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Effects of nitrogen dilution for coal synthetic gas fuel on the flame stability and NOx formation

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Abstract−Experimental studies were conducted to investigate the flame stability and the thermal/fuel NOx formation characteristics of the low calorific value (LCV) coal derived gas fuel. Synthetic LCV fuel gas was produced by mixing carbon monoxide, hydrogen and ammonia on the basis that the thermal input of the syngas fuel into a burner is identical to that of natural gas. The syngas mixture was fed to and burnt on flat flame burner. With the variation of the equivalence ratio for specific syngas fuel, flame behaviors were observed to identify the flame instability due to blow-off or flash-back and to define stable combustion range. Measurements of NOx content in exhaust gas were made to compare the thermal and the fuel NOx emissions from the LCV syngas combustion with those of the natural gas. In addition, the nitrogen dilution of the LCV syngas was attempted as an NOx reduction technique, and its effects on NOx emission and flame stability were investigated.

Key words: Coal Derived Gas, Flame Stability, NOx Emission, Nitrogen Dilution

INTRODUCTION

Recently, IGCC (integrated gasification combined cycle) is being considered as a next-generation clean coal technology because it shows higher thermal efficiency and superior environmental performance compared with a conventional fossil boiler. However, the syngas fuel produced from oxygen-blown coal gasification and gas clean-up processes of IGCC is mainly composed of hydrogen and carbon monoxide, so it has low calorific value of the fuel, 1/4-1/5 times smaller than the natural gas and shows very fast burning velocity, chemical reaction rate and high flame temperature due to the high content of hydrogen in fuel [1]. As a consequence, for the application of the premixed combustor, flame instability can hardly be avoided and NOx formation emission higher than the natural gas will be a very important technical problem. For this reason, many research efforts on premix type burners are being conducted to find how to make a stable flame and low NOx emission by using nitrogen and/or steam dilution of fuel [2,3].

Therefore, for an efficient premixed combustor in the IGCC power plant, the fundamental characteristics of combustion stability and NOx emission of the LCV fuel gas need to be investigated and would be useful in providing engineering guidelines for future R&D of a IGCC gas turbine combustor. In the present experimental study, a coal gas burner system was constructed with the flexibility in varying various fuel composition and equivalence ratio conditions, and flame behavior and stability of the coal gas were observed and furthermore thermal and fuel NOx emission values were measured.

EXPERIMENT

As shown in Fig. 1, the experimental apparatus is composed of fuel/air feeding, premix burner and gas sampling/analysis systems. LCV fuel gas is simulated as synthetic gas that is produced by mixing carbon monoxide, hydrogen, nitrogen and ammonia. The syngas is premixed with air, fed to and burnt on a flat flame burner with porous bronze water-cooled plate to produce uniform velocity distribution, and the burner does not employ the annular stream of inert gas as depicted in Fig. 1. Flame behavior picture is recorded by using a CCD/digital camera and image processing unit, and the NOx emission of sampled exhaust gas is analyzed.

RESULTS AND DISCUSSION

Before the syngas combustion test, a reference experiment was performed with natural gas fuel of the constant flow rate at 0.48 LPM. As shown in Figs. 2 and 3, the flame of natural gas remains stable on burner within the equivalence ratio range from 0.5 to 1.4, but blows out of the burner beyond this range. The blow-off at high equivalence ratio is caused by the breakdown of self-sustaining mechanism of flame that, at very high fuel/air condition, the heat release from flame is not sufficient for reactant to activate so flame is gradually reduced and blown out. But, the blow-off at low equivalence ratio is due to the high feeding velocity of reactant, exceeding the burning velocity of syngas. Fig. 3 also shows the NOx emission level from burning natural gas when equivalence ratio is varied and its peak is located at the equivalence of 1.

Syngas fuel is produced by mixing carbon monoxide and hydrogen to match the composition of actual coal gas fuel derived from oxygen blown gasifier, CO: 70-90% and H_2: 10-30% on volume basis. Fuel flow rate is determined on the basis that the thermal input of the syngas fuel is identical to that of natural gas as follows:

$$\text{Thermal input}=m_{NG}\times LHV_{NG}=m_{syngas}\times LHV_{syngas} \quad (1)$$

where m and LHV are the mass flow rate and the heating value of fuel, respectively.

