R&D Experiences for NH_3 combustion in KIER

- Fundamental staging-combustion behavior
- Co-firing with pulverized coal particles

Hookyung LEE (Ph.D.)

Combustion Group in Energy Efficiency Research Division

E-mail : hk.lee@kier.re.kr

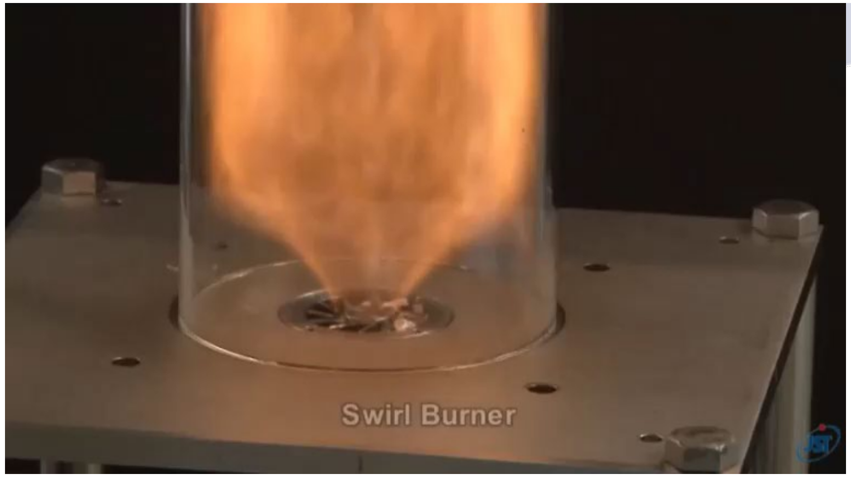
KIER 한국에너지기술연구원
KOREA INSTITUTE OF ENERGY RESEARCH

Most Known Facts about NH_3 Combustion

KIER Great 1st

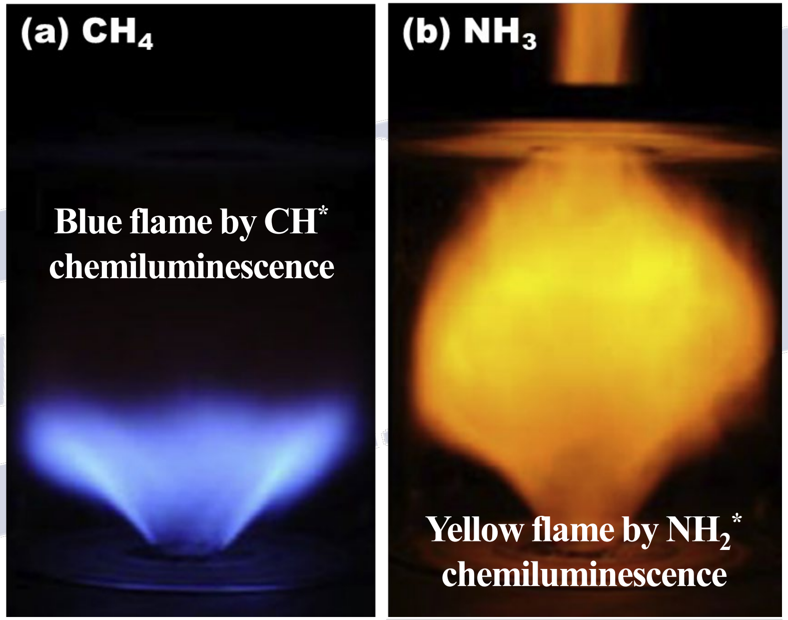
➢ **Difficult ignition and flame stability conditions due to very low burning rates**

Apparent flame images



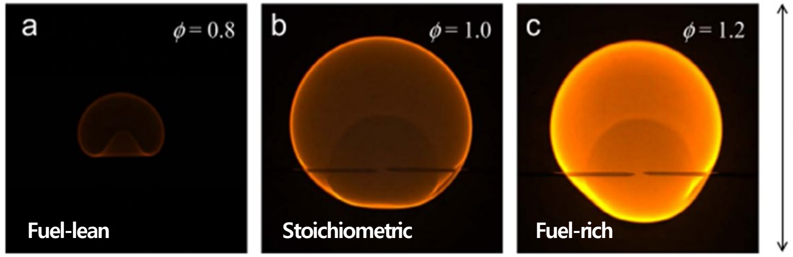
[SIP Energy Carriers PJT, Japan]

Stabilized premixed flame
under the same flow rate and equivalent ratio conditions (swirl flow condition)

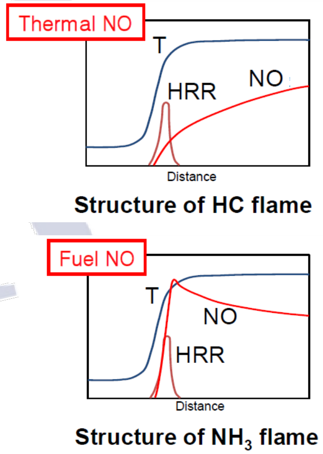


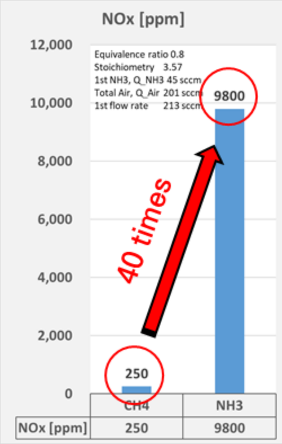
$CH_4+2(O_2+3.76N_2) \rightarrow CO_2+2H_2O+7.52N_2$ | $4NH_3+3(O_2+3.76N_2) \rightarrow 6H_2O+13.28N_2$

Spherical propagation flame according to equivalence ratio

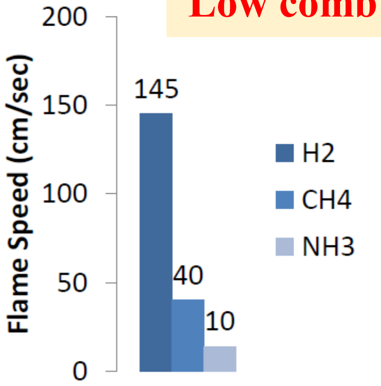


Excessive NO_x emission





Low combustion rate



Burning velocity

1/4 level compared to LNG (CH_4)

1/15 level compared to Hydrogen (H_2)

Key Policy for NH_3 Use in Co-generation in Korea

➢ **National Power Supply Plan : Advanced recognition of carbon emission reduction by using H_2 and NH_3**

[2030 NDC goal '21.10] <2030 Energy mix plan>

(unit: TWh)

	Nuclear	Coal	LNG	Renewable	NH_3	Others	Total
Gen. amount	146.4	133.2	119.5	185.2	22.1	6.0	612.4
Share	23.9%	21.8%	19.5%	30.2%	3.6%	1.0%	100.0%

[10_{th} National power supply plan '23.1]

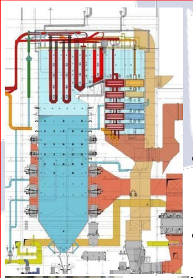
Forecast of gen. amount and share by power source (unit: TWh)

YEAR	-	Nuclear	Coal	LNG	Renewable	H_2 NH_3	Others	Total
'30년	Gen.amount	201.7	122.5	142.4	134.1	13.0	8.1	621.8
	Share	32.4%	19.7%	22.9%	21.6%	2.1%	1.3%	100%
'36년	Gen.amount	230.7	95.9	62.3	204.4	47.4	26.6	667.3
	Share	34.6%	14.4%	9.3%	30.6%	7.1%	4.0%	100%

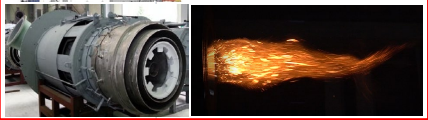
Forecast of H_2 and NH_3 power generation in 2030

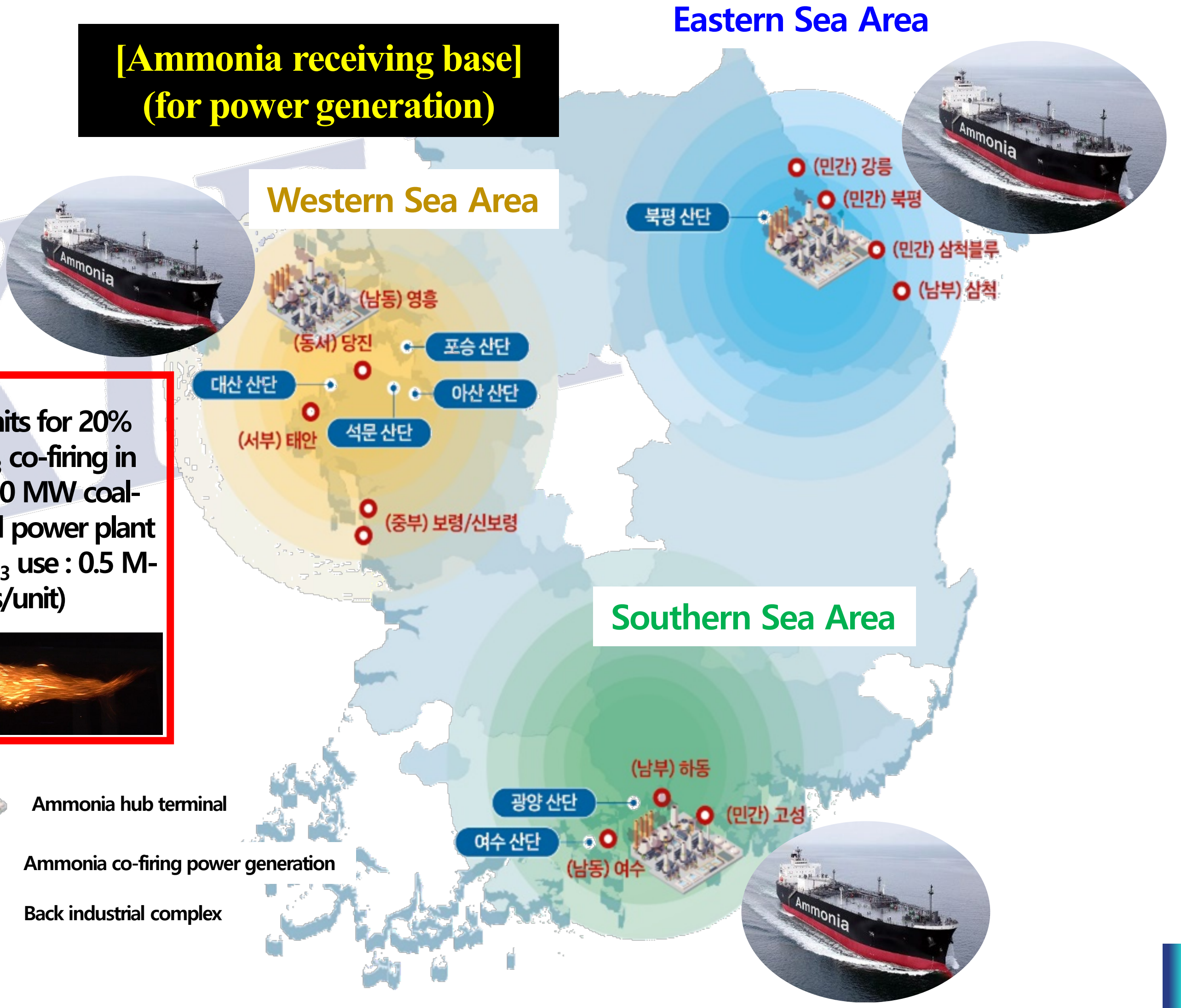
-	Fuel amount	Gen. amount	Target Power
Hydrogen	0.3 million-tons	6.1TWh	LNG
Ammonia	2.96 million-tons	6.9TWh	Coal

-	'30년	'36년
Hydrogen Gen. amount (TWh)	6.1	26.5
Ammonia Gen. amount (TWh)	6.9	20.9



6 units for 20% NH_3 co-firing in 1,000 MW coal-fired power plant (NH_3 use : 0.5 M-tons/unit)

