Experimental and Numerical Study on the Effect of COG/NH_3 Co-Combustion in Laminar Diffusion Burner

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Contents

Research background

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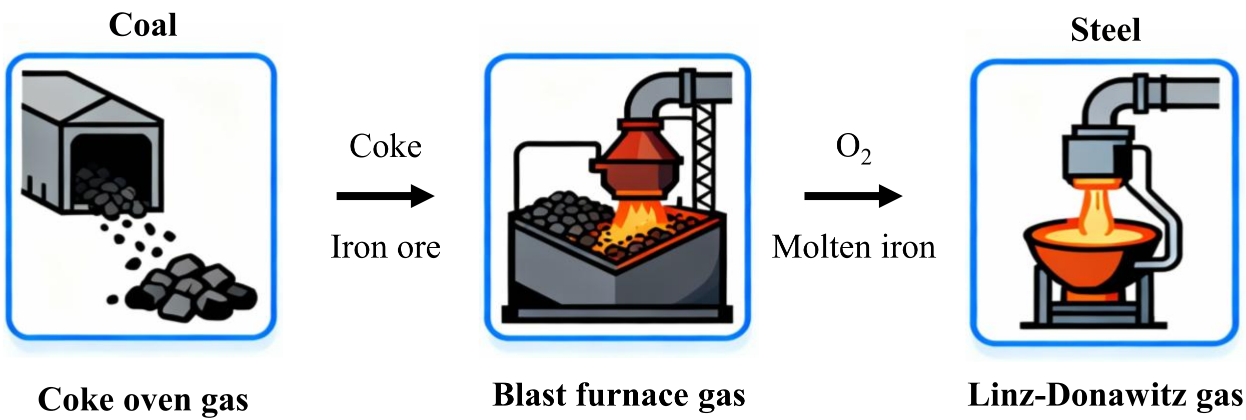
Steel industry by-product gases

: COG(Coke oven gas), BFG(Blast furnace gas), LDG(Linz-Donawitz gas)



By-product gas	H_2 (%)	CH_4 (%)	CO (%)	CO_2 (%)	N_2 (%)	Calorific Value (kJ/Nm^3)
Coke oven gas	55~60	22~28	7~10	1~3	3~5	17,580 ~ 18,420
Blast furnace gas	2~3	-	25~30	15~19	55~60	3,000 ~ 3,800
Linz-Donawitz gas	0~3	-	60~70	15~20	10~20	6,800 ~ 10,000

Ref. Coke oven gases processing by vacuum swing adsorption: Carbon capture and methane recovery, Jian Wang et al, *Separation and Purification Technology*, 2025

Research background

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Utilization of coke oven gas

Coke oven gas

- **Hydrogen extraction**
  - ✓ High-value utilization, industrial linkage
- **Use as fuel in boiler and burner**
  - ✓ Fuel cost reduction, internal energy recovery + NH_3
- **Use as blast furnace injection**
  - ✓ Improved process efficiency, CO_2 emission reduction

By-product gas	H_2 (%)	CH_4 (%)	CO (%)	CO_2 (%)	N_2 (%)	Calorific Value (kJ/Nm^3)
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Coke oven gas/NH_3 co-combustion in premixed conditions

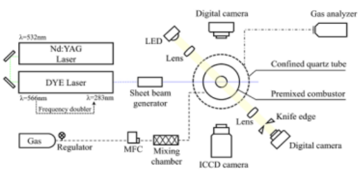
Experimental and numerical study of ammonia addition effects.., Jeon et al, *Case Studies in Thermal Engineering*, 2025

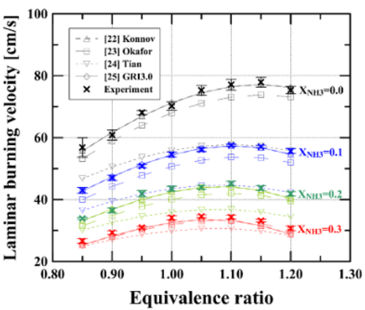
- **As the NH_3 concentration increases,**

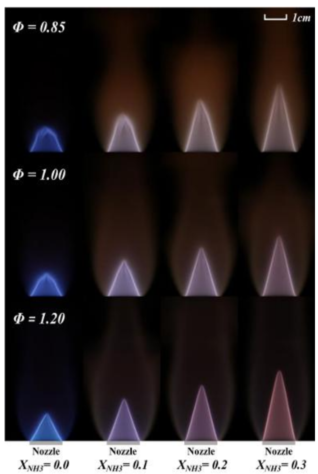
– The higher heating value decreases.