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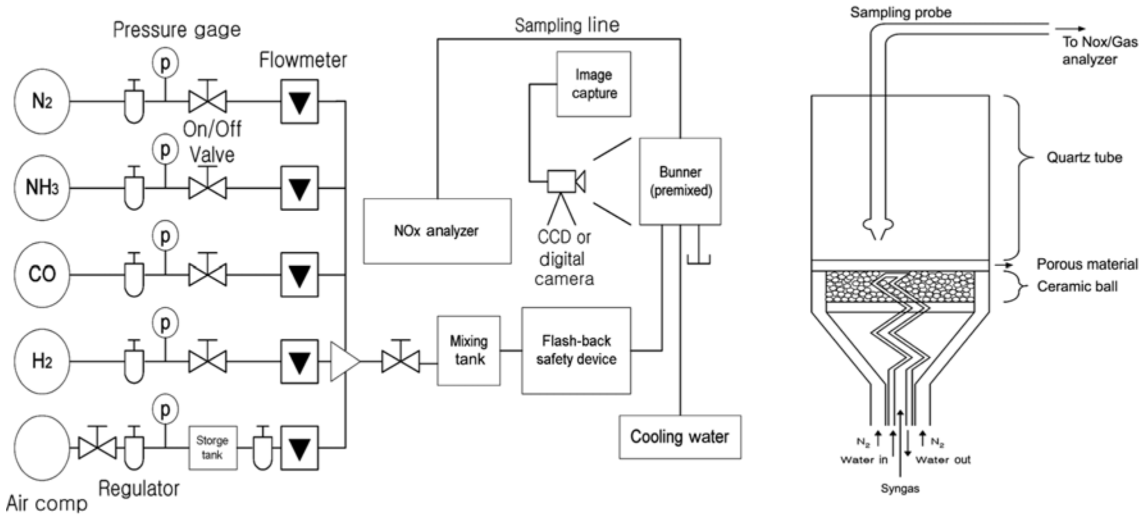


Fig. 1. Schematic Diagram of Experimental Apparatus and flat flame burner.

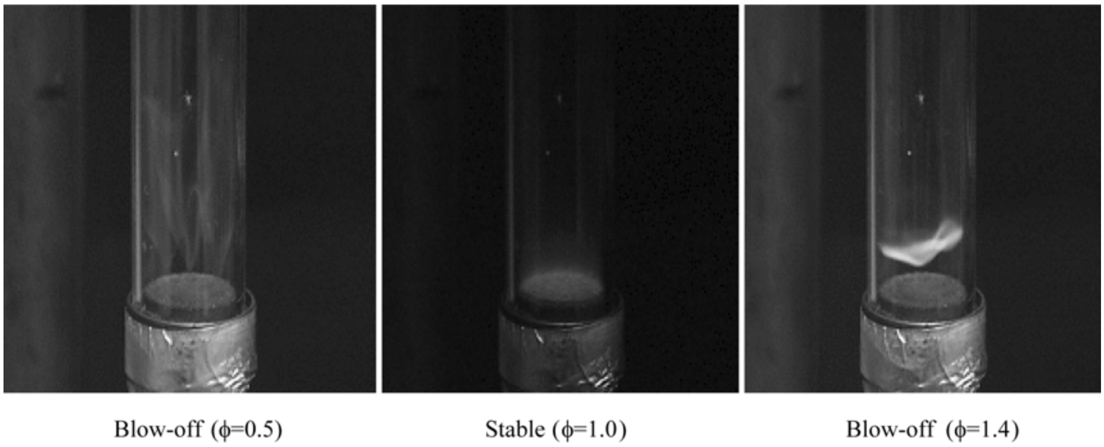


Fig. 2. Flame behavior of natural gas.

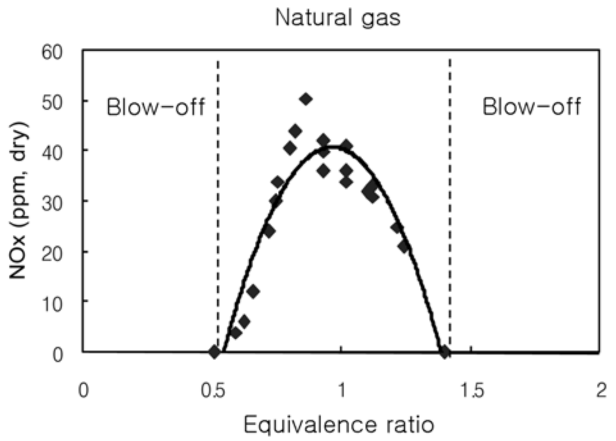


Fig. 3. NOx emission and flame stability of natural gas.

