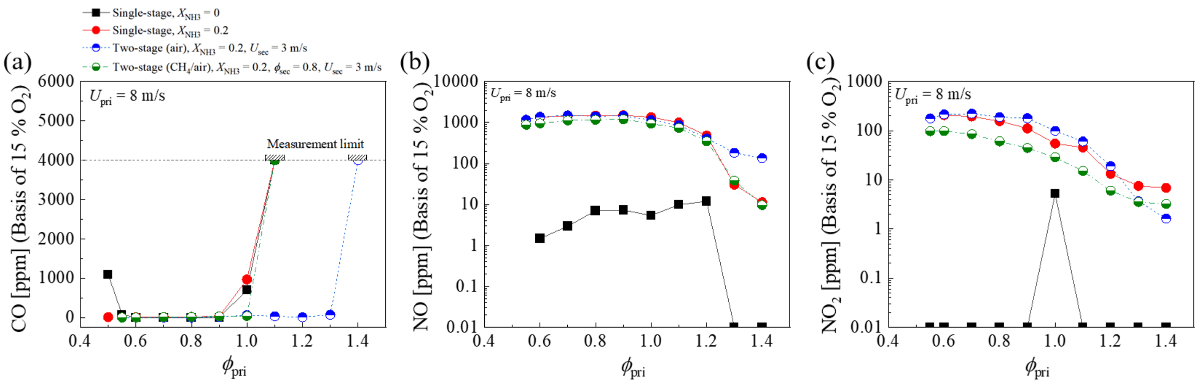


Figure 5: CO, NO and $NO_2$ emissions against $\phi_{\rm pri}$ in single- and two-stage combustions.

# 5 Conclusion

Flame shapes and CO, NO and $NO_2$ emission characteristics were investigated in the single- and two-stage model gas turbine combustors using the blended fuel of 80% $CH_4$ and 20% $NH_3$ in volume. The following conclusions were made:

1) Flame stability map is presented in the $\phi_{\mathrm{pri}} - U_{\mathrm{pri}}$ space for the single-stage combustion. Five flame regimes are identified based on the flame shape in the single-stage combustion: a brush flame (Regime I), an M-shape flame (Regime II), a conical flame (Regime III), a columnar flame (Regime IV), and a yellow flame around the main blue flame (Regime V). The lean blowout limit of $\phi_{\mathrm{pri}}$ = 0.45 is identified regardless of $U_{\mathrm{pri}}$.

2) The CO emission in the single-stage combustion with a blended fuel of 80% $CH_4$ and 20% $NH_3$ increases drastically at $\phi_{\mathrm{pri}} \geq 1.0$. The similar trend was obtained for the two-stage combustion with the secondary methane/air injection. For the two-stage combustion with the secondary air injection, however, the CO emission increases drastically at $\phi_{\mathrm{pri}} > 1.3$.

3) For the two-stage combustion, the secondary air or methane/air injection significantly decreases NO emission, as compared with those for single-stage combustion, implying that the two-stage combustion technique can be adopted to effectively reduce NO and $NO_2$ emissions. CO, NO, and $NO_2$ emissions are expected to significantly affect the interaction of primary and secondary flames, which will be reported in the future study.

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# References

[1] H. Kobayashi, A. Hayakawa, K.K.A. Somarathne, E.C. Okafor, Proc. Combust. Inst. 37 (2019) 109–133.

[2] G. Wang, T.F. Guiberti, S. Cardona, C.A. Jimenez, W.L. Roberts, Proc. Combust. Inst. 000 (2022) 1-12.

[3] G.T. Kim, J. Park, S.H. Chung, C.S. Yoo, Fuel 323 (2022) 124227.

[4] M. Zhang, Z. An, X. Wei, J. Wang, Z. Huang, H. Tan, Fuel 291 (2021) 120135.

[5] Z. An, M. Zhang, W. Zhang, R. Mao, X. Wei, J. Wang, Z. Huang, H. Tan, Fuel 304 (2021) 121370.

[6] O. Kurata, N. Iki, T. Inoue, T. Matsunuma, T. Tsujimura, H. Furutani, M. Kawano, K. Arai, E.C. Okafor, A. Hayakawa, H. Kobayashi, Proc. Combust. Inst. 37 (2019) 4587-4595.

[7] K.D.K.A. Somarathne, S. Hatakeyama, A. Hayakawa, H. Kobayashi, Int. J. Hydrog. Energy 42 (2017) 14010-14018.

[8] G.T. Kim, C.S. Yoo, S.H. Chung, J. Park, Combust. Flame 212 (2020) 403-414.

[9] G.T. Kim, J. Park, S.H. Chung, C.S. Yoo; in preparation.