→ The laminar burning velocity **decreases**.

→ The Flame length **increases**.







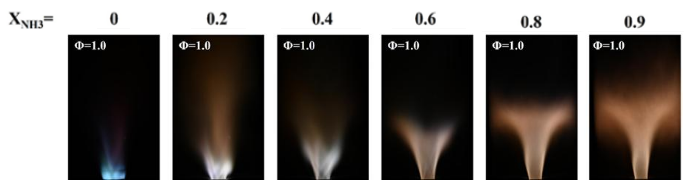
Combustion and emission characteristics of premixed coke oven gas-ammonia swirling flames, Sato et al, *Fuel*, 2026

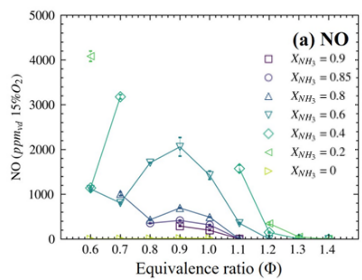
- **As the NH_3 concentration increases,**

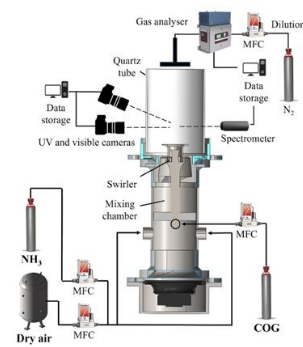
– The combustion reaction slow down & speed decreases.

→ The flame temperature **decreases**.

→ The entire flame elongated **downstream**.







Literature review

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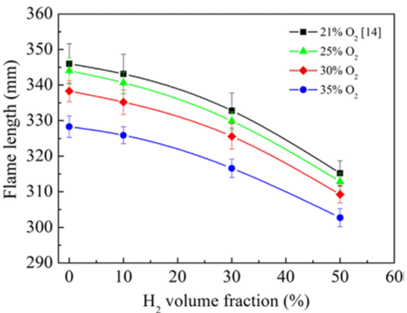
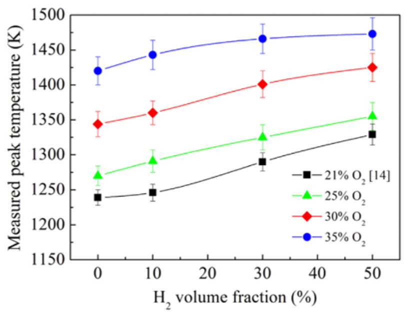
Variation of flame length and temperature with oxygen concentration

Ref. Experimental study on the effects of hydrogen addition on the emission and heat transfer characteristics of laminar methane diffusion flames with oxygen-enriched air, Long Wu, *International Journal of Hydrogen Energy*, 2016





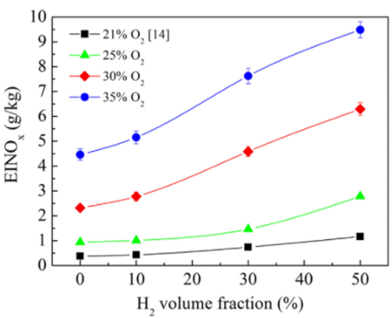
- **As the O_2 concentration increases,**

– The combustion reaction proceeds faster.

→ Flame length becomes **shorter**.

& Peak temperature **rises**.

Rising O_2 & Temperature



- **Promoting O radical formation & Increasing temperature**

→ Enhancing thermal NO_X production

- **NO_X formation via N_2O intermediate pathway** :

$N_2O + O \rightarrow N_2 + O_2$

$N_2O + O \rightarrow NO + NO$

$O + N_2 (+M) \rightarrow N_2O (+M)$

$N_2O + H \rightarrow NO + NH$

Object

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Experiment Cases

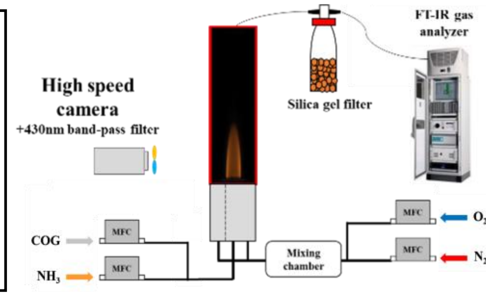
1. COG 100%
2. COG 90%, NH_3 10%
3. COG 80%, NH_3 20%
4. COG 70%, NH_3 30%