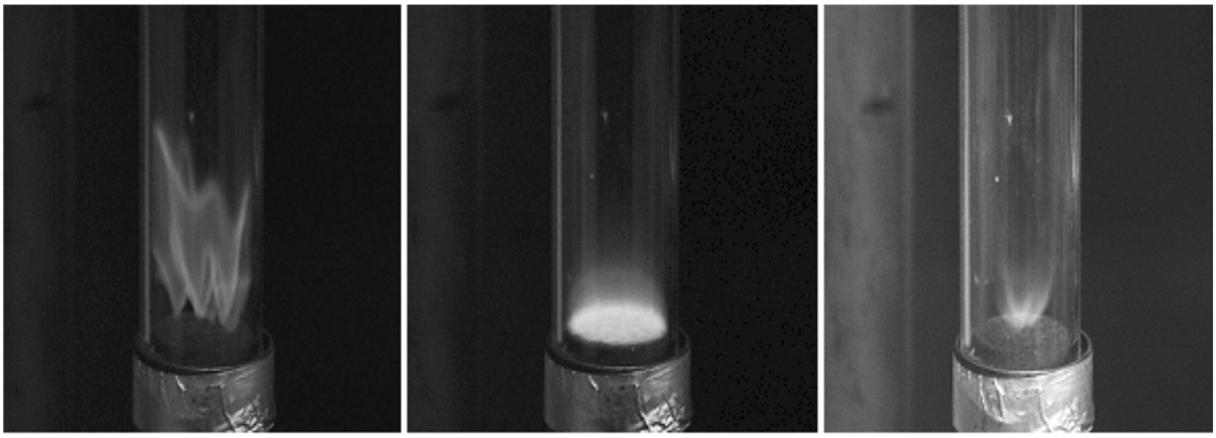
This fuel feeding condition with the same thermal input is required to simulate the actual burning condition of the combustor using syngas instead of natural gas and also to keep the heat loss from the burner for the syngas the same as the natural gas. Table 1 represents the fuel flow rates and the compositions of three different syngas fuels used in the present study.

Table 1. Composition and flow rate of syngas fuel

Syngas no.	CO (%)	H_2 (%)	H_2/CO (%)	Flow rate (LPM)
1	91.0	9.0	9.9	1.64
2	70.0	30.0	42.8	1.69

Fig. 4 is the set of pictures showing typical flame behaviors of syngas. As shown in Fig. 4, flash-back occurs at high equivalence ratio unlike the natural gas case because of the high burning velocity due to the H_2 content of syngas fuel.

Figs. 5 and 6 compare the flame stability ranges and the NOx emission levels of two syngases with H_2/CO=9.9 and 42.8%, respectively. They show that the flame stability range of syngas is shrunken into narrower range at higher H_2/CO ratio. These experimental results can be explained by the fact that the flashback point is shifted to lower equivalence ratio due to higher burning velocity of the syngas fuel containing higher H_2 content [4]. It is deduced from these measured results that if coal gas firing gas turbine com-



Blow-off (ϕ=0.6) Stable (ϕ=1.0) Flash-back (ϕ=1.5)

Fig. 4. Flame behavior of syngas #1.

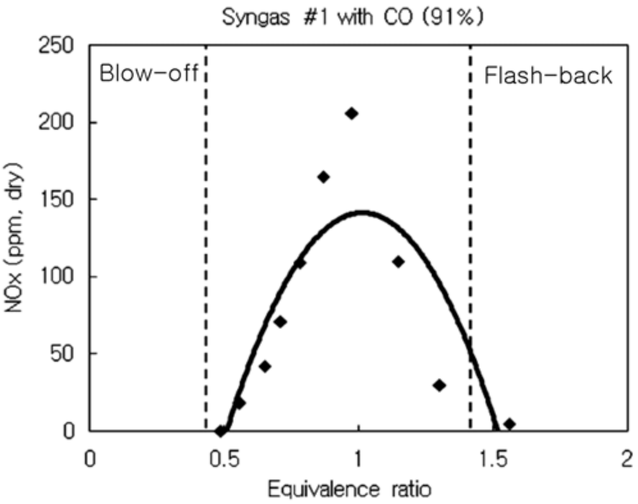


Fig. 5. NOx emission and flame stability of the syngas #1 without NH_3.