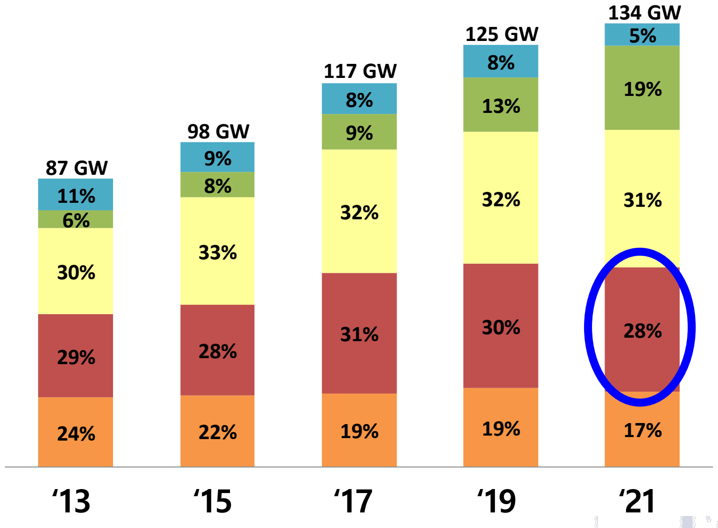




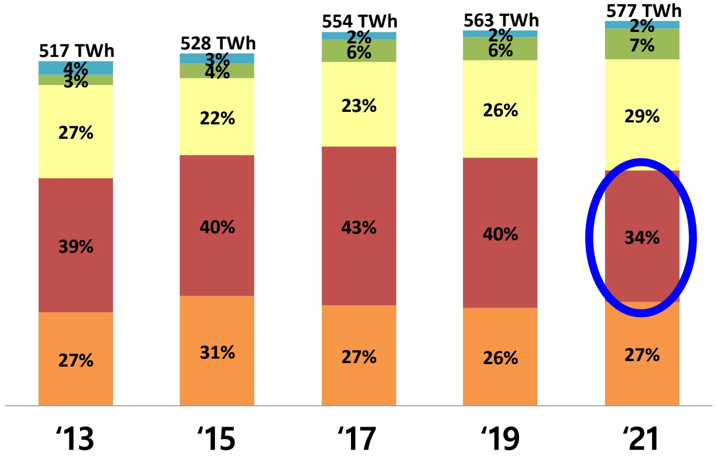
Demonstration Plants for Fuel Conversion to NH_3 (first-step with coal)

Nuclear | Coal | LNG | Renew. | Etc

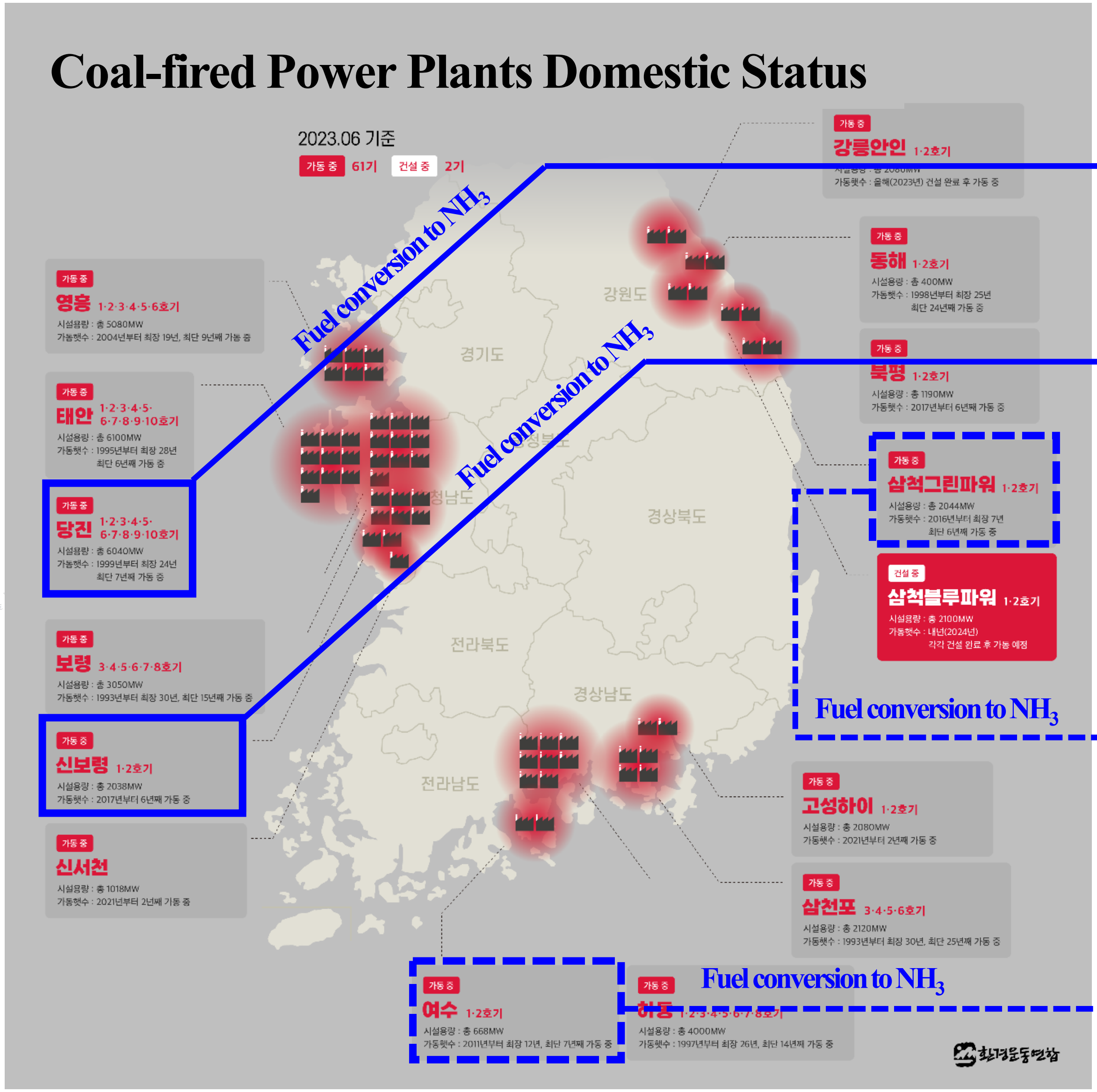
➢ Facility capacity in power sources [GW]



➢ Power gen. amount in power sources [TWh]



10_{th} National power supply plan



Pulverized coal - 20% NH_3 co-firing

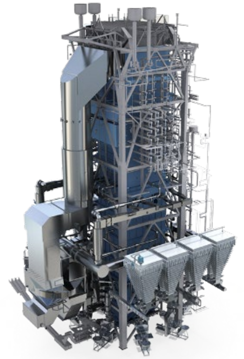
CFBC - 20% NH_3 co-firing

Current Status of NH_3 Combustion Research in Korea

- **National R&D is underway in the power generation sector, such as coal-fired boilers and gas turbines (marine engine), and in the steel sector, such as heating furnace burners**

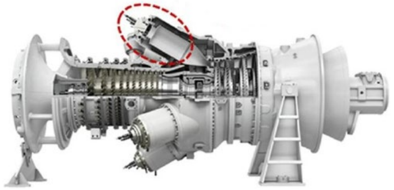
Power (Coal-fired BLR)

- ~ '22: NH_3-coal co-firing fundamental R&Ds
- '23 ~ '27: 20% [NH_3] co-firing complete in 1,000 MW PC TPP
- '30: Higher* [NH_3] co-firing
  * TBD (R&D in progress)
- '35: 100% [NH_3] firing complete



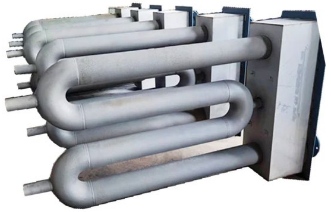
Power (Gas TBN combustor)

- '13 ~ '19: 270 / 380 MW NG-GT R&D with proprietary tech. (Doosan Enerbility)
- '21 ~ '24: NG-NH_3 co-firing fundamental R&Ds
- '24: NG-GT complete in commercial-scale CCPP
  NG-H_2 50% co-firing R&D combustor (270 MW)
- '25: 100% [H_2] firing R&D (5 MW)
- ~ '35: 100% [NH_3] firing
  100% [H_2] firing
  NH_3 cracked H_2 firing



Industrial (Furnace BNR)

- ~ '25: 100% [NH_3] Radiant tube BNR R&D
- ~ '27: 100% [NH_3] Radiant tube BNR complete in commercial scale



**Planning of R&D programs for NH_3 utilization is also underway in petrochemical and cement plants*

Korea Institute of Energy Research (KIER)

KIER Great 1st

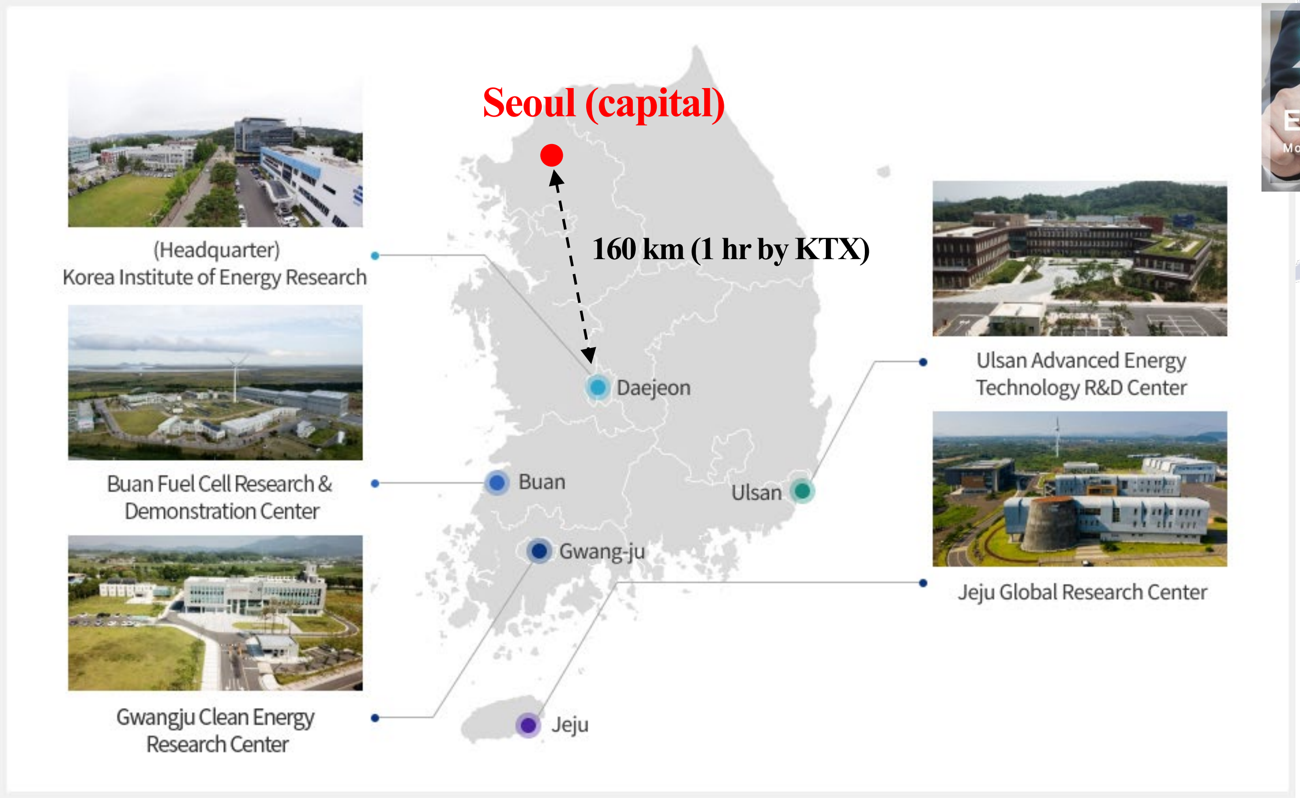
➢ **One of the National Research Institute Funded by Korean Government**

