Progress with NH3 Combustion Research at Georgia Tech

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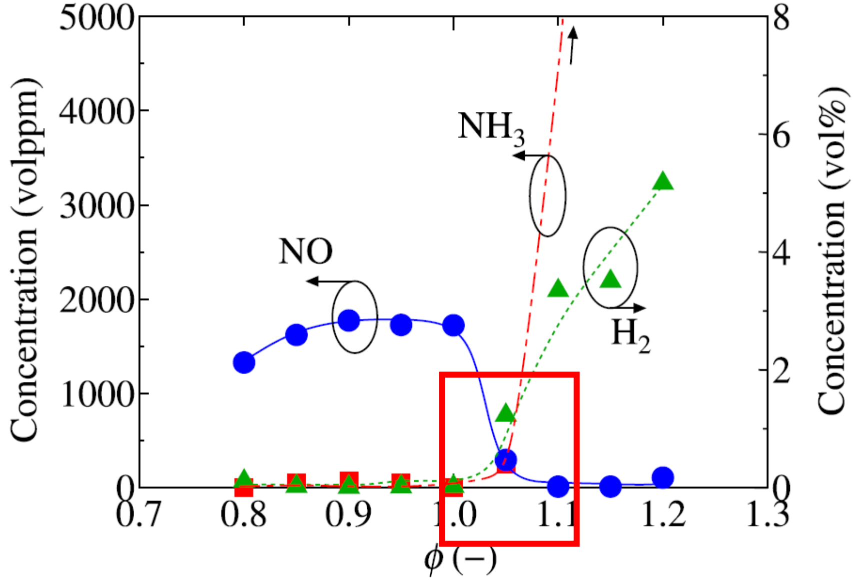
Background



RQL (Rich **Q**uick-Mixed **L**ean**)**

- Rich NH_3 flames for low NO emissions
- Unburnt fuel from the main rich combustion zone, mainly H_2!!
- Additional air is injected to oxidize all the remaining fuel

RRQL (Rich **Relax Q**uick-Mixed **L**ean**)**

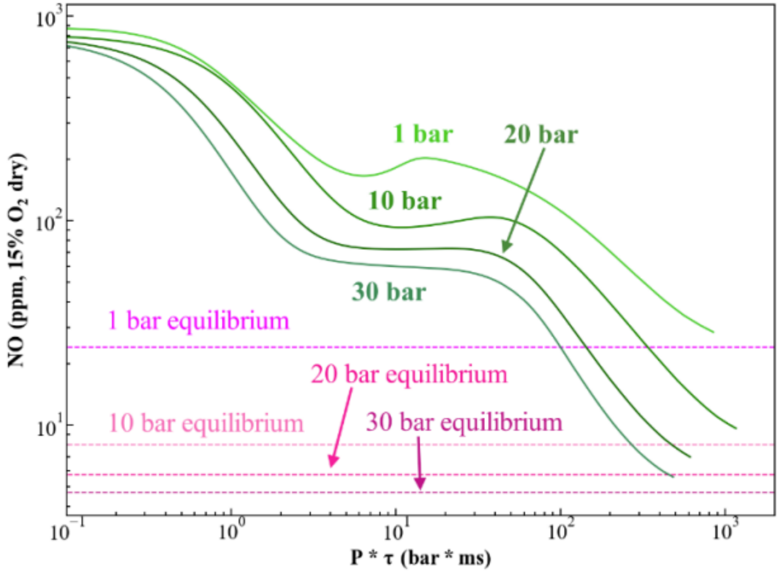


FIGURE 2: NOx RELAXATION IN PRIMARY STAGE, Φ=1.22, OF COMBUSTOR FOR VARIOUS PRESSURES. DASHED LINES REPRESENT EQUILIBRIUM VALUES, AND SOLID LINES DENOTE PRIMARY STAGE NOx. REPRODUCED WITH PERMISSION FROM GUBBI ET AL. [13].

Could also impact NH_3 cracking → NO_x production in the secondary stage

[1] Hayakawa, A. et al. 2017: 10.1016/j.ijhydene.2017.01.046
[2] Cole, Renee, et al. GT2024-122369
[3] Gubbi, S., et al. ACS Energy Letters, 8(10), pp. 4421-4426.

Swirl pattern effect on exhaust emissions and chemiluminescence distribution for NH_3-air premixed swirl flames

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Experimental setup

Constant:

- $U_0 = 0.90$ m/s
- NH_3-air premixed flames
- Primary Quartz length = 178 mm

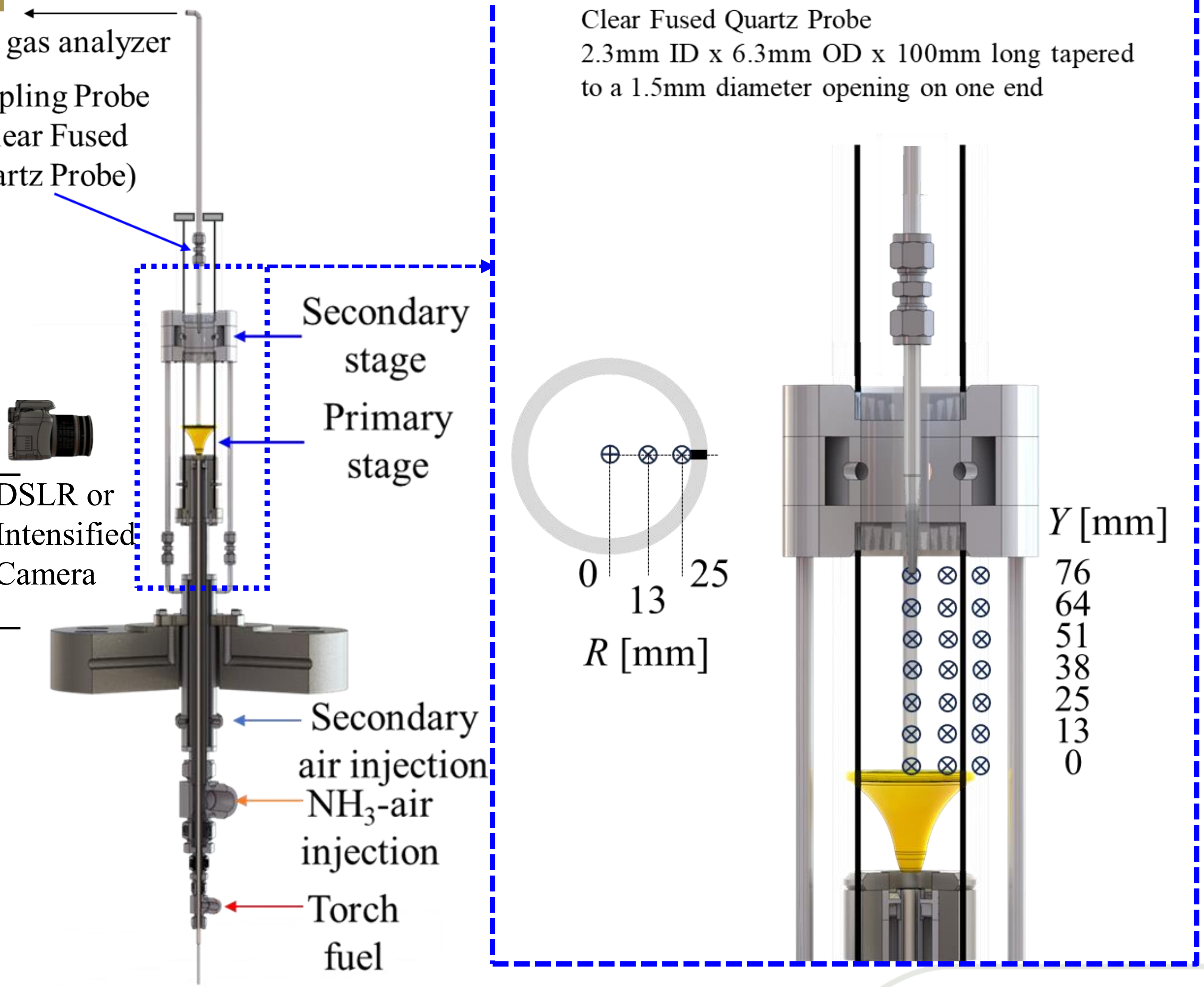
We varied:

- Probe position
- Swirler geometry

Tag	S_g [-]	# of vanes [-]	Vane type [-]	Vane angle [deg]	Effective are [m^2]
S_g*0.7-S16*	0.7	16	Straight	43.25	6.7E-4
S_g*1.1-C8*	1.1	8	Curved	45.18	8.8E-4
S_g*1.1-C12*	1.1	12	Curved	35.90	7.8E-4
S_g*1.1-S12*	1.1	12	Straight	55.95	7.8E-4
S_g*1.1-S16*	1.1	16	Straight	55.95	6.7E-4

We measured:

- Exhaust emissions
  NO_x-N_2O-NH_3-O_2 (CAI 700 FTIR and LX)
- Flame images
  OH^* → 308 ± 10 nm
  NH_2^* → 633 ± 10 nm