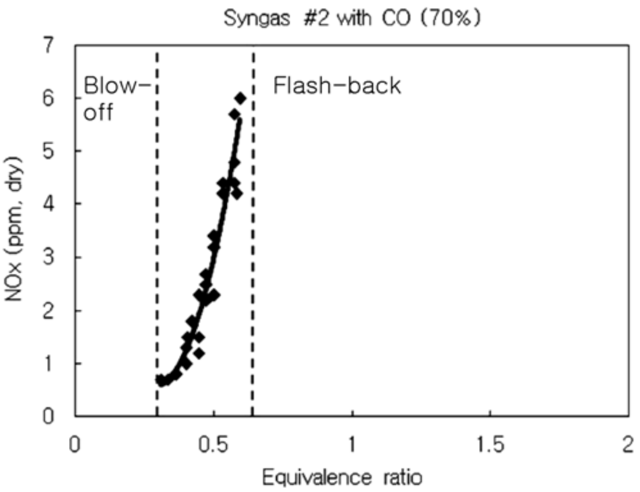


Fig. 6. NOx emission and flame stability of the syngas #2 without NH_3.

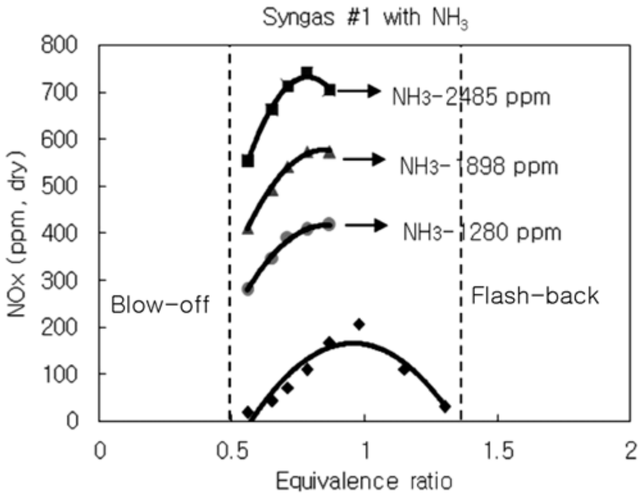


Fig. 7. NOx emission and flame stability of the syngas #1 with NH_3.

bustor is designed with the same burner as the natural gas case, it can be operated only at narrow stable combustion condition range, so careful design modification must be made on air distribution in combustor. Comparing Fig. 3 and Fig. 5, thermal NOx emission levels from syngas #1 are 100 ppm higher than the natural gas under the same equivalent ratio condition because the adiabatic flame temperature of syngas is about 200 K higher than the natural gas. However, as shown in Figs. 5 and 6, NOx emission is markedly reduced by increasing the H_2/CO ratio in syngas fuel because syngas fuel with higher H_2/CO ratio results in stable combustion range at lower equivalence ratio, giving very low flame temperature and NOx production rate.

In addition, the present study considers the NH_3 content of 0-3,000 ppm in syngas fuel, a major source of fuel NOx, to investigate the effect of NH_3 on total NOx formation. Figs. 7 and 8 show the variations of the NOx emission from the syngas containing NH_3. NOx emission is more produced by the magnitude of 200-500 ppm when compared with the results without NH_3, Figs. 5 and 6. The point for peak NOx emission is shifted to lower equivalence ratio com-

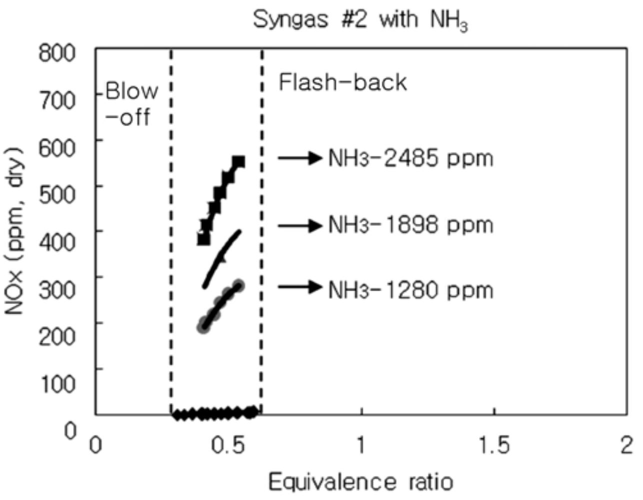


Fig. 8. NOx emission and flame stability of the syngas #2 with NH_3.