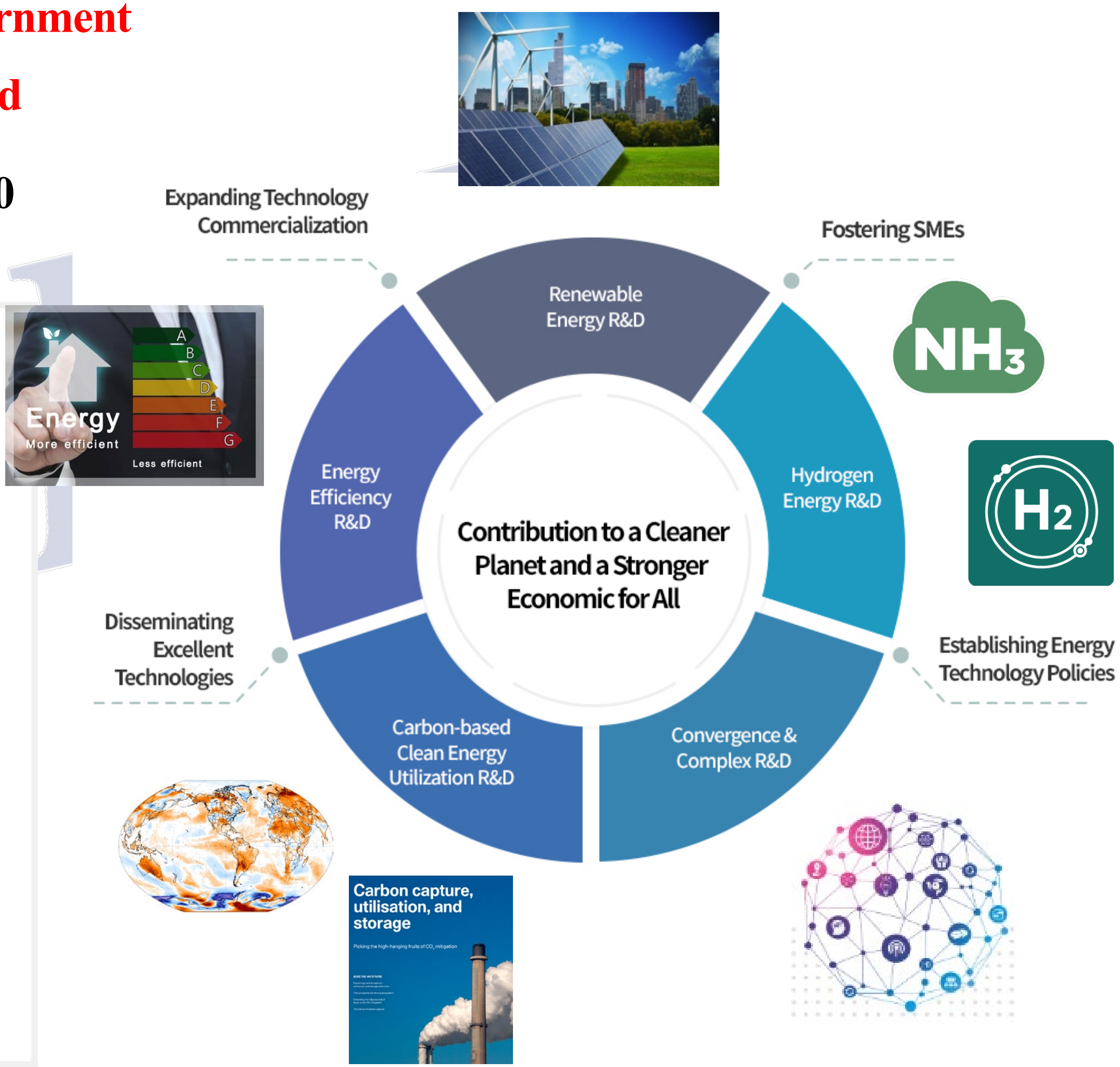
- Representative R&D Institute in the Combustion & Energy Field

Personnel : 550 (full-time) / Ph.D. 350

H/Q Location : Daejeon

Budget : $ 160 M/yr (USD)





Combustion Group in KIER

KIER Great 1st

➢ **A group of combustion experts (15) who have been conducting combustion research <u>for over 40 years in a KIER lab.</u>**

- Application to power generation, steel treatment and petrochemical processes

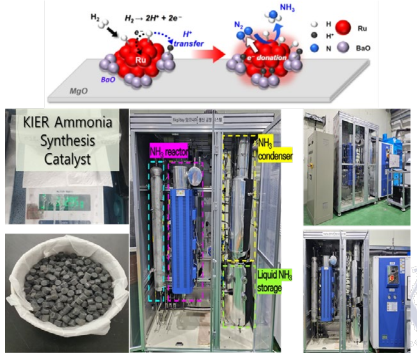
	1990s	2000s	2010s	2020s
Body system	Rolling heating furnace design *Al* melting furnace	Roller kiln Shuttle kiln Forging furnace Shuttle kiln	Oxy-fuel heating furnace Smart EAF CAL system	Smart furnace design platform
Comb. device	Low P pneumatic oil BNR Flat BNR Hot air BNR Low NOx BNR Metal fiber BNR	High V BNR Heat storage BNR RT heat storage BNR	sCO2 combustor Oxy-fuel BNR Porous media BNR Semi-conductor process BNR	H_2/NH_3 firing BNRs NH_3 co-firing BNRs & system NH_3 firing BNRs & system
Waste heat recovery	Waste heat recovery BNR Channel recuperator Radiation recuperator	Ceramic recuperator		
Furnace control	Furnace control / PLC design		Furnace combustion optimization	
etc	Gas torch	Plasma	Oxy-fuel boiler	Electrification

Ammonia Research Flows in KIER

➢ **Full-cycle research is being conducted from NH_3 production, utilization (combustion, fuel cell) and post-treatment technology**

Production

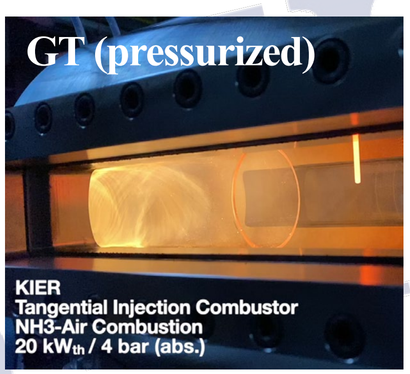
➢ NH_3 synthesis in low T and low P



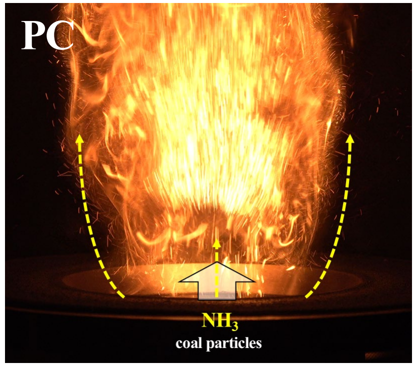
➢ H_2 prod. with NH_3 decomposition

Utilization

➢ NH_3 -only combustion



➢ NH_3 combustion with other fuels

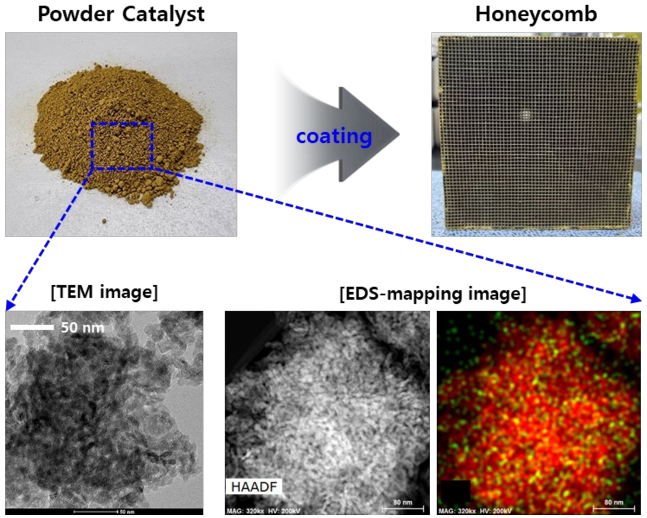


Post-treatment

➢ N-complex species

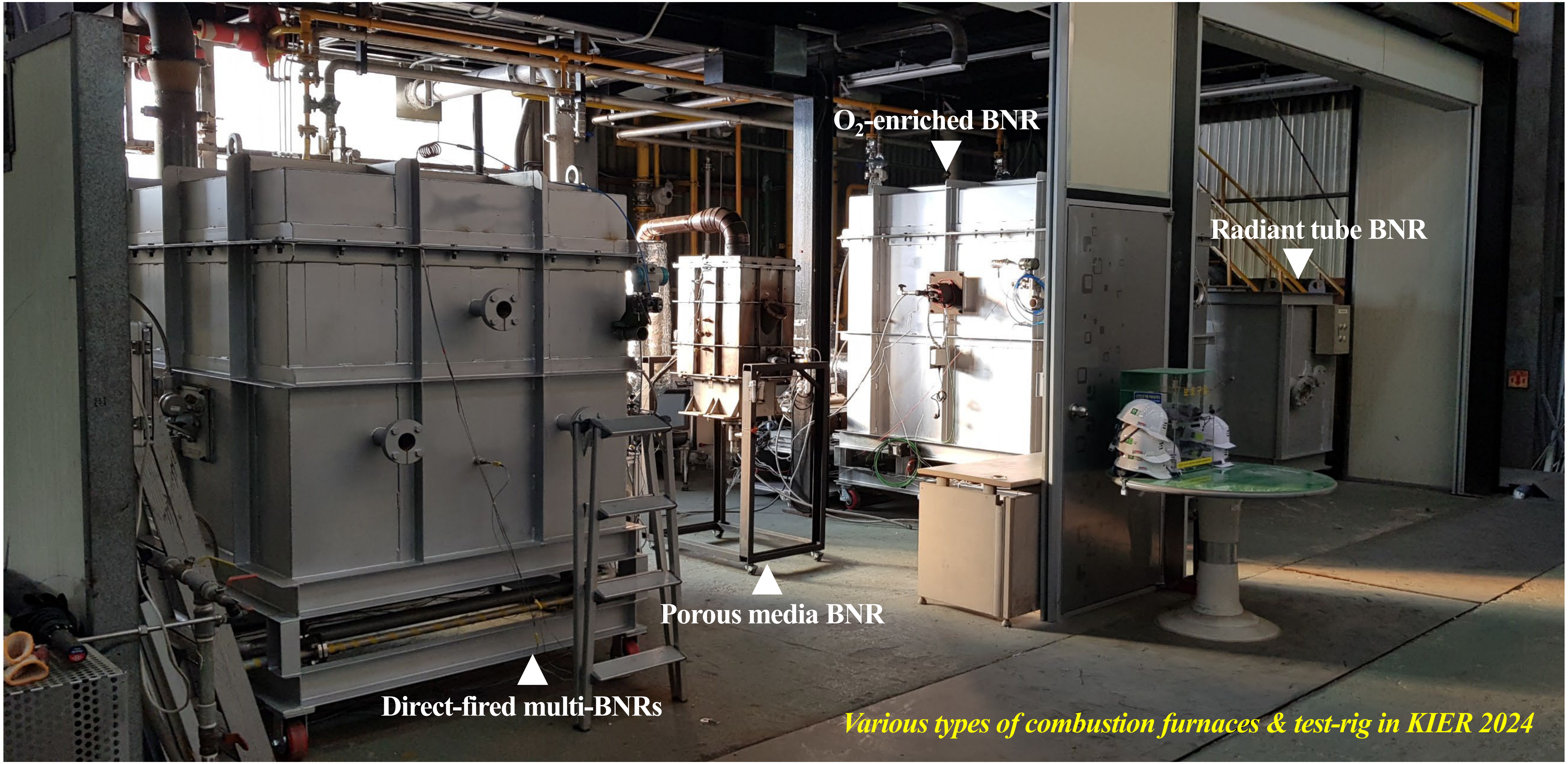
- NO, NO_2, N_2O, (slipped) NH_3
- Simultaneous reduction