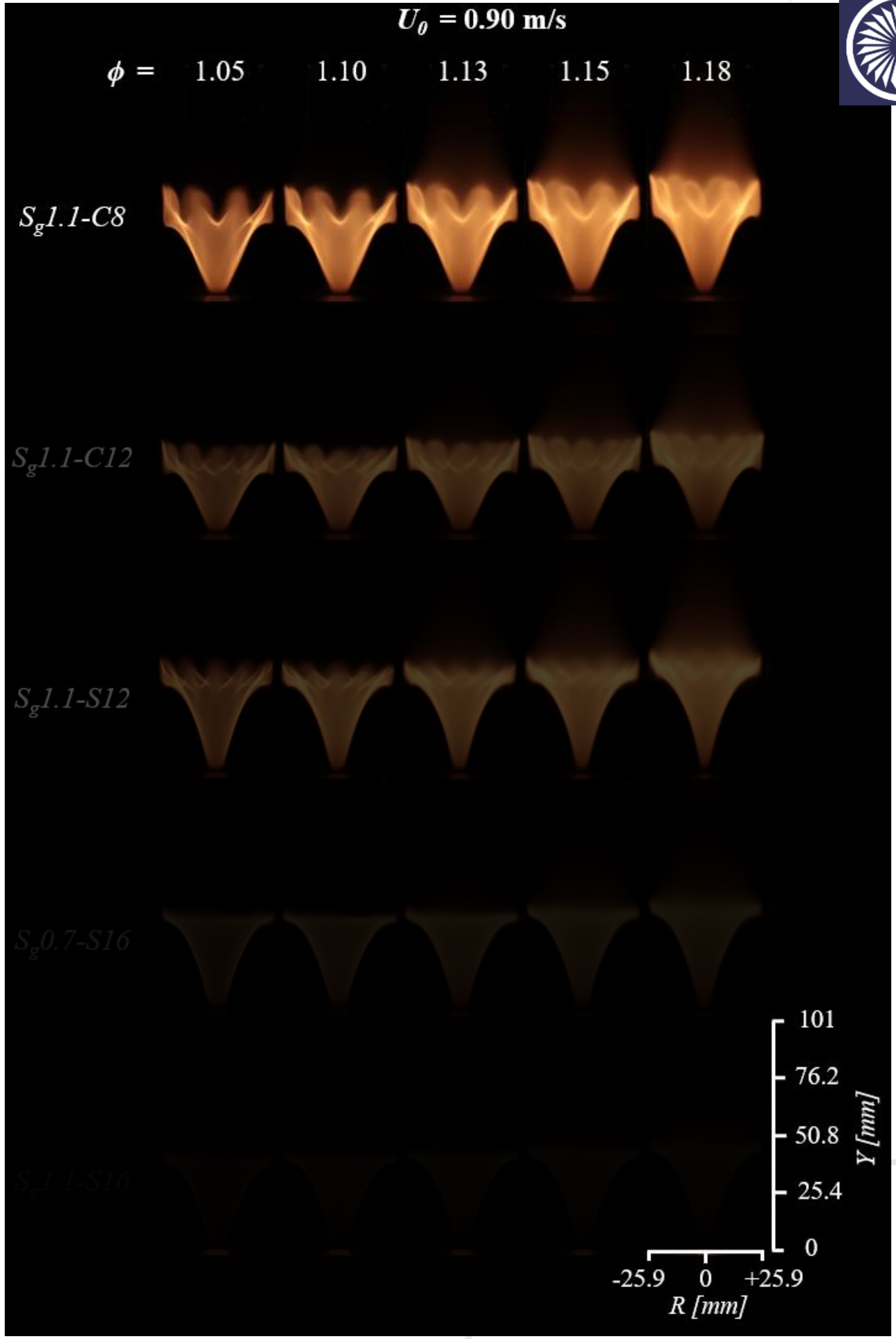


Exhaust emissions

- ***S_g1.1-C8*** is documented (Cole, R. et al. GT2024-122369)
  - Lobe structures and liner interaction seen with NH$_3$
- Increasing the number of vanes (***S_g1.1-C12***) minimizes lobe features
- Changing vane geometry (***S_g1.1-S12***) elongates the flame and minimizes lobe features
- Increasing the number of vanes (***S_g1.1-S16)*** creates smooth IRZ flame

Takeaway:

- Compared to ***S_g1.1-C8***, ***S_g1.1-S16*** minimizes lobe structures and liner interaction

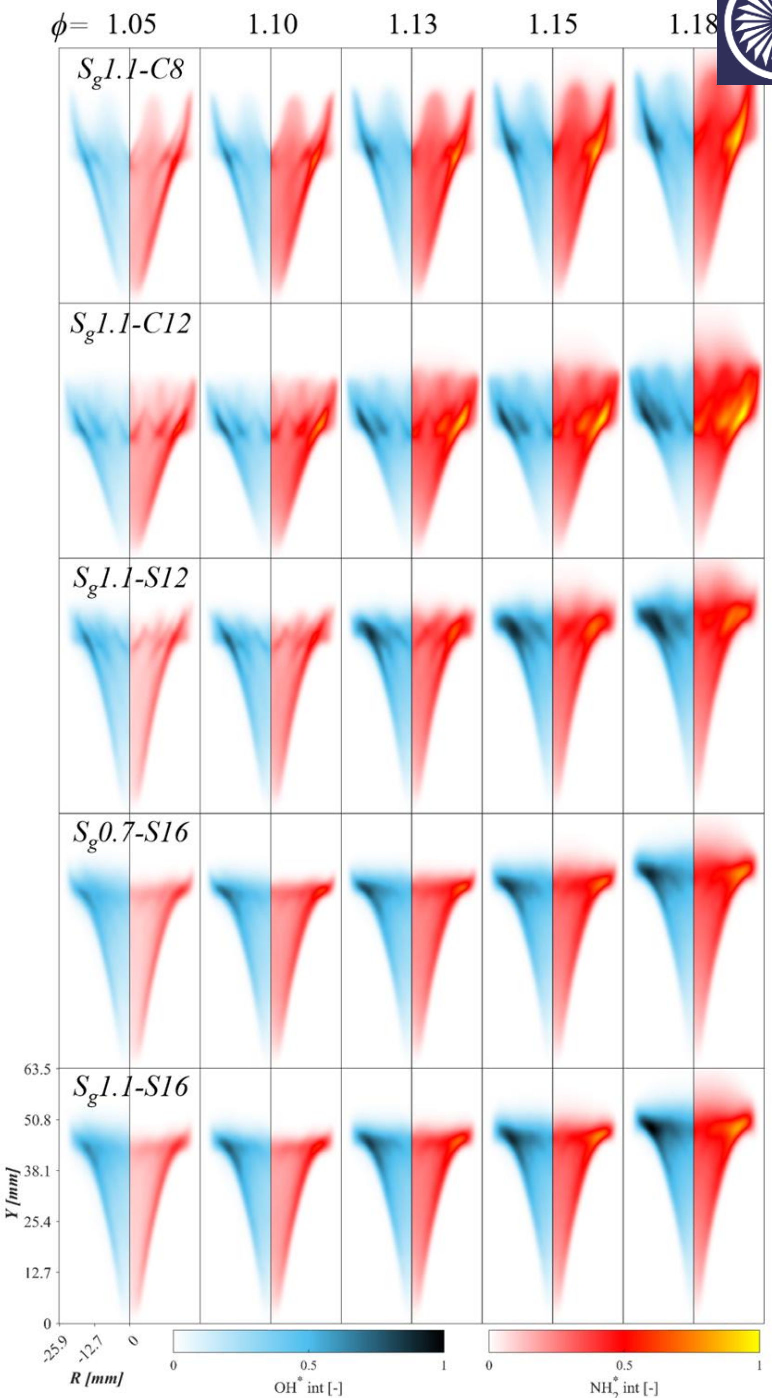


Flame Chemiluminescence

- Lobed swirlers (**S_g1.1-C8, C12, S12**) show reduced areas of increased radical concentration, especially for NH_2^*
  - Swirler-induced flow stratification and azimuthal non-uniformities near the outlet
- Traditional swirlers (**S_g1.1-S16**) produce smooth NH_2^* profiles and compact, lifted OH^* regions, consistent with stable inner recirculation zone (IRZ) structures and improved radial mixing