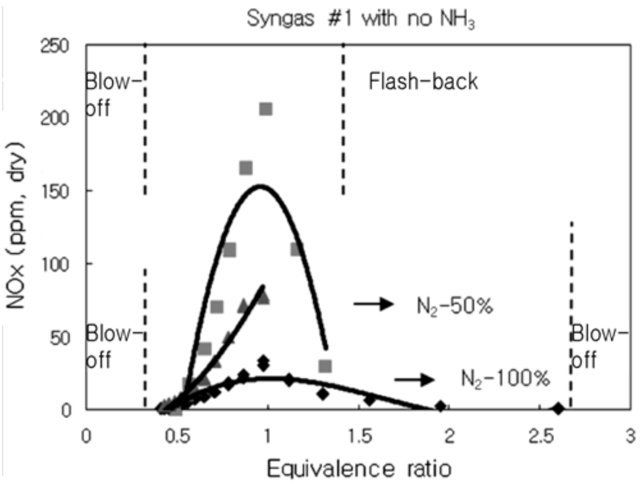


Fig. 9. NOx emission and flame stability of the N_2-diluted syngas #1 without NH_3.

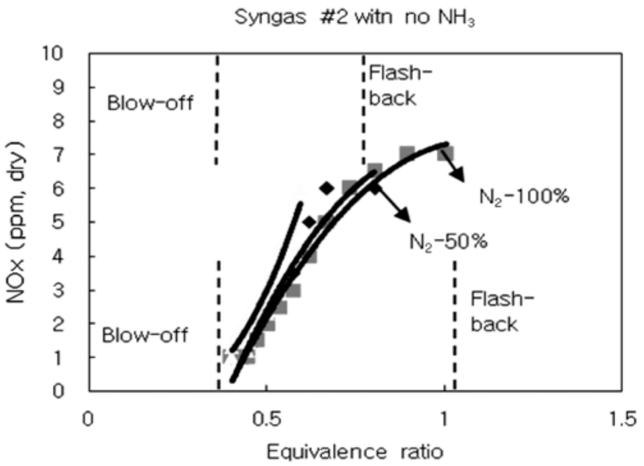


Fig. 10. NOx emission and flame stability of the N_2-diluted syngas #2 without NH_3.

pared with the thermal NOx cases shown in Figs. 5 and 6 because ammonia is known to be more easily converted to NOx at a low

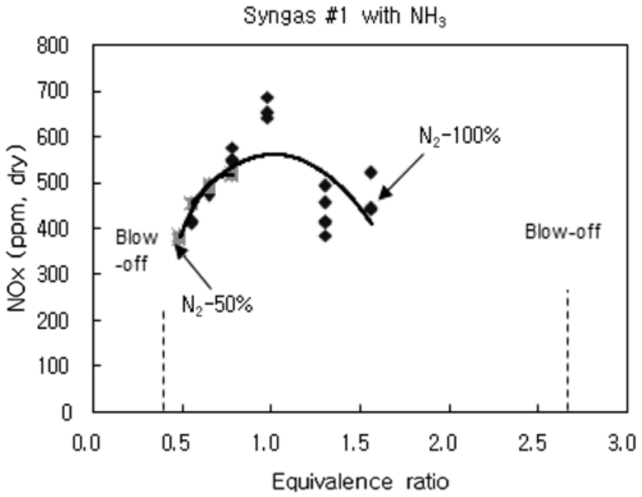


Fig. 11. NOx emission and flame stability of the N_2-diluted syngas #1 with NH_3.

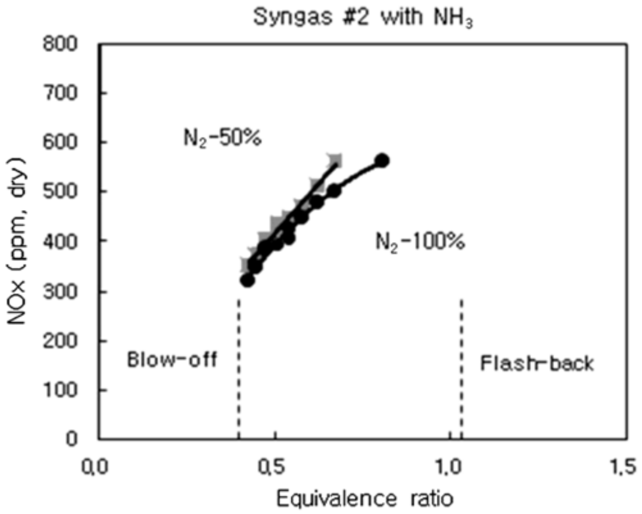


Fig. 12. NOx emission and flame stability of the N_2-diluted syngas #2 with NH_3.