KIER SCR Catalyst



NG-NH_3 Co-firing Facility at KIER

KIER Great 1st

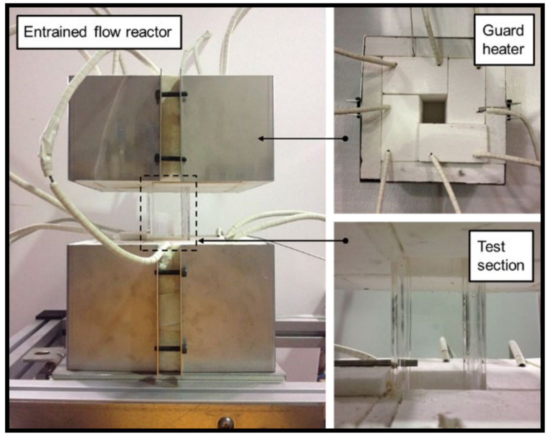


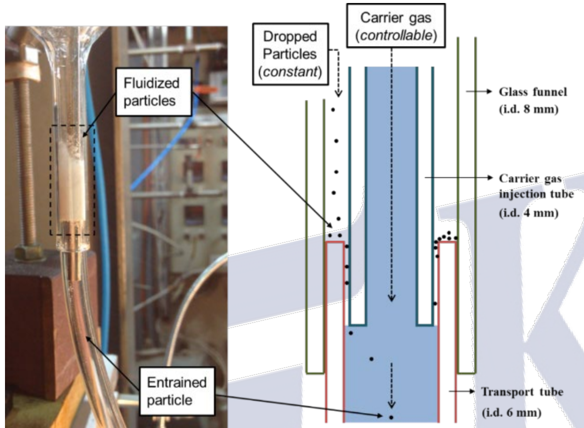
Various types of combustion furnaces & test-rig in KIER 2024

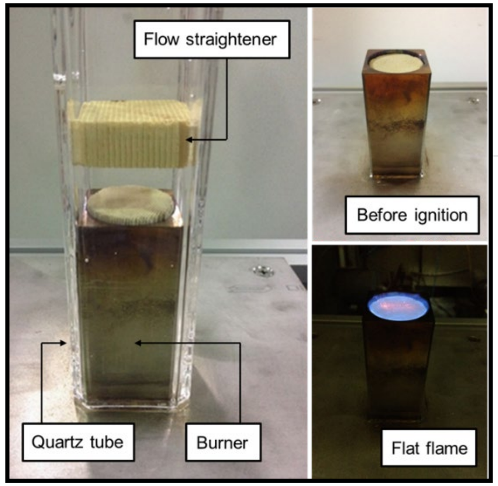
Pulverized Coal-NH_3 Co-firing Facility at KIER

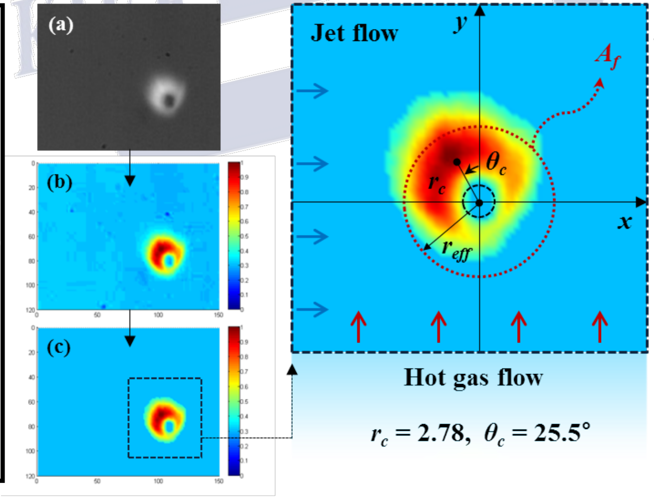
KIER Great 1st

「Single coal particle combustion system」

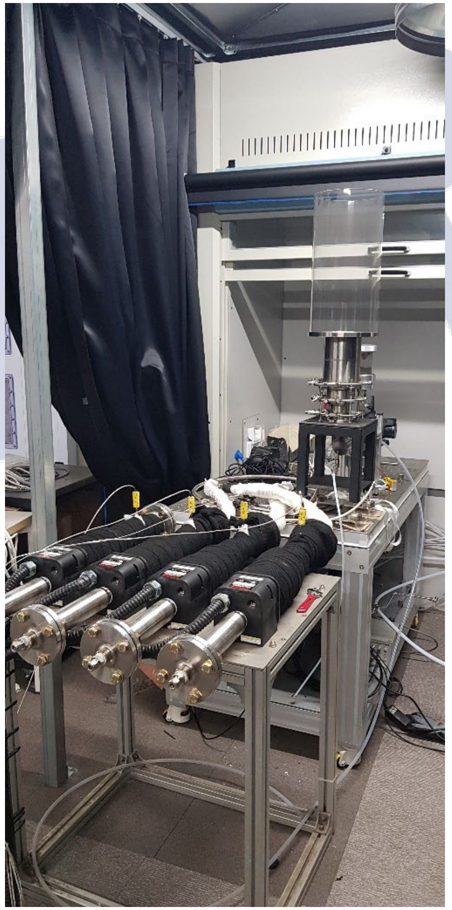








「30 kW PC & NH_3 Co-firing Flame-Emission Measurement」



Coal 100%

80:20 (PA)

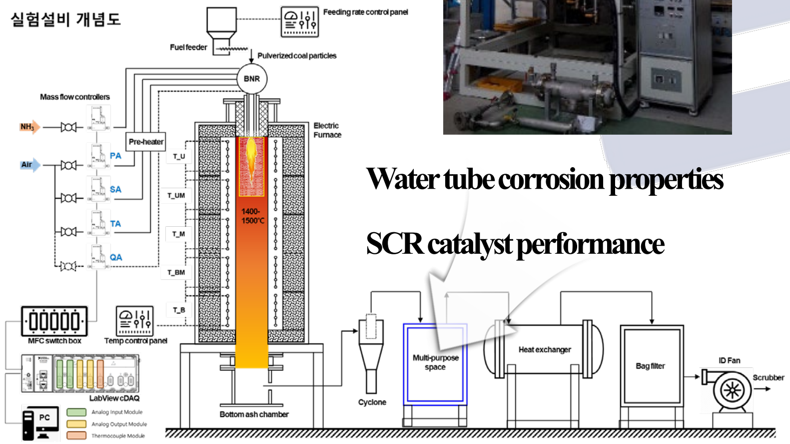
80:20 (TA)

80:20 (QA)

Pulverized Coal-NH_3 Co-firing Facility at KIER (cont'd)

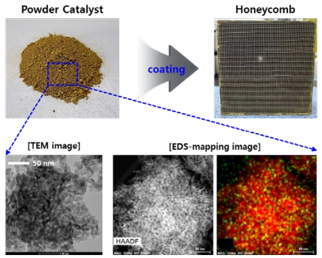
KIER Great 1st

「30 kW PC-NH_3 co-firing system (single BNR)」

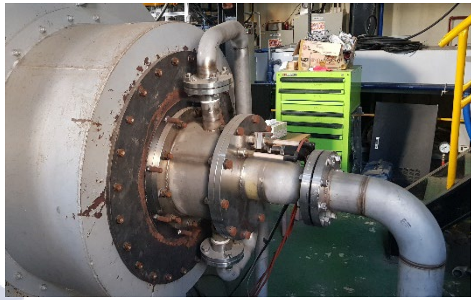


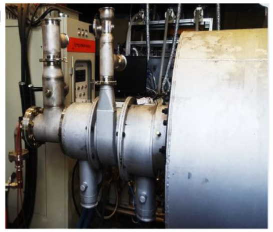
KIER Absorbent

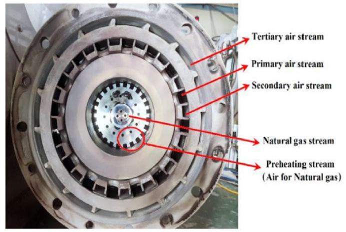
KIER SCR Catalyst

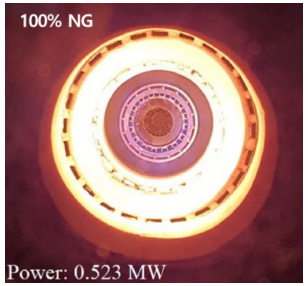


「1.0 MW PC & Gas fuel co-firing combustor (single BNR)」





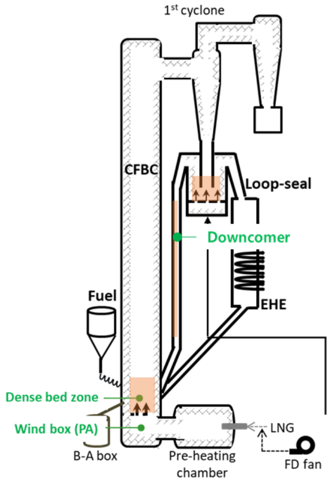




NH_3 Co-firing (coal/biomass/waste) Facility in CFB at KIER

KIER Great 1st

「100 kW NH_3 co-firing CFB system」



에너지기술연구원, 국내 최초 암모니아 혼소기술 개발

100 kWth급 순환유동층 시스템
암모니아 혼소 운전 기술 확보
기존 발전소에서 청정발전 가능

양인범 기자 2022.07.13 13:22:00 수정 2022.07.14 06:15:50 1537호

0.1MWth급 순환유동층 암모니아 혼소 시스템
(0.1MWth Circulating Fluidized Bed Combustion test-rig for NH_3 co-firing)

국내 최초로 암모니아 혼소 운전기술 개발한 에기연 연구진(좌측부터 조성호 박사, 박성진 기술원, 문태영 박사, 김성주 박사)

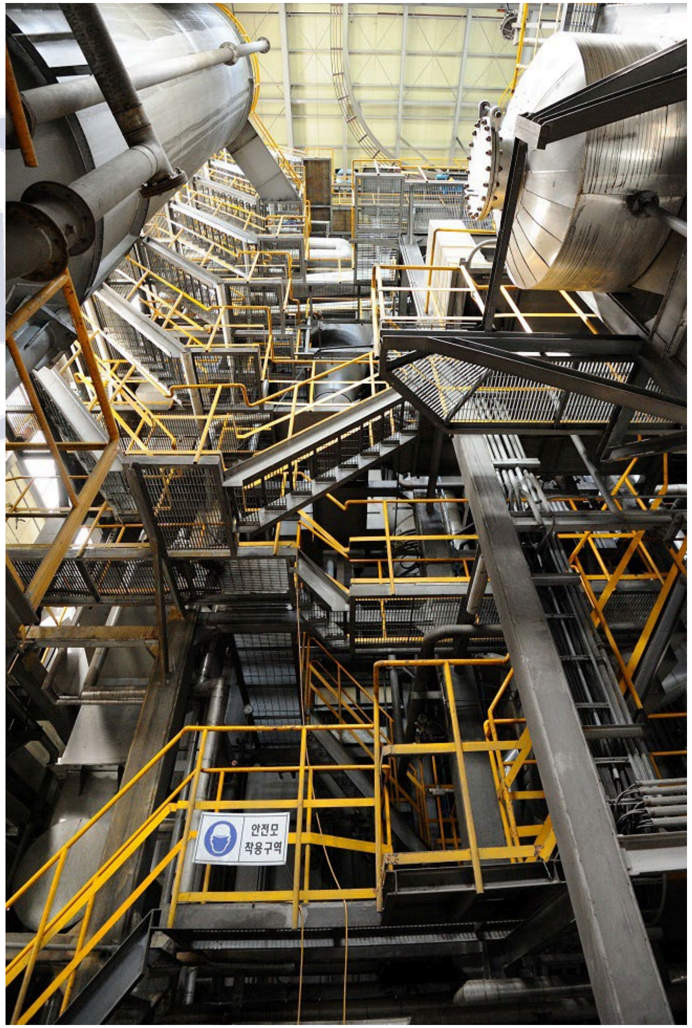
[가스신문 = 양인범 기자] 전력수급의 안정성을 확보하면서 석탄발전을 청정발전으로 전환시킬 '암모니아 혼소' 기술이 국내 최초로 개발됐다.

한국에너지기술연구원(원장 김종남) 청정연료연구실 문태영 박사 연구진은 국내 최초로 순환유동층 연소시스템에서 이산화탄소 발생을 감축시키는 암모니아 혼소 운전 기술을 개발했다.