Takeaway:

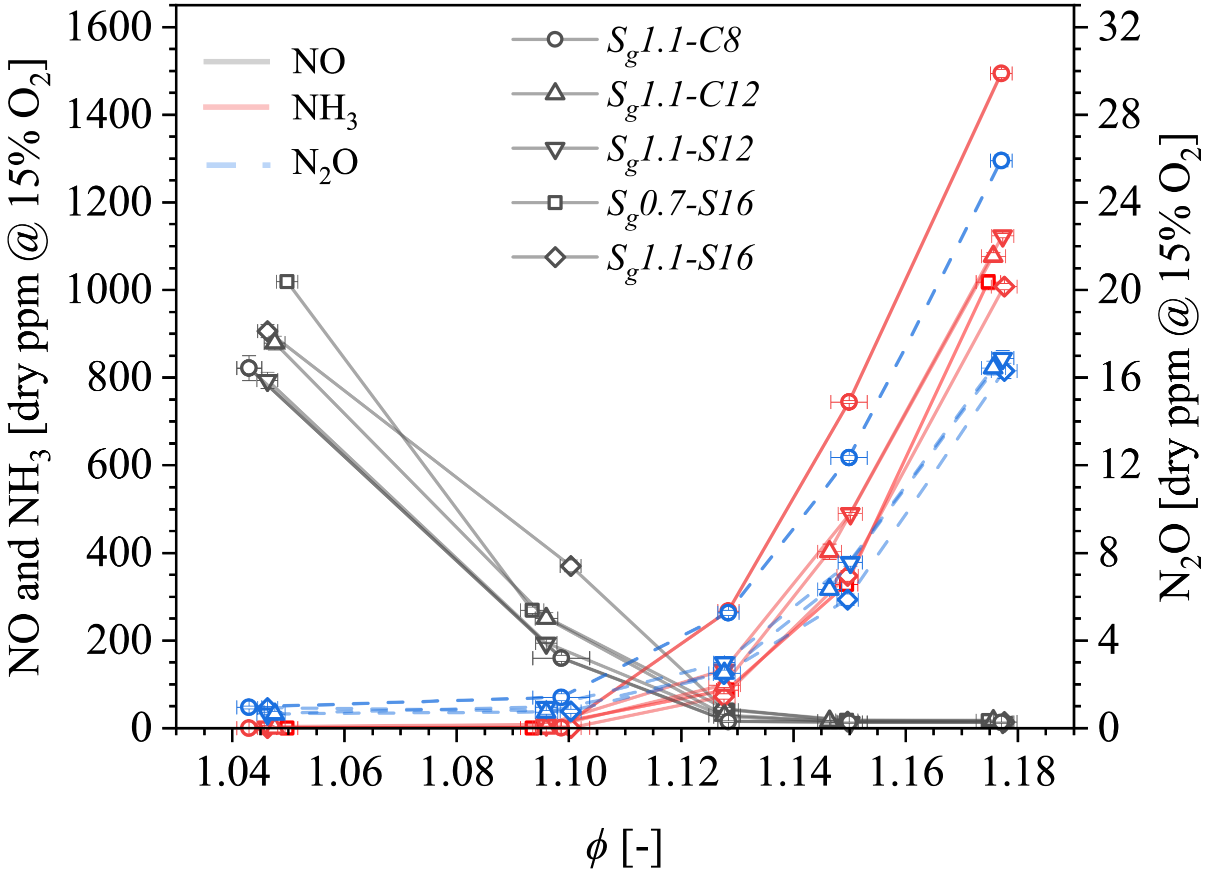
- Compared to ***S_g1.1-C8***, ***S_g1.1-S16*** minimizes lobe structures and liner interaction



Area Averaged Emissions

- Consistent overall emissions trends with known fuel-rich NH_3 combustion

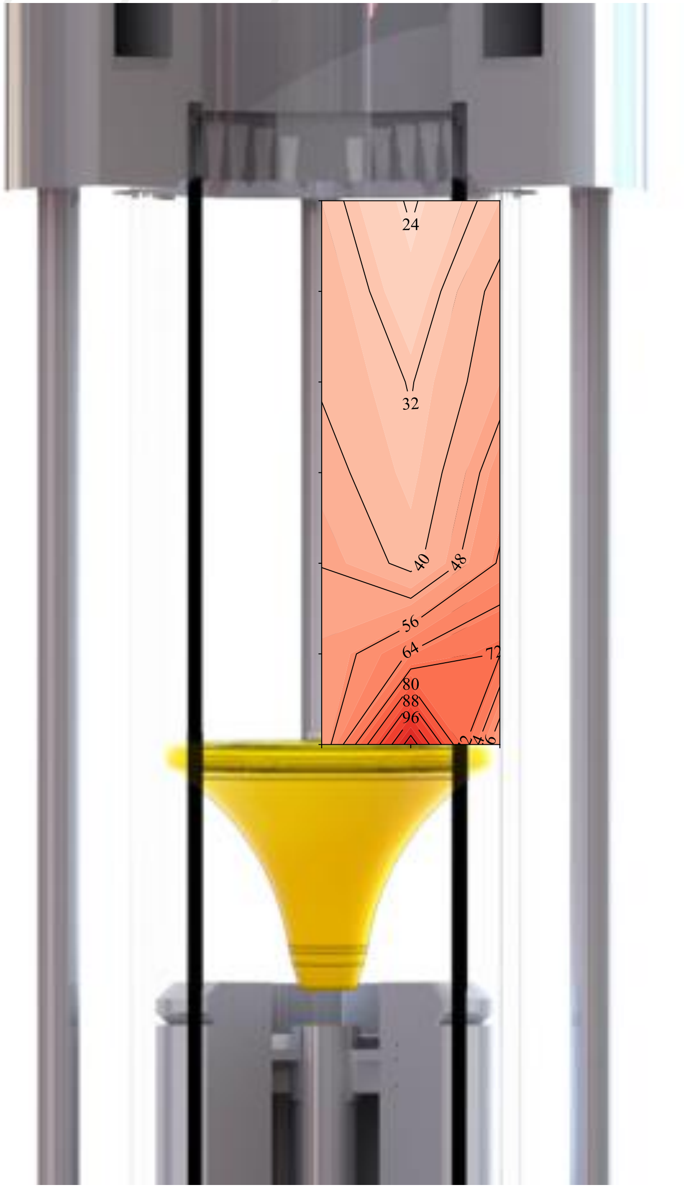
- Swirler geometry shifts the optimal ϕ with minimal NO_x/ NH_3 balance