equivalence ratio of less than 1, oxygen rich condition, where OH, O radicals are enough to oxidize ammonia [5,6]. It is also noted from Figs. 7 and 8 that the NH_3 content in syngas has no influence on flame stability range.

The effects of nitrogen dilution in syngas without NH_3 on NOx reduction are examined in Figs. 9 and 10. The present study considers the nitrogen diluent that is blended with syngas fuel before entering the burner, and its amount is considered as 50 or 100% of total fuel flow rate on volume basis. From Figs. 9 and 10, the effects of nitrogen dilution are shown positive in not only reducing NOx emission but also widening stable flame range. These results due to nitrogen dilution can be explained from the fact that thermal NOx emission is reduced by lowering flame temperature while flame stability enhancement is achieved by lowering burning velocity of syngas fuel at high equivalence condition.

For the syngases with NH_3 of 2,485 ppm, the effects of nitrogen dilution are shown in Figs. 11 and 12. Comparing Fig. 11 with Fig.

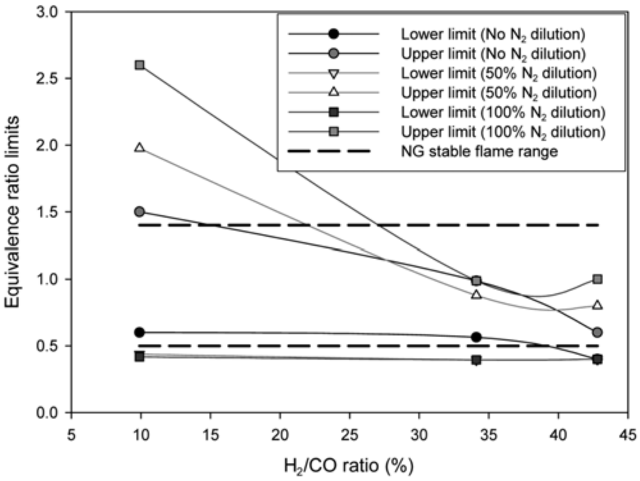


Fig. 13. Effect of the nitrogen dilution on flame stability range of syngas.

9, nitrogen dilution gives similar results on the stable flame ranges for both the syngases with and without NH_3. However, the NOx emission of Fig. 11 (thermal and fuel NOx) shows much higher level than that of Fig. 9 (thermal NOx only) since the NOx emission of the N_2-diluted syngas containing NH_3 is governed mainly by fuel NOx mechanism. This similar tendency is observed for the N_2-diluted syngas #2 with NH_3. From the above results, it is known that the nitrogen dilution of syngas fuel severely affects thermal NOx reduction but has minor effect on fuel NOx.

Fig. 13 shows the flame stability ranges for the syngases with nitrogen dilution. As can be seen in Fig. 13, for low H_2/CO syngas, nitrogen dilution markedly raises the upper limit due to flash-back while having minor effect on the lower limit due to blow-off, but for high H_2/CO syngas, nitrogen dilution cannot change the lower and upper limits of stable flame.

CONCLUSIONS

Flat flame burner tests were conducted for investigating flame stability and NOx emission characteristics of three LCV syngas fuels with the same thermal input as the natural gas case. Flame stability range is reduced to a narrower band of equivalence ratio and thermal NOx is less produced when burning the syngas with higher H_2/CO ratio. The effect of the nitrogen dilution in the syngas without NH_3 is very favorable both in reducing NOx emission and in widening stable flame range, and is more enhanced for the syngas with low hydrogen content.

The NH_3 content in syngas fuel results in additional fuel NOx emission as well as the shift of peak NOx point to the lower equivalence ratio compared with the thermal NOx case, and the major source of total NOx emission is due to fuel NOx mechanism. So, the effect of nitrogen dilution in the syngas with NH_3 is favorable in widening stable flame range while being minor in reducing NOx emission.

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