석탄화력과 열병합발전소에서 '암모니아 혼소' 기술은 기존 발전 플랜트 및 송·배전선로 등 전력 인프라를 그대로 활용(좌초자산 방지)할 수 있다는 장점이 있다. 또한 재생에너지 간헐성에 따른 수급 불균형 해소는 물론 더 나아가 탄소중립 산단 구축, RE100 구현 및 탄소국경조정제도에 대한 대응이 가능하다.

그러나 세계적으로 순환유동층 암모니아 혼소 분야에 대한 기술이 전무한 상태로, 발전분야에서 암모니아를 연료로 이용하기 위한 국산 기술 확보가 시급하다.

「10 MW NH_3 co-firing CFB system with steam TBN (2 MWe)」



Fundamental Researches for 100% NH_3 Combustion

KIER Great 1st

➢ Study on stability and emission characteristics of ammonia-air flames in globally lean - locally lean two-stage combustion condition

- Tangential injection combustor
  : Intense angular momentum
  : Remarkable mixing performance

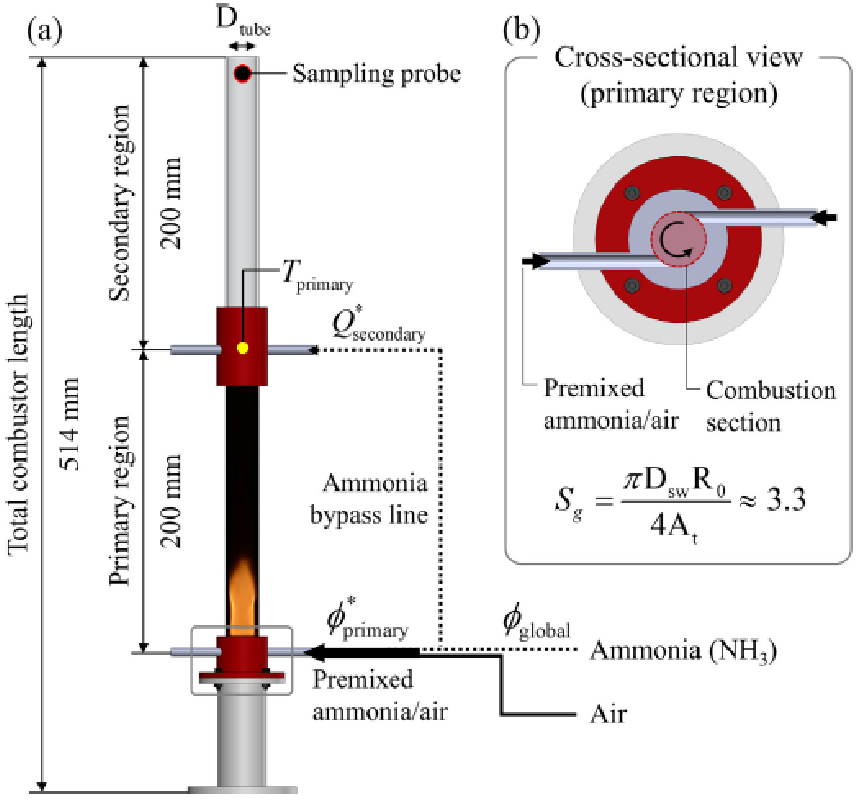


Fig. 1. (a) Schematic of a fuel-staged, tangential injection combustor with an emission measurement system. (b) Cross-sectional view of a primary combustion zone.

T. Lee et al, Combust Flame 248 (2023) 112593

Measurement techniques

- Flame stability limit

- Recorded flame detachment/blowoff conditions

- Emission measurement

- FTIR (Fourier Transform Infra-Red) system
- NO (corrected) and N_2O concentration in ppmvd
- NO was adjusted by the theoretical O_2 concentration

- Secondary ammonia injection

- To reduce massive fuel NOx emissions by using SNCR reaction (Thermal DeNOx process)
- Ammonia feeding lines were distributed into primary and secondary injection ports

Test conditions

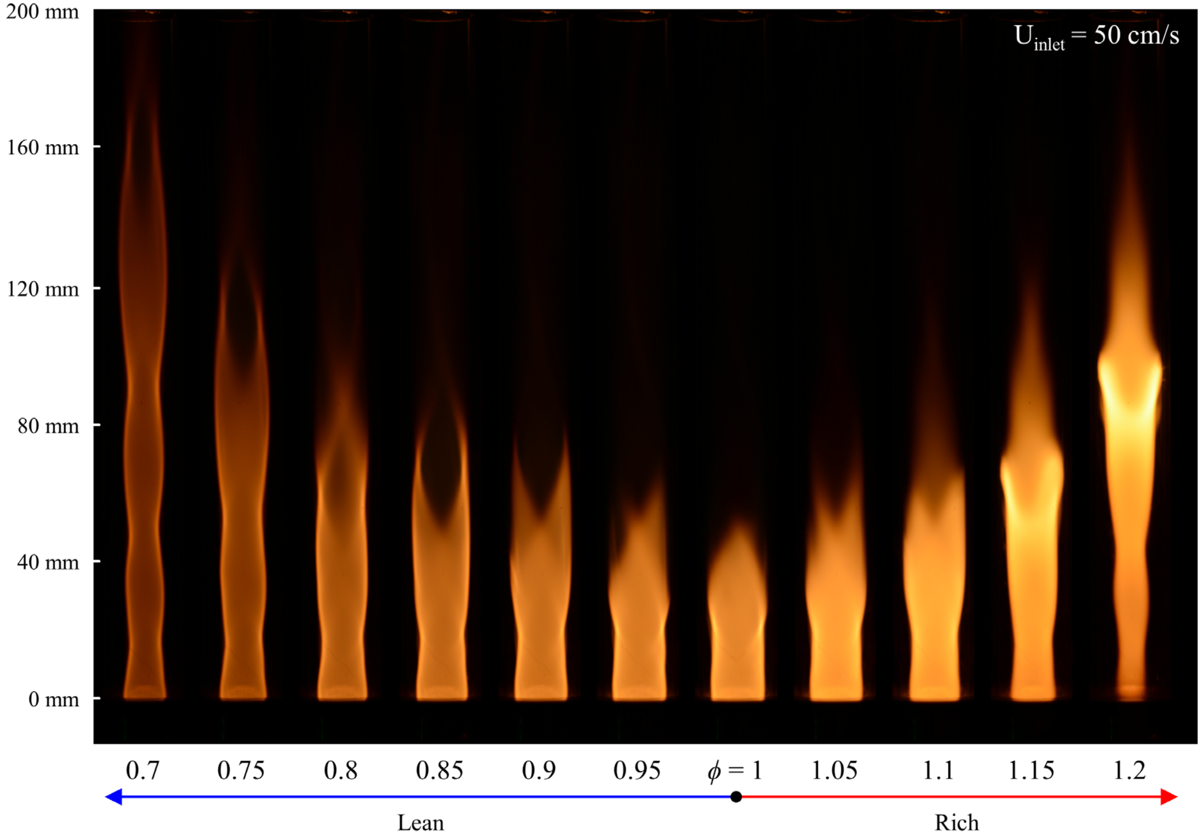
- U_{inlet} = 10 ~ 200 cm/s
- ϕ_{global} = 0.60 ~ 1.3
- $\phi^*_{primary}$ = 0.75 ~ 0.95 ($Q^*_{secondary}$ = 0.1 ~ 0.4 SLPM)

Apparent Flame Structures

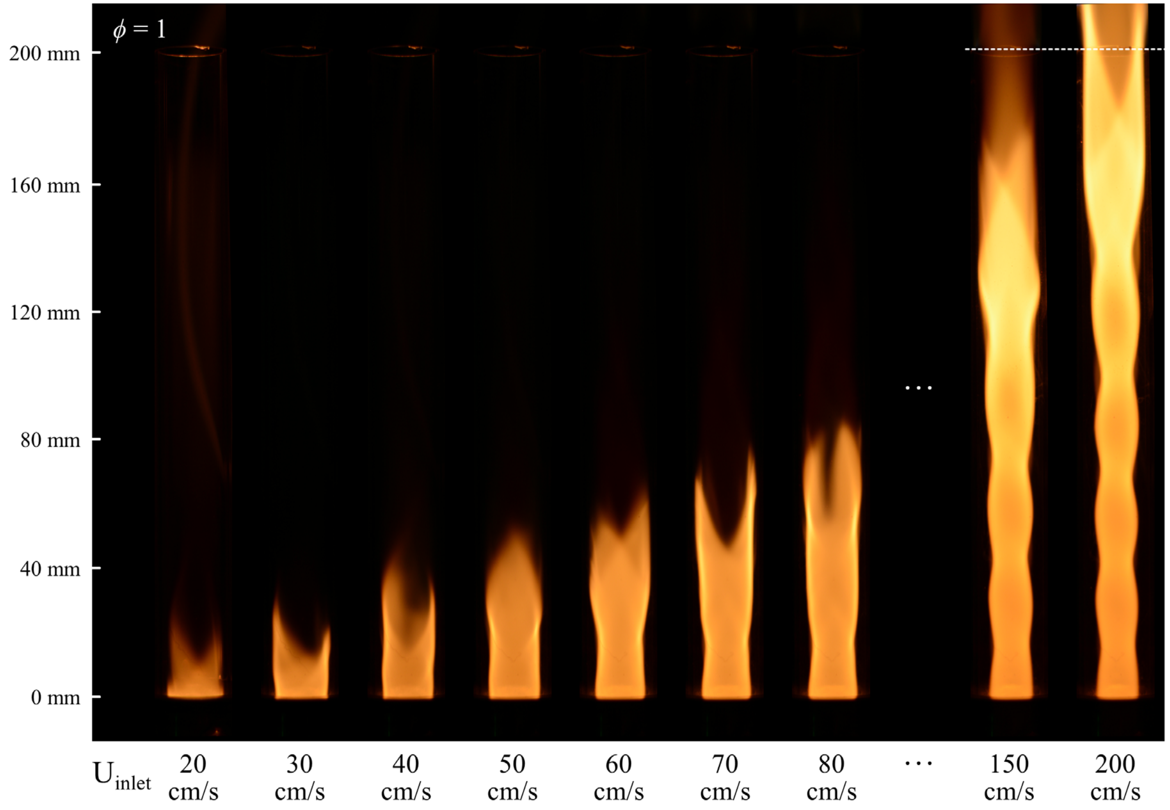
KIER Great 1st

➢ **Effects of equivalence ratio (*Φ*) and inlet velocity (U_{bulk}) on flame structures**

「Equivalence ratio effect」



「Inlet velocity effect」



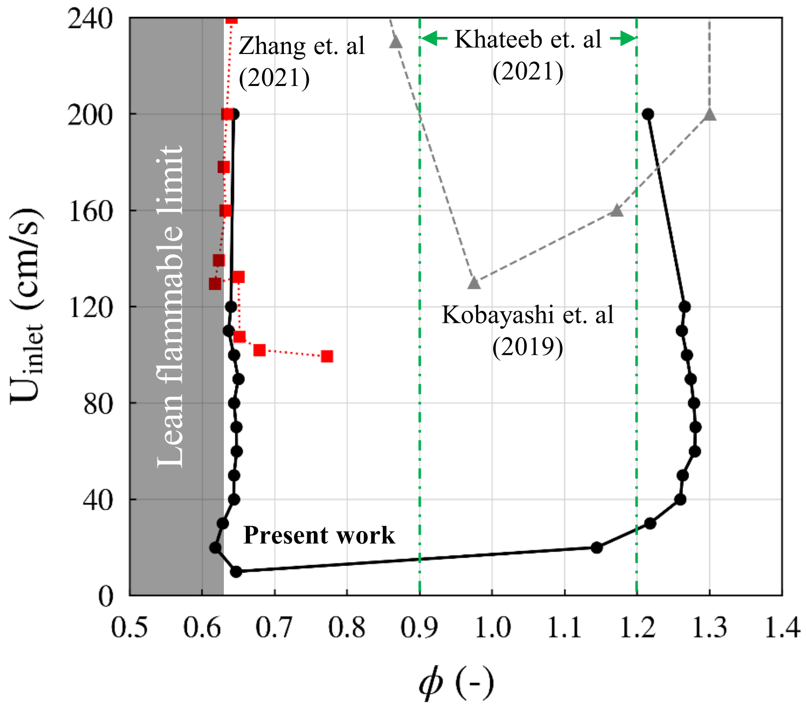
T. Lee et al, Combust Flame 248 (2023) 112593