Combustion improvement

Formation of oxygen-enriched conditions

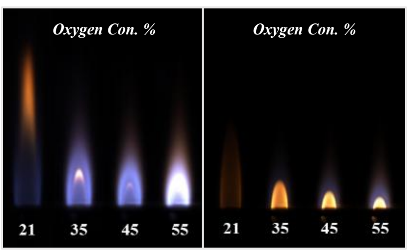
O_2 concentration [%]

21/25/30/35/40/45/50/55



Flame structure analysis

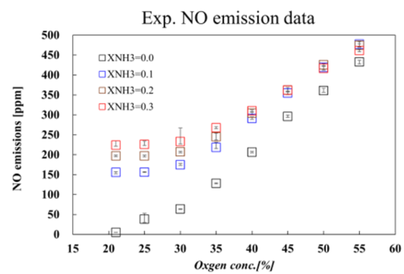
- Flame image comparison
- Flame intensity



$X_{NH3} = 0.0$ $X_{NH3} = 0.3$

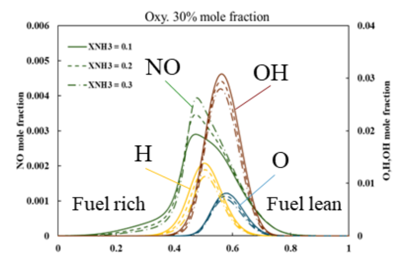
Gas emission analysis

- CO_2 emissions
- NO_X emissions



Reaction pathway

- Reaction pathway
- NO_X formation mechanism



Utilizing byproduct gases co-combustion NH_3 under oxygen-rich conditions

Reducing CO_2 emissions and analyze NO_X formation pathway

Experimental apparatus

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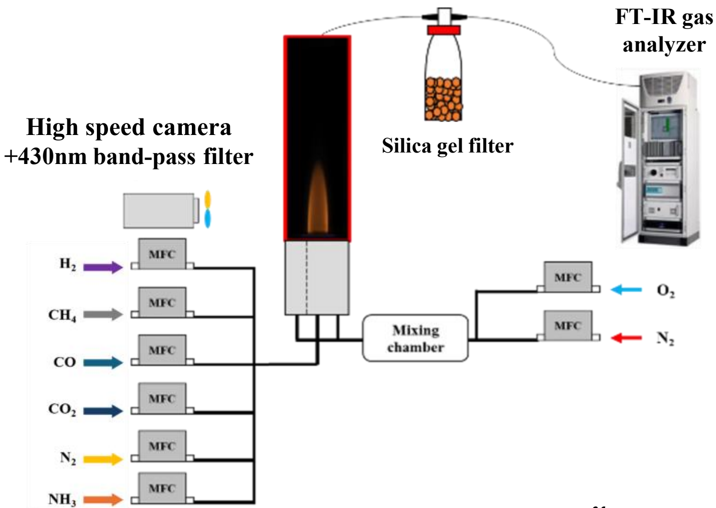
Schematic of an experimental apparatus



- **Fuel composition of coke oven gas**

Fuel composition	Concentration (vol. %)
H_2	62
CH_4	22
CO	6
CO_2	3
N_2	7

$$* X_{NH3} = \frac{x_{NH3}}{x_{fuel} + x_{NH3}}$$

- **Experimental conditions**

Experimental parameters	Value
$* X_{NH3}$	0/0.1/0.2/0.3
Fuel flow rate (L/min)	1
Oxygen concentration (%)	21/25/30/35/40/45/50/55

- ***Fuel Higher heating value(HHV)**

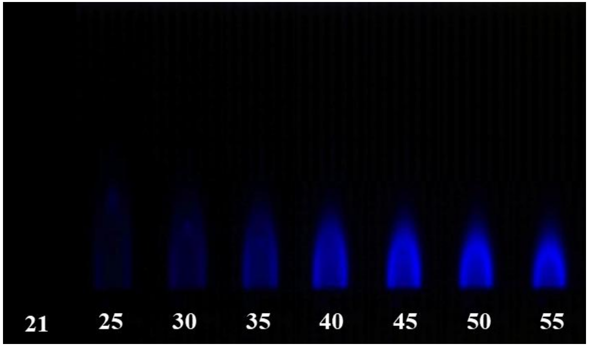
X_{NH3}	HHV	
	MJ/kg	Kcal/Nm^3
0.0	40.87	4756.81
0.1	38.15	4689.58
0.2	35.71	4622.06
0.3	33.49	4554.45