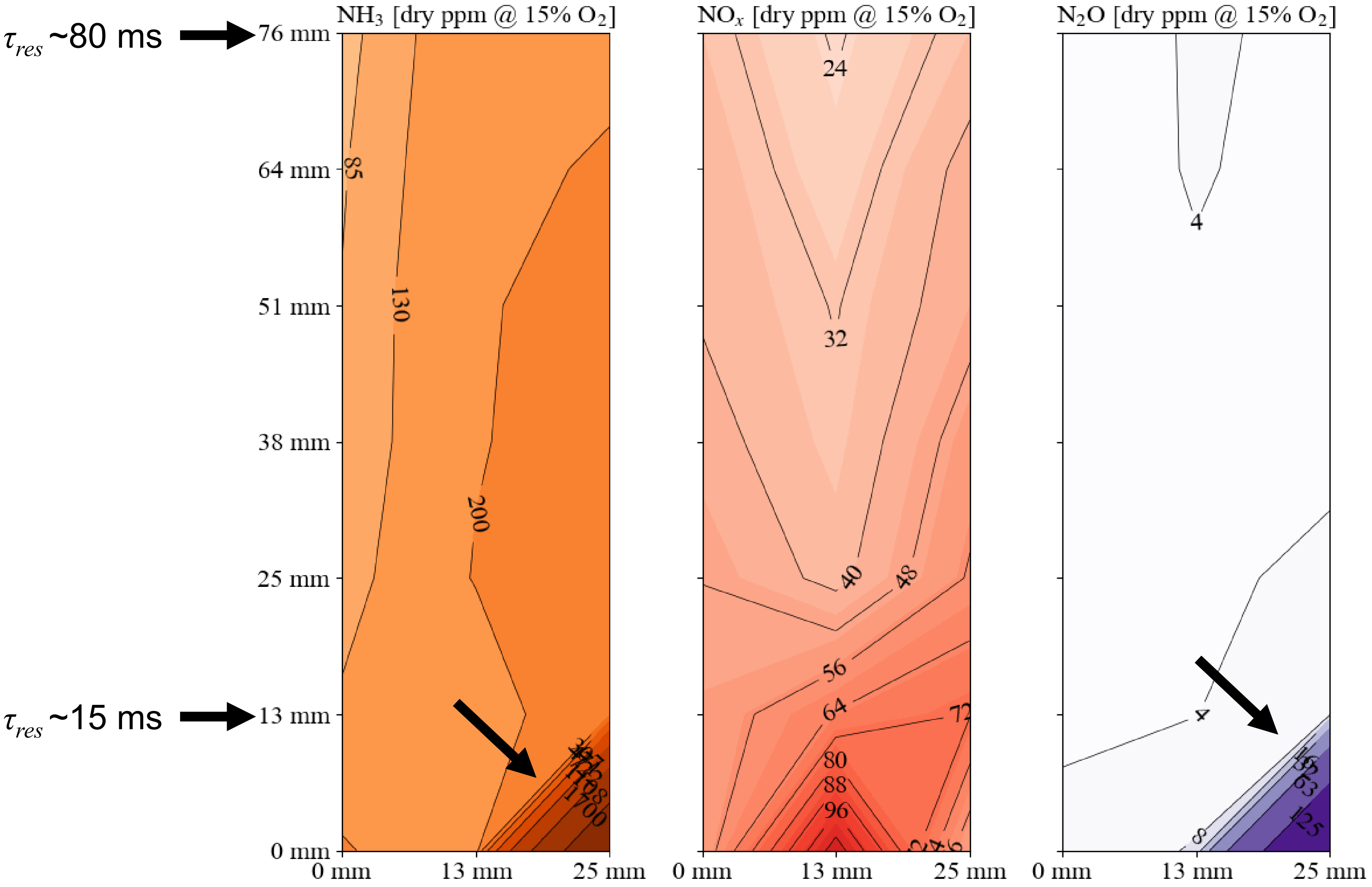


Takeaway:

- Swirler geometry impacts ϕ which minimizes NO_x and NH_3 emissions

Emissions Evolution: $\phi_{primary} = 1.13$ / $S_g 1.1$-$S16$





Summary

- Chemiluminescence images showed that less flame-wall interaction is achieved by increasing the number of vanes
- The low NO_x-NH_3 sweet spot shifts towards richer ϕ by increasing the number of vanes
- ***S_g1.1-C8*** swirler achieves slightly lower NO_x emissions but higher N_2O and NH_3 in contrast with ***S_g1.1-S16*** at the same ϕ
  - Lower NH_3 cracking → higher fuel-NO_x in a further lean secondary stage
  - Lower H_2 concentration for the secondary stage, hence lower thermal power
  - Heat losses through the walls due to the lobes-like structures → higher N_2O concentration