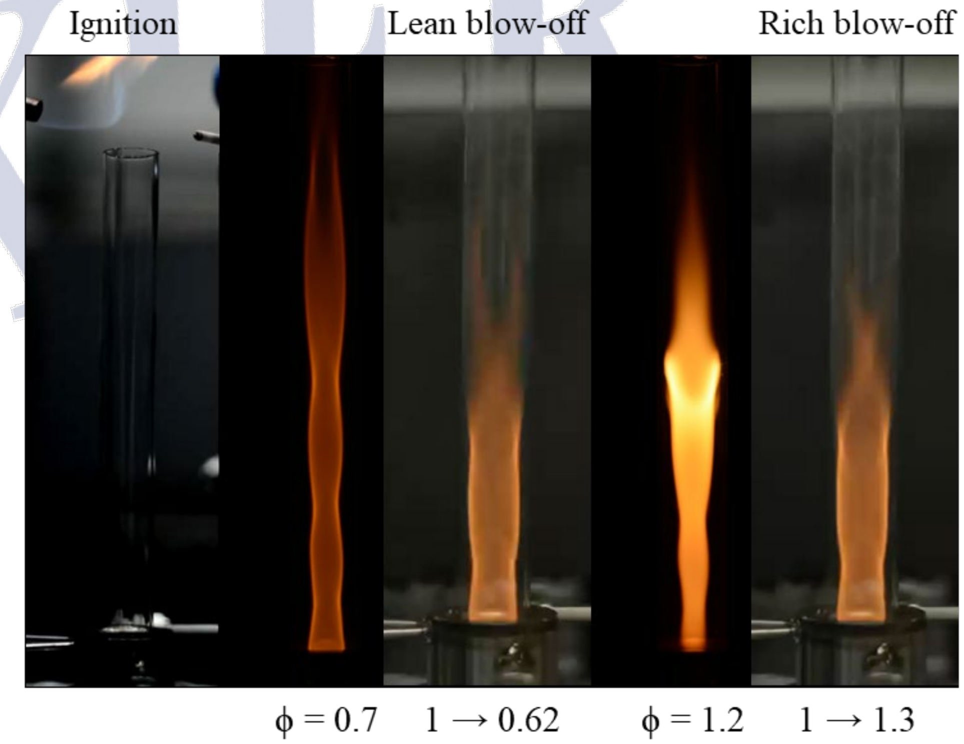
Flame Stability Characteristics

KIER Great 1st

➢ **Stability map of the premixed NH_3 flame and varying flame structures with respect to the global equivalence ratio**

- Premixed ammonia flames in the high-swirl combustor are stabilized even in the vicinity of lean flammable limit and at low velocity condition of 10 cm/s, and have a relatively wide range of operation window.
- Lean and rich blow-off processes are markedly different, especially for the initial point of flame extinction.



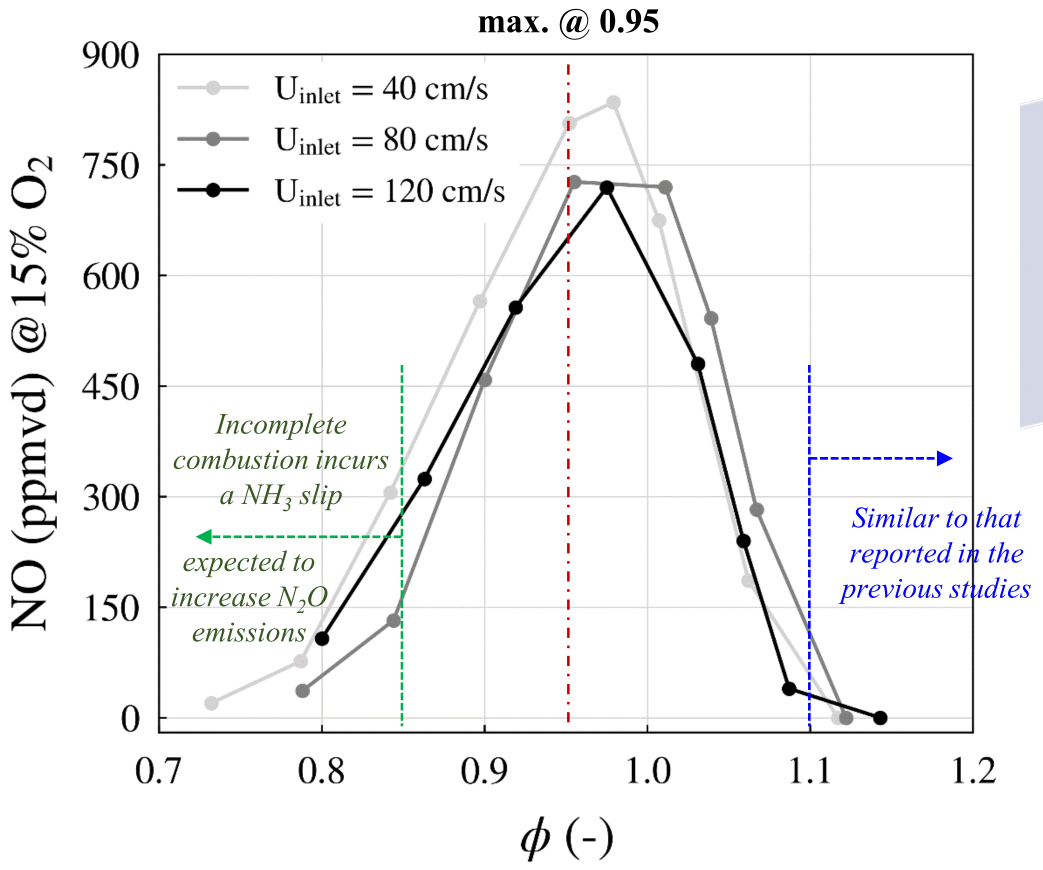


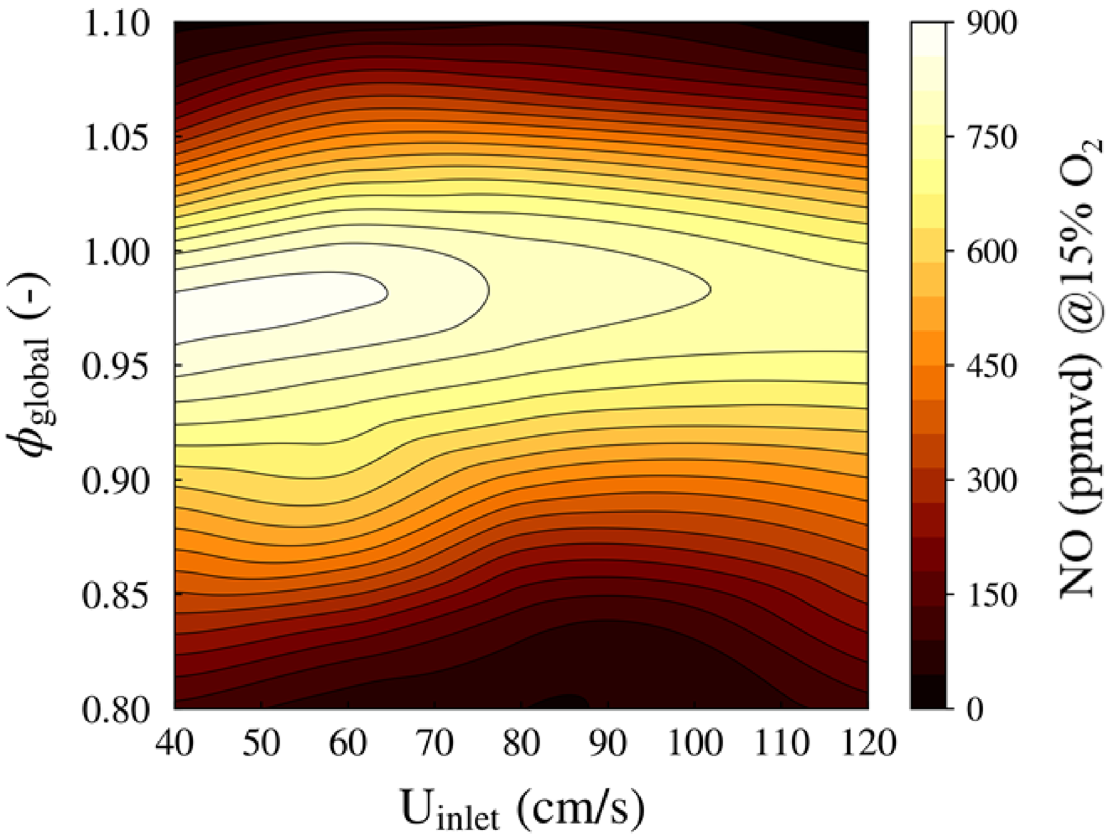
T. Lee et al, Combust Flame 248 (2023) 112593

Emission Characteristics

➢ **Exceptional NO emission trend under lean conditions, the abrupt decrease in [NO] in the rich-burn regime is similar to that reported**

- Salient feature of low [NO] is observed but it is associated with heat loss through the wall and ambient inlet mixture temperature
- Increasing U_{bulk} give rise to a gradual increase in the NO mole fraction due to the elevated $T_{primary}$ → Improved combustion efficiency



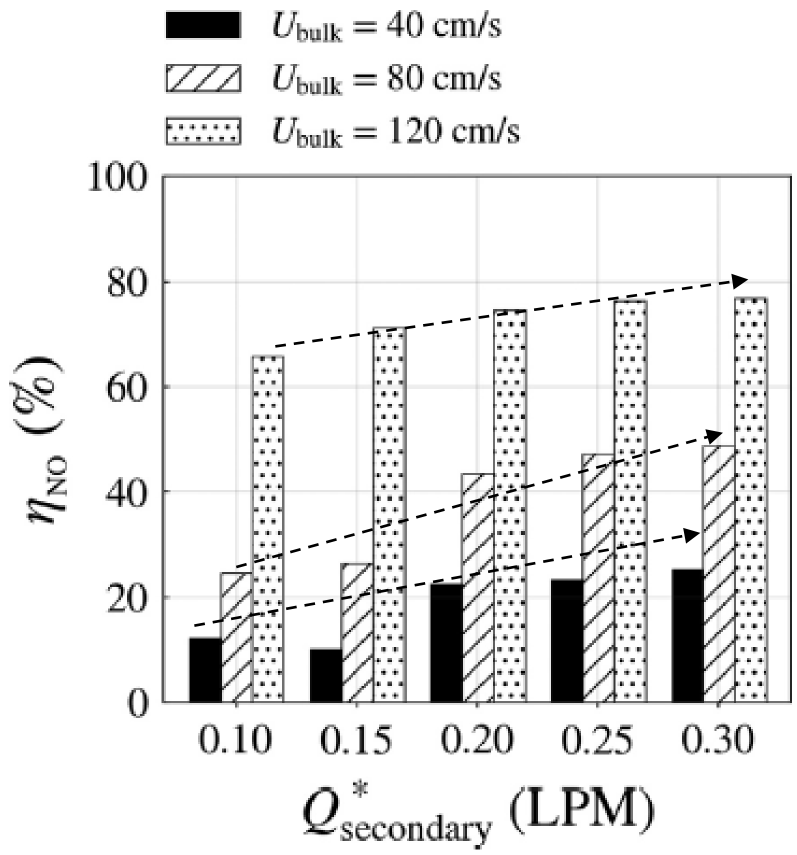


T. Lee et al, Combust Flame 248 (2023) 112593

Emission Characteristics with Fuel Staging

KIER Great 1st

➢ **To maximize the NO reduction rate, delicate control of the temperature distribution by the U_{bulk} and Φ is pivotal in this strategy**



$$\eta_{NO}(\%) = \left\{ 1 - \frac{[NO]_{staging}\big|_{\phi^*_{primary}}}{[NO]_{baseline}\big|_{\phi_{global} = \phi^*_{primary}}} \right\} \times 100$$