Ref. Experimental and numerical study of ammonia addition effects on combustion characteristics…, Jeon et al, *Case Studies in Thermal Engineering*, 2025

Research results

Laminar diffusion flame image at X_{NH3} = 0.0

X_{NH3}=0.0 direct image



X_{NH3}=0.0 CH radical image*

- As O_2 increases, the flame length decreases.
  → The combustion reaction proceeds faster, expecting an increase in flame temperature.
  → The flame color shifts from yellow hues to blue hues.
- At Oxy. 21~35%, CH_4 and CO fuels are not completely combusted.
  → The emission of fine carbon particles (soot), *producing the yellow flame color.
- At Oxy. Above 35%, there is sufficient O_2 for complete combustion of CH_4 and CO.
  → Minimal soot formation and emission from CH* radical causes the flame to appear blue.

Ref. Study on Soot Emission Characteristics of Methane/Oxygen Inverse Diffusion Flame, Wu et al , *ACS OMEGA*, 2021

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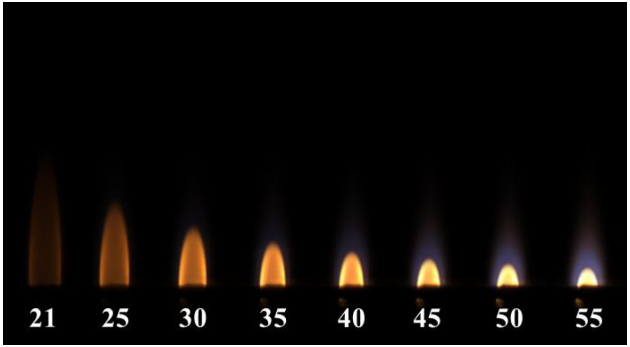
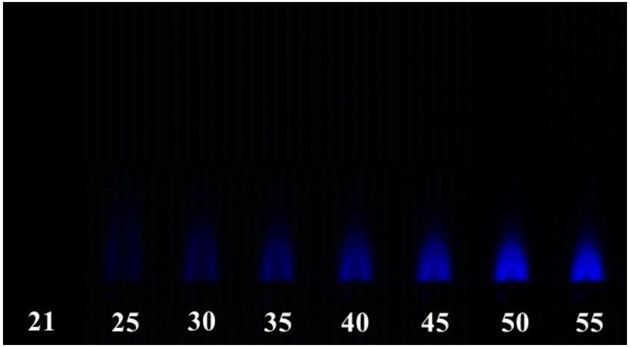
Laminar diffusion flame image at X_{NH3} = 0.3



X_{NH3}=0.3 direct image



X_{NH3}=0.3 CH radical image*

- As O_2 increases, the flame length decreases.
  → The combustion reaction proceeds faster, expecting an increase in flame temperature.
- Complete combustion of NH_3 produces intensified orange flame color. (NH* radical spectral)
- Increasing O_2, CH_4 and CO undergo complete combustion.
  → Blue flame color caused by CH* radical emission.

➡ The high O_2 promotes the combustion reaction even with NH_3 co-combustion.

Research results

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Experimental CO_2 emissions data

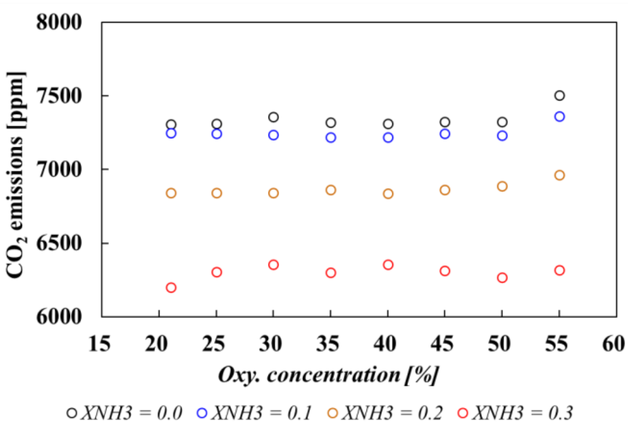
$$* \left(1 - \frac{CO_{2_X}}{CO_{2_{COG}}}\right) \times 100\ [\%]$$