We chose ***S_g1.1-S16*** for further RRQL studies

Effects of the primary combustion zone length and secondary stage number of holes on stability and emissions

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Experimental setup

Constant:

- $U_0 = 0.90$ m/s
- NH_3-air premixed flames
- $S_g = 1.1$ (straight 16 vanes)
- Holes diameter: 2.03 mm

We varied:

- $\phi_{primary} = 1.13$-1.15-1.18

Campaign 1 (5H)

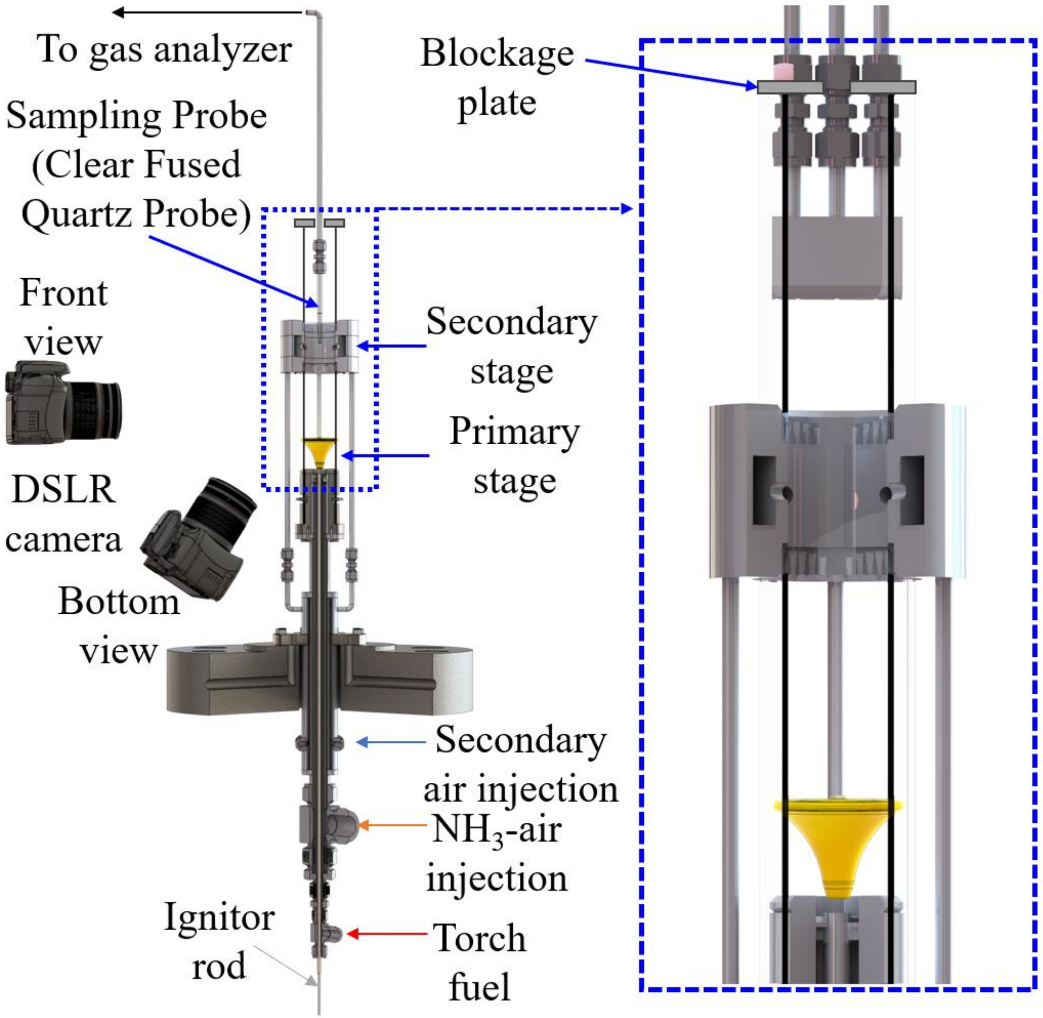
- Quartz length = 76 or 178 mm
- $\phi_{global} = 1.10$ down to 0.5 or blowout

Campaign 2 (5H/10H/16H)

- Quartz length = 178 mm
- $\phi_{global} = 1.10$ down to 0.5 or blowout

We measured:

- Exhaust emissions
  NO_x-N_2O-NH_3-O_2 (CAI 700 FTIR and LX)
- Flame images

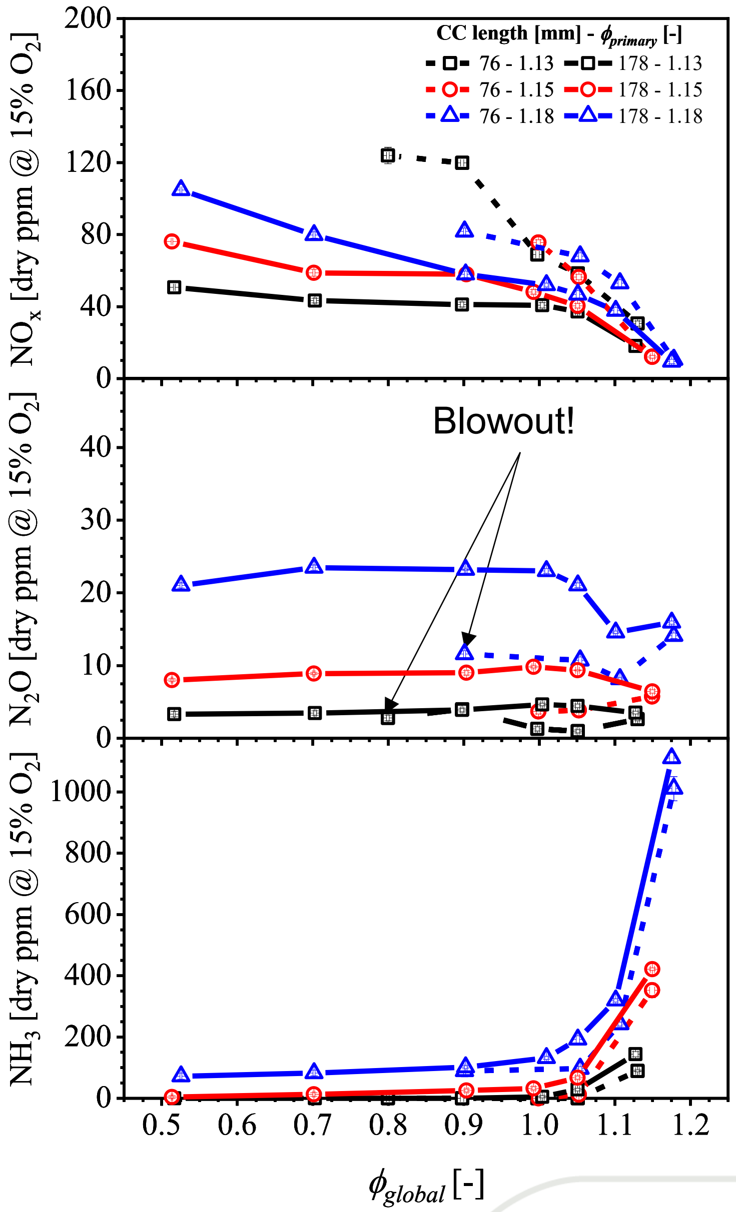


Exhaust emissions

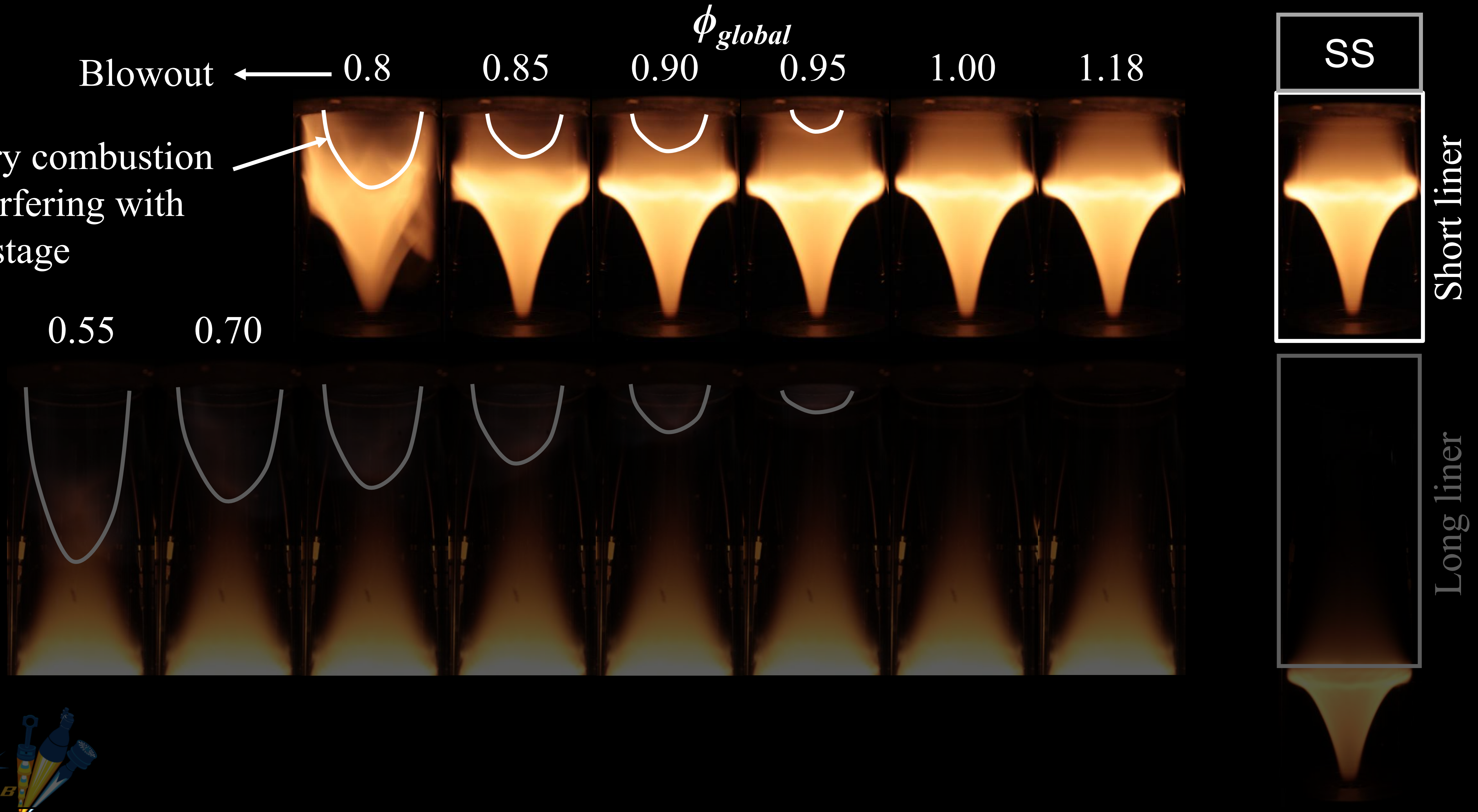
- NO_x increases as a function of ϕ_{global} while N_2O is constant and NH_3 decreases
- Increasing $\phi_{primary}$ reduces flame speed and increases N_2O and NH_3 emissions
- Lower operability range with short CC → primary flame blows out due to strong interaction with second stage jets ($\phi_{global} = 0.76$)
- Higher NO_x emissions → high interaction between air jets and primary flame may produce local lean pockets
- Lower N_2O is measured for short CC → probably higher temperatures → long CC means also higher heat losses
- This is also observed for NH_3 emissions → probably a leaner flame is produced with short CC, explaining high NO_x