NO reduction rate dramatically increased with increasing bulk velocity as a result of the elevated temperature

- U_{bulk} = 40 cm/s

- NO emissions decreased by up to 25% when Q*secondary is 0.3 LPM ($\phi^*_{primary}$ = 0.77)

- U_{bulk} = 120 cm/s

- $T_{primary}$ = 680 °C promotes a substantial NO reduction of up to 77% despite the small addition of the bypassed NH_3, which corresponds to 8% of the total fuel flow rate

- Nevertheless, it could not reduce the [NO] below 160 ppmv

- Over U_{bulk} = 120 cm/s

- Elongated flame structure went beyond the primary region

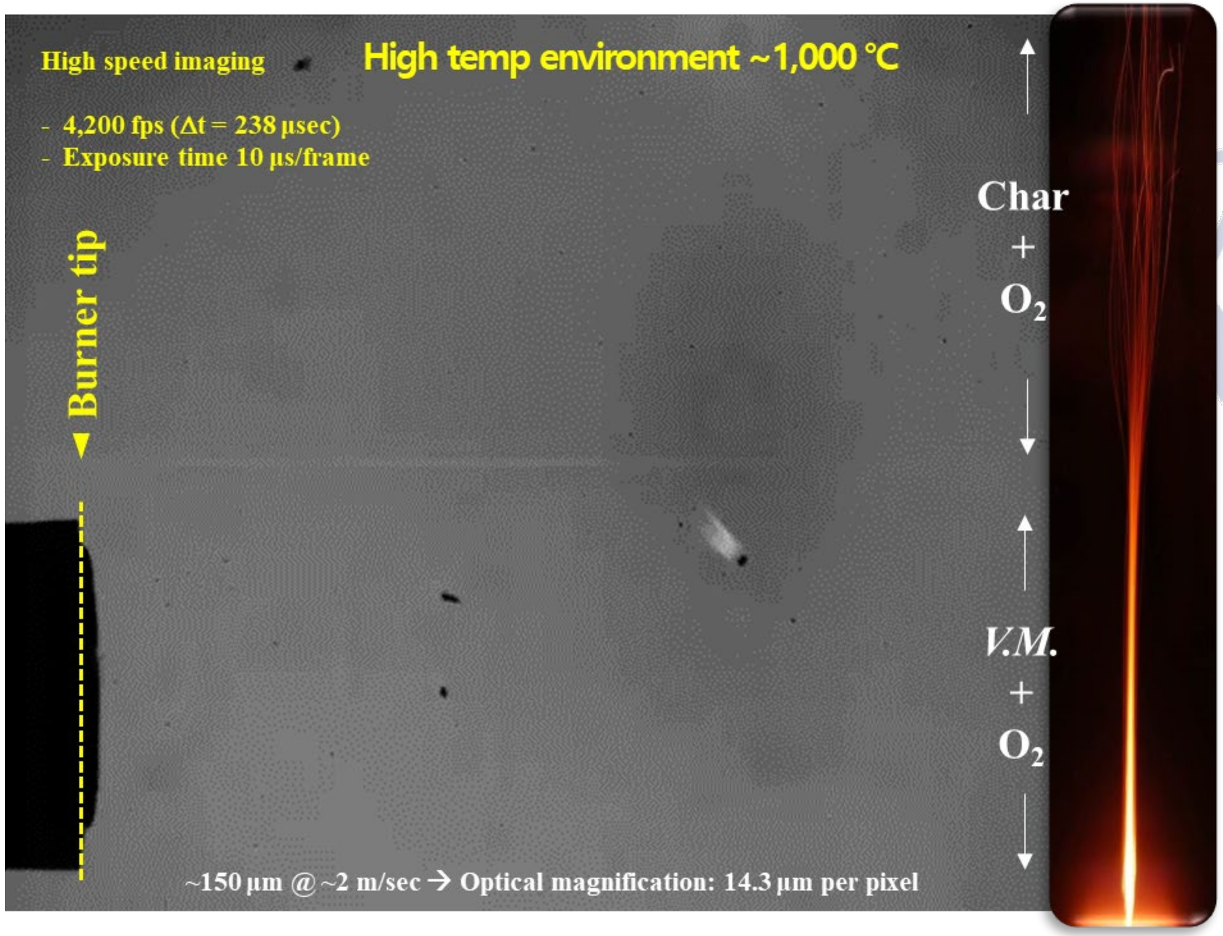
- Then, NH_3 is directly burned ammonia instead of facilitating the SNCR process.

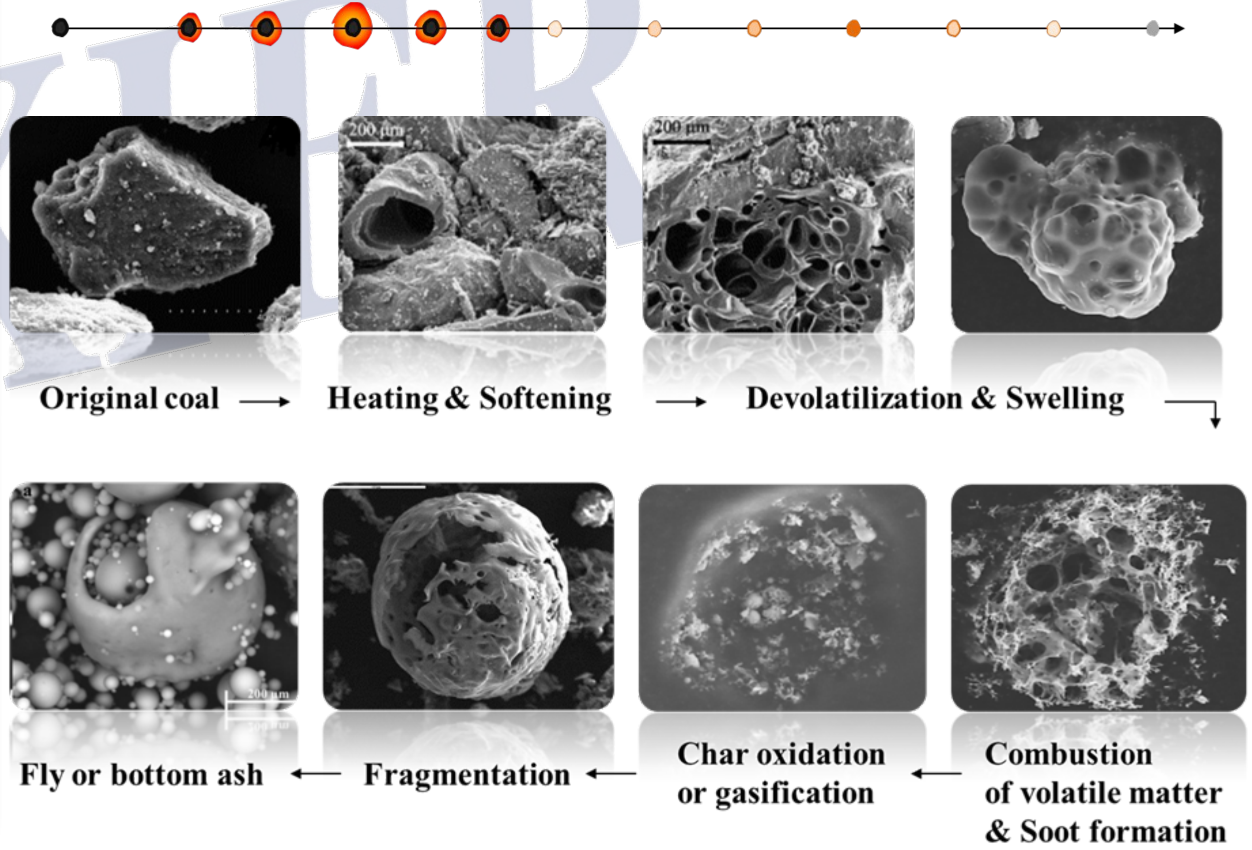
T. Lee et al, Combust Flame 248 (2023) 112593

Phenomenological Characteristics of PC Combustion

KIER Great 1st

- For approach to detailed observation : d_p ~100 µm moving at ~3 m/s, Time resolution(Δt) ~100 µs, Size resolution (pixel) ~10 µm
- Extremely heterogeneous behavior : Unable to expect uniform data when using gaseous fuel



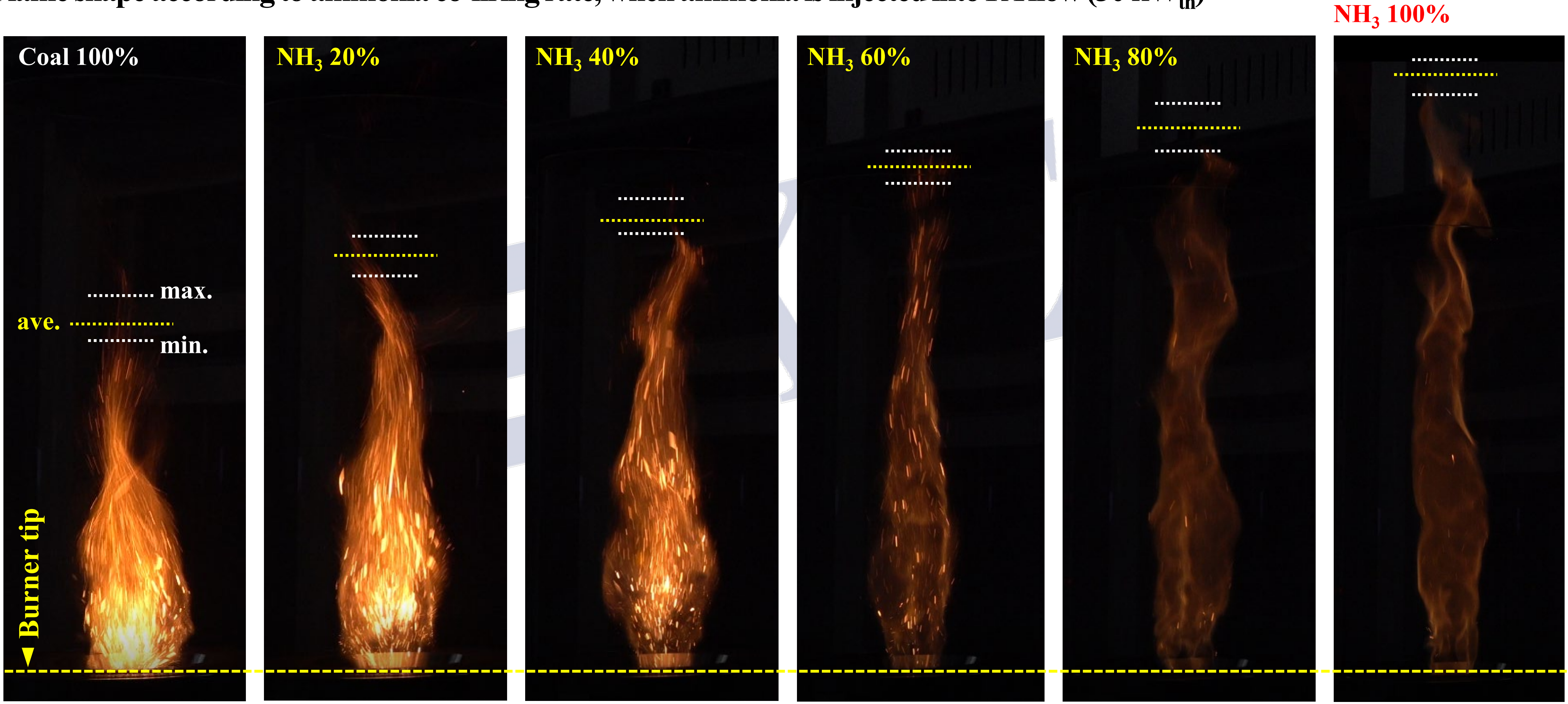


H. Lee, S. Choi, Combust Flame, 2015

Apparent Flame Behavior in PC-NH_3 Co-firing Conditions

KIER Great 1st

- Flame shape according to ammonia co-firing rate, when ammonia is injected into PA flow (30 kW_{th})