- **Gas concentration differences with COG [LPM]**

Gas	$X_{NH3} = 0.1$	$X_{NH3} = 0.2$	$X_{NH3} = 0.3$
CH_4	- 0.02	- 0.04	- 0.06
CO	- 0.01	- 0.01	- 0.02
CO_2	- 0.01	- 0.01	- 0.01

- **CO_2 reduction rate compared to COG basis**

O_2 [%]	$X_{NH3} = 0.1$	$X_{NH3} = 0.2$	$X_{NH3} = 0.3$
21	0.77	6.33	15.14
35	1.37	6.23	13.92
55	1.92	7.24	**15.82**



- NH_3 addition increases lead to a CO_2 decrease.
- Complete combustion of CH_4 and CO causes CO_2 increase.
- Compared to COG, the reduction rate of CO_2 increases.

Research results

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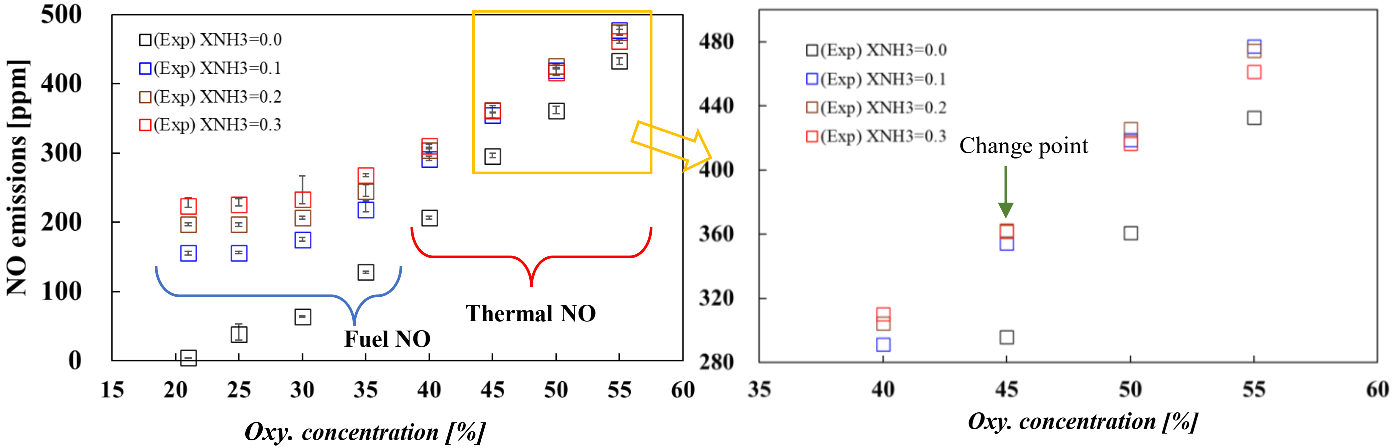
Experimental NO emissions data



- The addition of NH_3 increases the fuel N, resulting in increase NO formation. (**Fuel NO**)
- As O_2 increases, the intervals become narrower.
- When above oxy. 45%, a reversal in NO values is observed. (**Thermal NO**)

  → The addition of NH_3 lowers the heating value of the fuel.