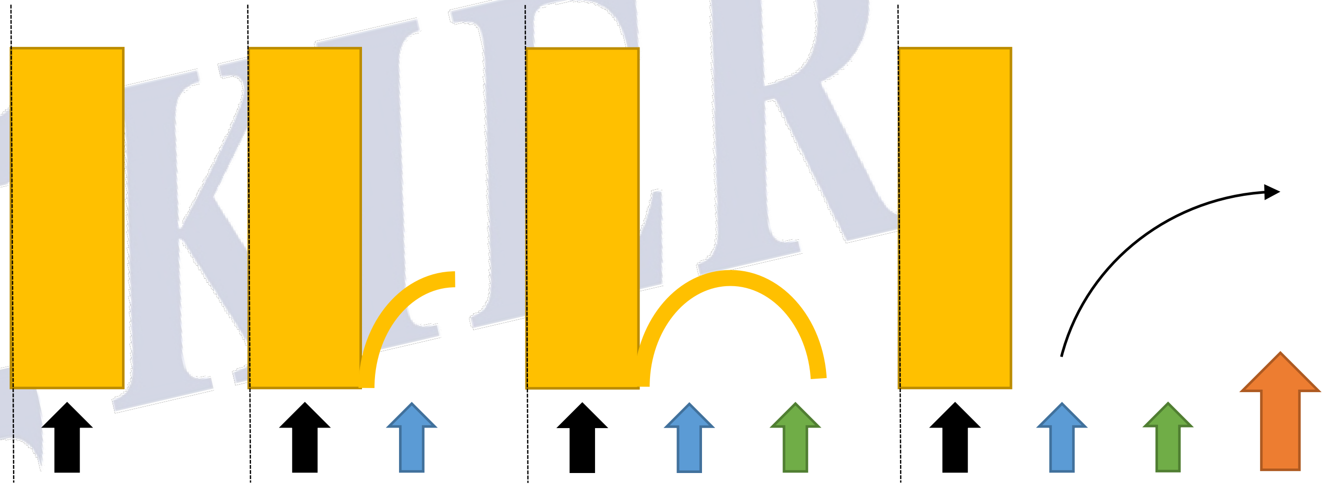


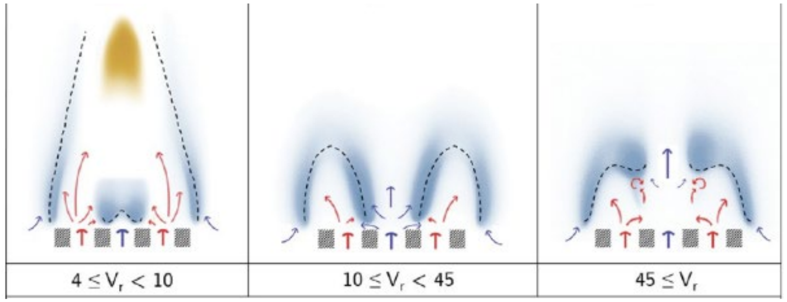
(a) (b) (c) (d) (e) (f)

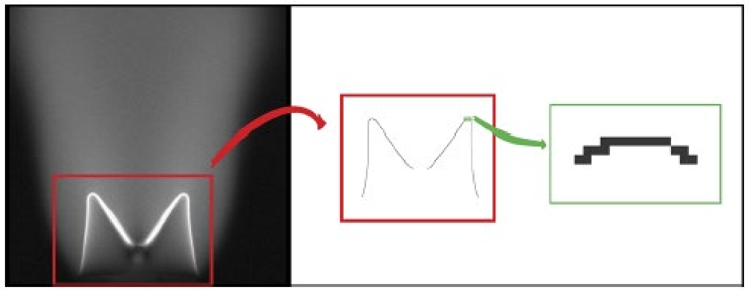
Relation between Fuel-staging and Flame Stability

- **If the swirl intensity of the outermost flow is strong, it adversely affects the flame stability**

One of the stable forms of such a flame configuration is the stabilization of the front in the vortex zone behind the stabilizer and in the vortex zone at the thin edge of the nozzle.
That stable flame is called M-shaped one.



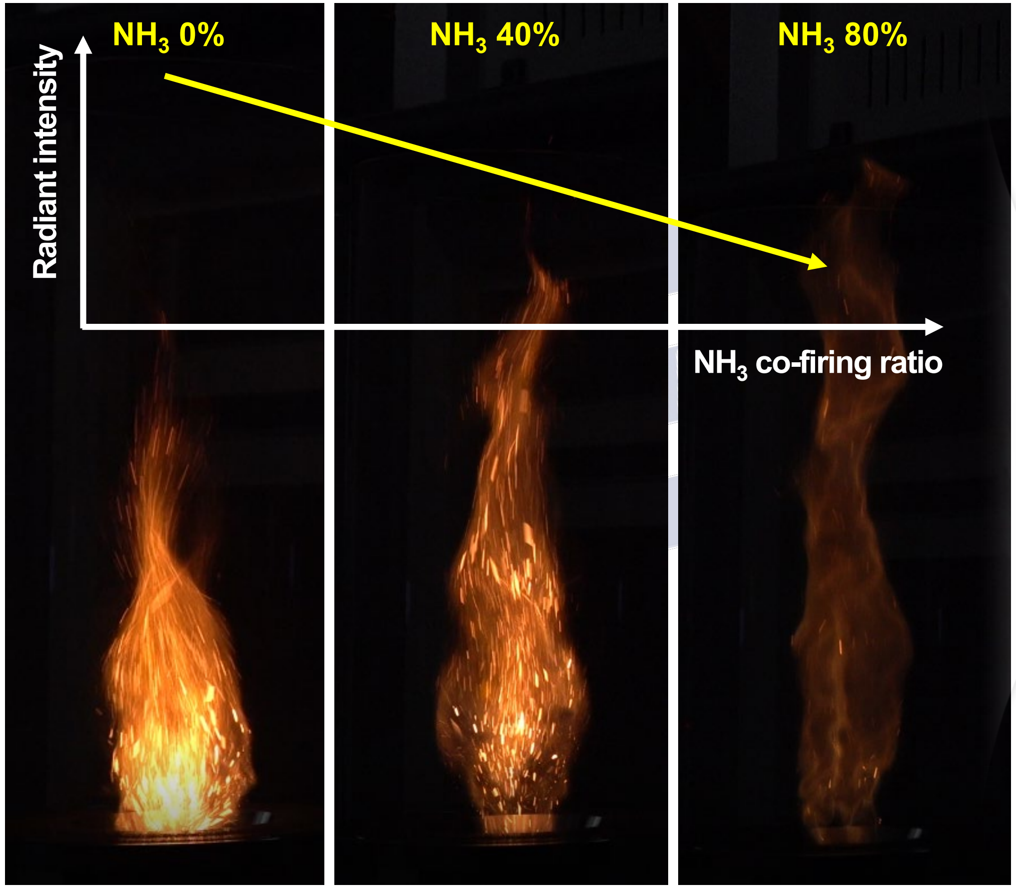


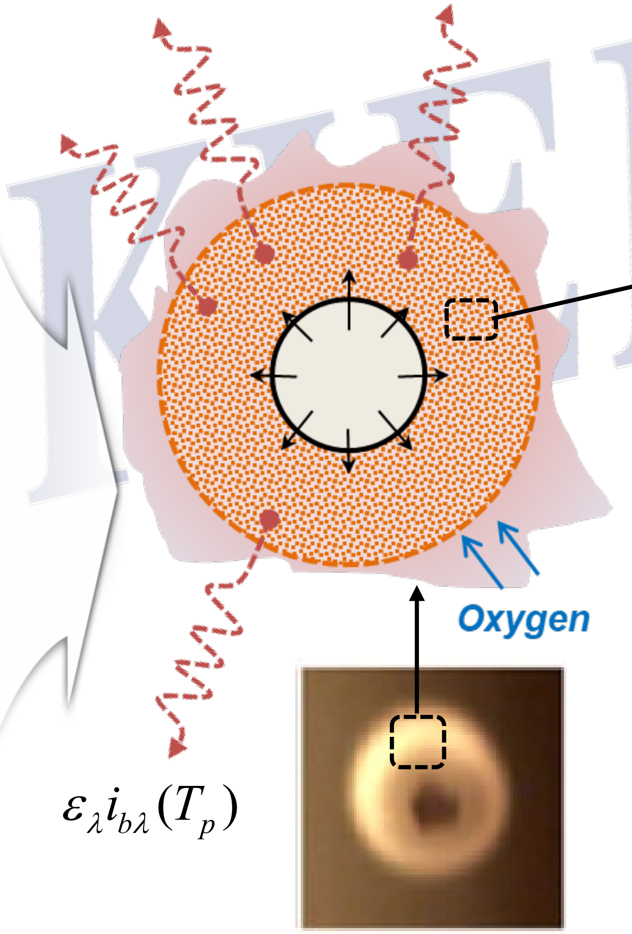


PC-NH_3 Co-firing Flame Radiant Intensity

KIER Great 1st

- Most radiative heat transfer is caused by the radiation of soot particles in a coal flame
- Lower coal flow (Higher NH_3 co-firing ratio) → Lower radiant intensity

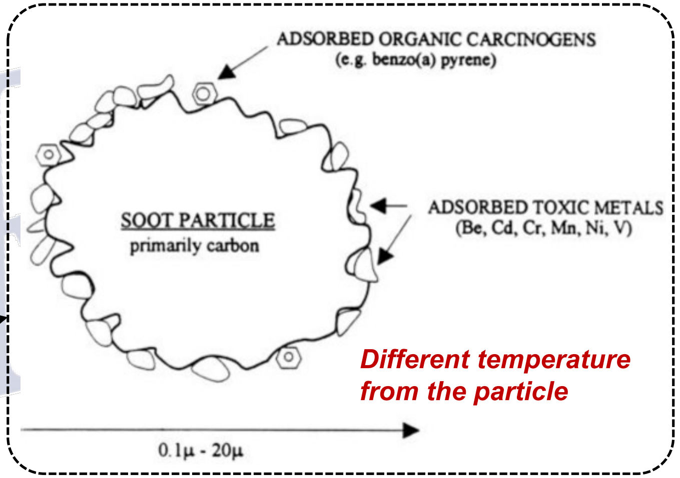


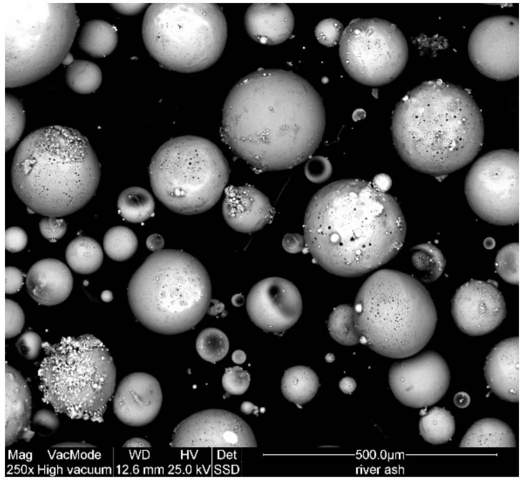


$$\varepsilon_\lambda i_{b\lambda}(T_p)$$

Y.A. Levendis (2013)

One of the soot particles





North Carolina Health News

Concluding Remarks

KIER Great 1st

Proper NH_3 staging induces the SNCR (selective non-catalytic reduction) effect

- Excessive staging causes NH_3 slip
- A small amount (~10 ppm) of N_2O is also generated from pulverized coal co-firing conditions

PC- 20% NH_3 co-firing can be overcome with well-controlled combustion techniques

High co-firing rate or NH_3 combustion requires new nozzle design

- Will it create a stable flame? Would you be satisfied with adding NH_3?

NH_3-ready burner design is required considering NH_3 supply (commercial)

- Global R&D trends indicate that no facilities can use only one fuel

EOD

Questions?

KIER Great 1st

Please e-mail any questions to :

Dr. Hookyung Lee (hk.lee@kier.re.kr)

Korea Institute of Energy Research (KIER)
152 Gajeong-ro, Yuseong-gu, Daejeon (34129) TEL : +82-42-860-3307