  → The X_{NH3} = 0.1 flame temperature will be higher than X_{NH3} = 0.3

Research results

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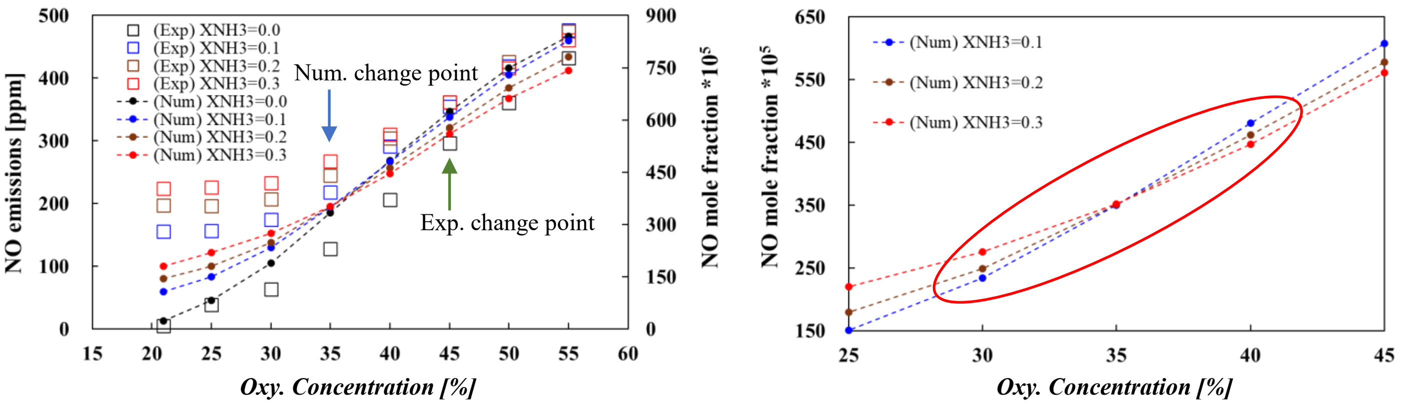
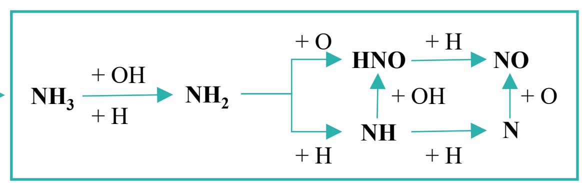
1-D analysis : NO mole fraction



- Adiabatic conditions in 1-D analysis, num. flame temperature is higher than exp. flame.
- Increasing O_2, the abundance of O*, H*, OH* radical will influence NO formation.
- In oxy. 30 ~ 40% range, The reversal of NO formation was also confirmed. (Exp. Oxy. 45 ~ 55%)



Research results

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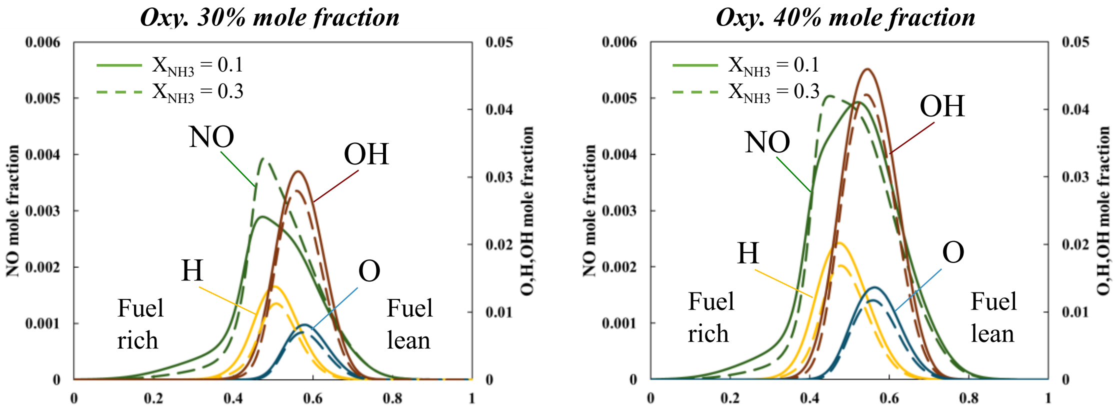
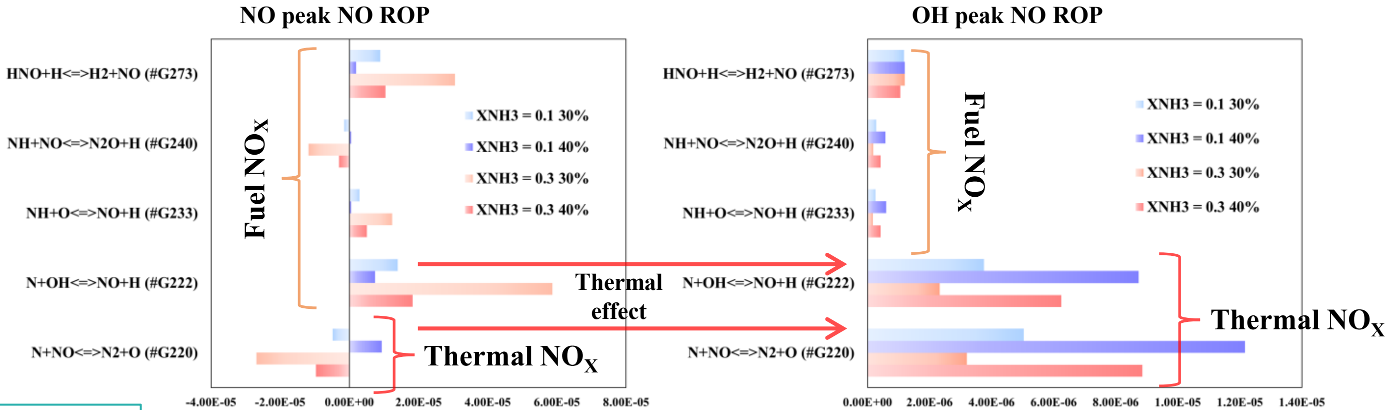
Numerical NO mole fraction



- At Oxy. 40%, O, H, OH, NO formation increases sharply. (Especially, NO value at $X_{NH3} = 0.1$)
  → accelerating the combustion and causing the OH peak to shift toward the fuel.
- The OH marks the flame front where fuel and oxidizer react most actively.
- The NO mole fraction exhibits a similar trend to the H mole fraction.
  → The NO ROP (Rate of Production) reaction pathway analyzed at the OH peak.
  → The reaction pathways in which NO and H main products.

Research results



NO peak

- The main reactions yield both NO and H. (#G222, #G233)
- The radicals generated from NH_3 mainly influence NO formation. ($NH_3 \rightarrow NH_2 \rightarrow NH \rightarrow N$)
  $\rightarrow$ **Fuel NO** > Thermal NO

OH peak

- The reaction is most active, leading to a sharp increase in NO. (Thermal effect)
- $X_{NH3} = 0.1$ has a higher heating value than $X_{NH3} = 0.3$.
- At the $X_{NH3} = 0.1$, thermal NO is generated. (#G220 $N_2 + O \rightarrow N + NO$).
- The N produced from #G220 causes further excessive NO formation. (#G 222 $N + OH \rightarrow NO + H$)
  $\rightarrow$ Fuel NO < **Thermal NO**

Conclusions

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Flame structure analysis

- As O_2 increases, the combustion reaction proceeds faster.
  - The flame length decreases.
  - The flame color shifts from yellow hues to blue hues.

  → The high O_2 promotes the **combustion** and **flame stability** even with NH_3 co-combustion.

Gas emission analysis

- CO_2 emissions
  - NH_3 addition increases lead to a CO_2 decrease.
  - Compared to COG, the reduction rate of CO_2 increases.
- NO emissions
  - NO emissions increases with increasing oxygen concentration.
  - At low O_2 concentrations, the **fuel NO** effect becomes more dominant due to increased fuel N.
  - At high O_2 concentrations, the **thermal NO** is more significant due to elevated flame temperature.

Future work

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Experimental contents

- Flame temperature measurement.
- OH radical flame image observation.
- Conduct experiments with increased NH_3 ratio. (XNH_3 = 0.4, 0.5, 0.6 ----)

Numerical contents

- Conduct 1-D analysis considering heat loss based on flame temperature measurements.
- Apply alternative models to identify a model that better fits the experimental results.
- Perform further analysis of fuel NO_X and thermal NO_X formation mechanisms.
- Explore solutions for NO_X reduction.

Acknowledgment

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THANK YOU FOR YOUR ATTENTION!

Pusan National University

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Appendix

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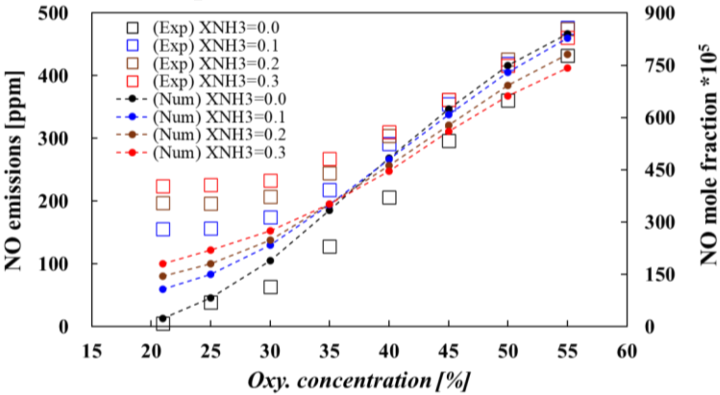
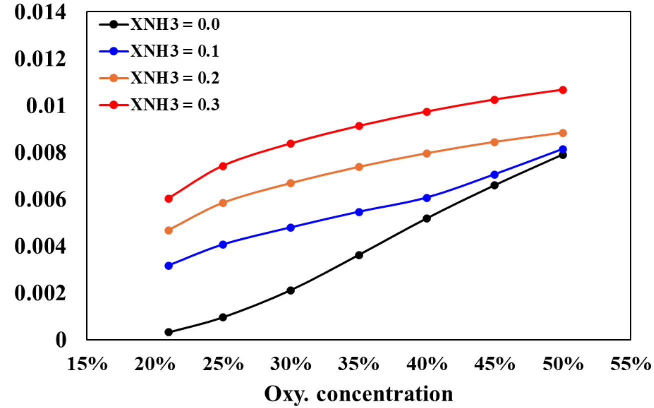
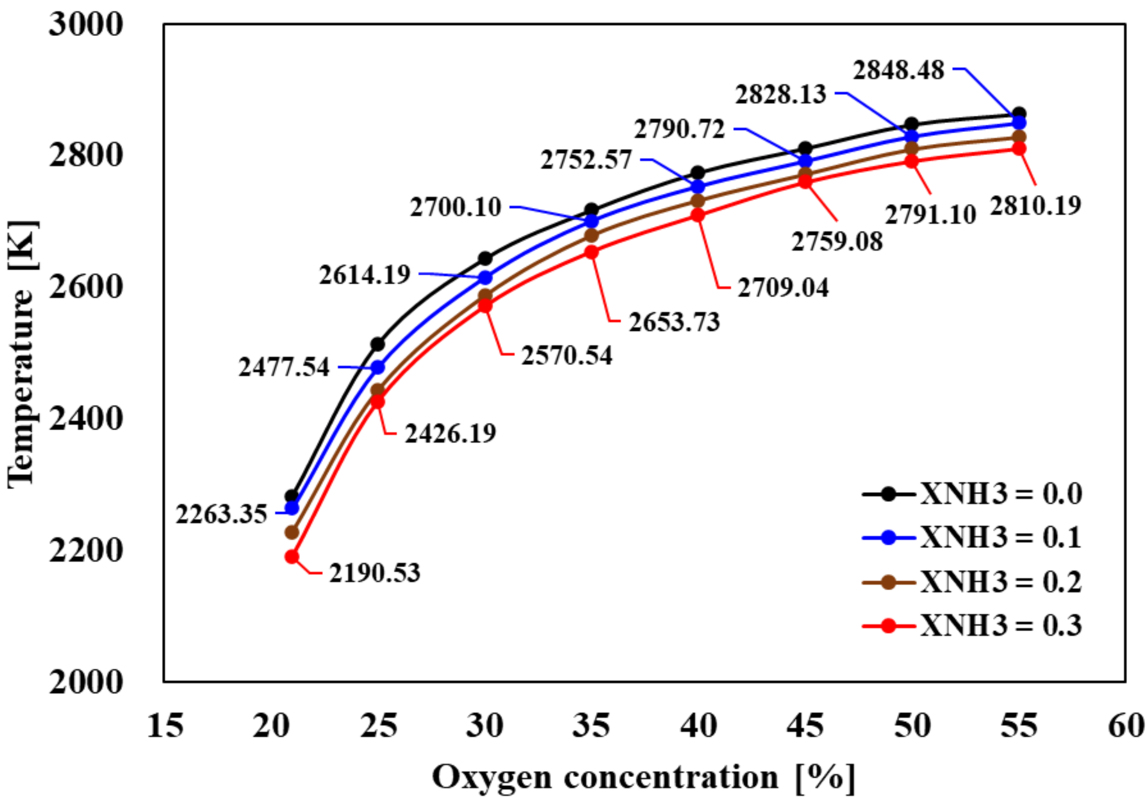
Experiment & Okafor model



NO mole fraction_Gri model




3000
2800
2600
2400
2200
2000
Temperature [K]
15
20
25
30
35
40
45
50
55
60
Oxygen concentration [%]
2848.48
2828.13
2790.72
2752.57
2700.10
2614.19
2477.54
2263.35
2190.53
2426.19
2570.54
2653.73
2709.04
2759.08
2791.10
2810.19
XNH3 = 0.0
XNH3 = 0.1
XNH3 = 0.2
XNH3 = 0.3