Takeaway:

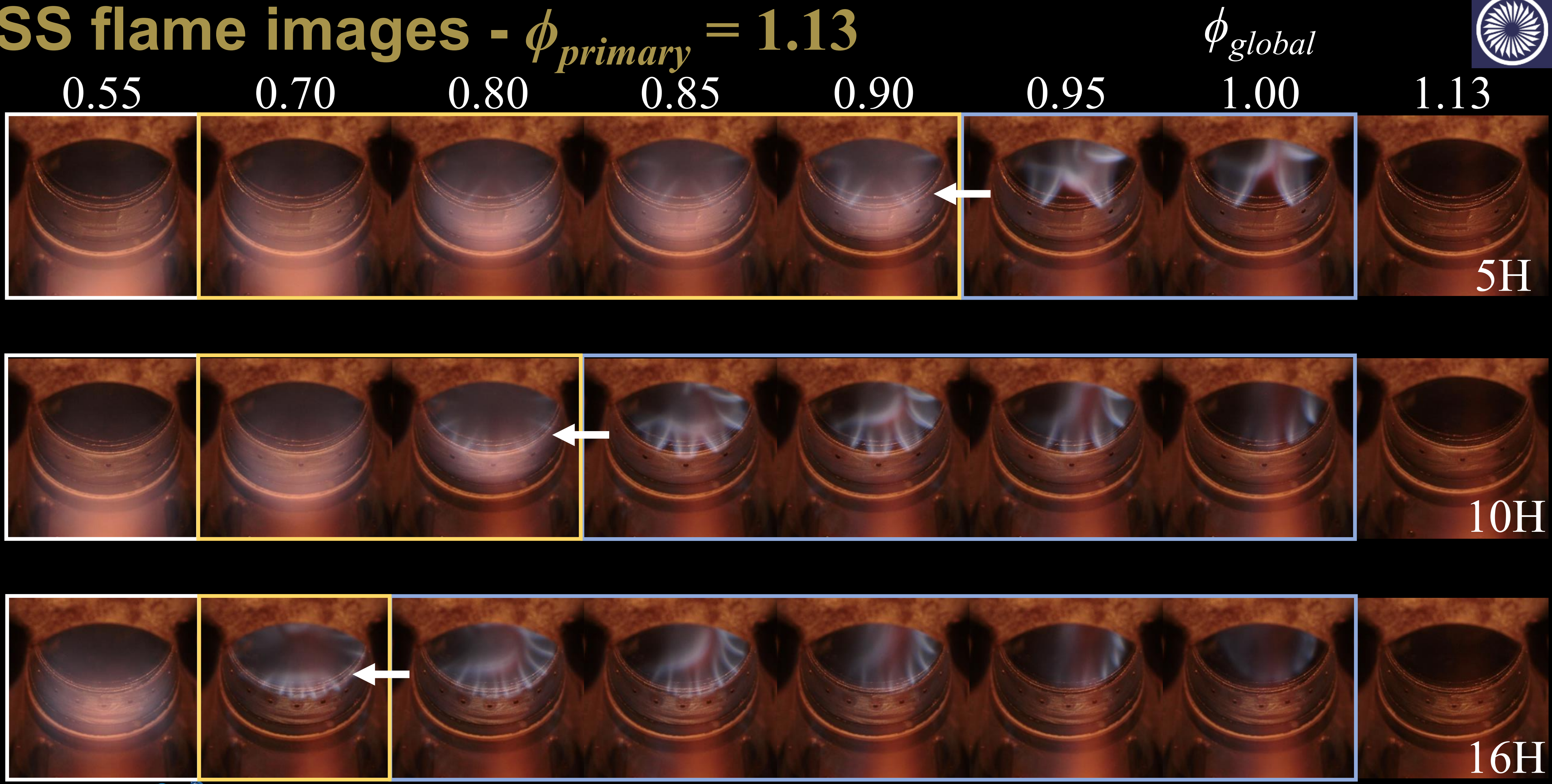
- Long CC is better not only for lower NO_x but higher stability
- $\phi_{primary} = 1.13$ yields better results



Results: Flame images



SS flame images - $\phi_{primary} = 1.13$



Transition from diffusion-like (Jet structures) to partially premixed-like (mixed and uniform)

Secondary stage interacting with primary flame for $\phi_{global} < 0.70$

Summary

- Long combustion chamber is better → lower NO_x and higher stability → reduces PS-SS interaction
- $\phi_{primary} = 1.13$ yields better results → simultaneous low emissions
- Secondary stage geometry plays a role → 5H yields better NO-N_2O emissions
- Differences between geometries (NO and N_2O) are more noticeable by increasing $\phi_{primary}$
- Diffusion-like combustion found at low air additions ($0.90 \leq \phi_{global} \leq 1.10$) → such conditions not desirable due to low combustion efficiency
- Transition from diffusion-like to premixed-like combustion observed to yield lower NO_x emissions → $0.50 \leq \phi_{global} \leq 0.70$ seems to be an optimum range → TIT = 1450 – 1720 K

Conclusion:

- *Longer combustion chamber needed → increases PS residence time*
- *$\phi_{primary}$ and secondary stage geometry tuning is key*
- *Reach high J (low ϕ_{global}) for premixed-like combustion*

Exhaust emissions point measurements on the secondary stage of an NH_3 RRQL system

14th U.S. National Combustion Meeting
March 16-19, 2025
The Westin Copley Place
Boston, MA

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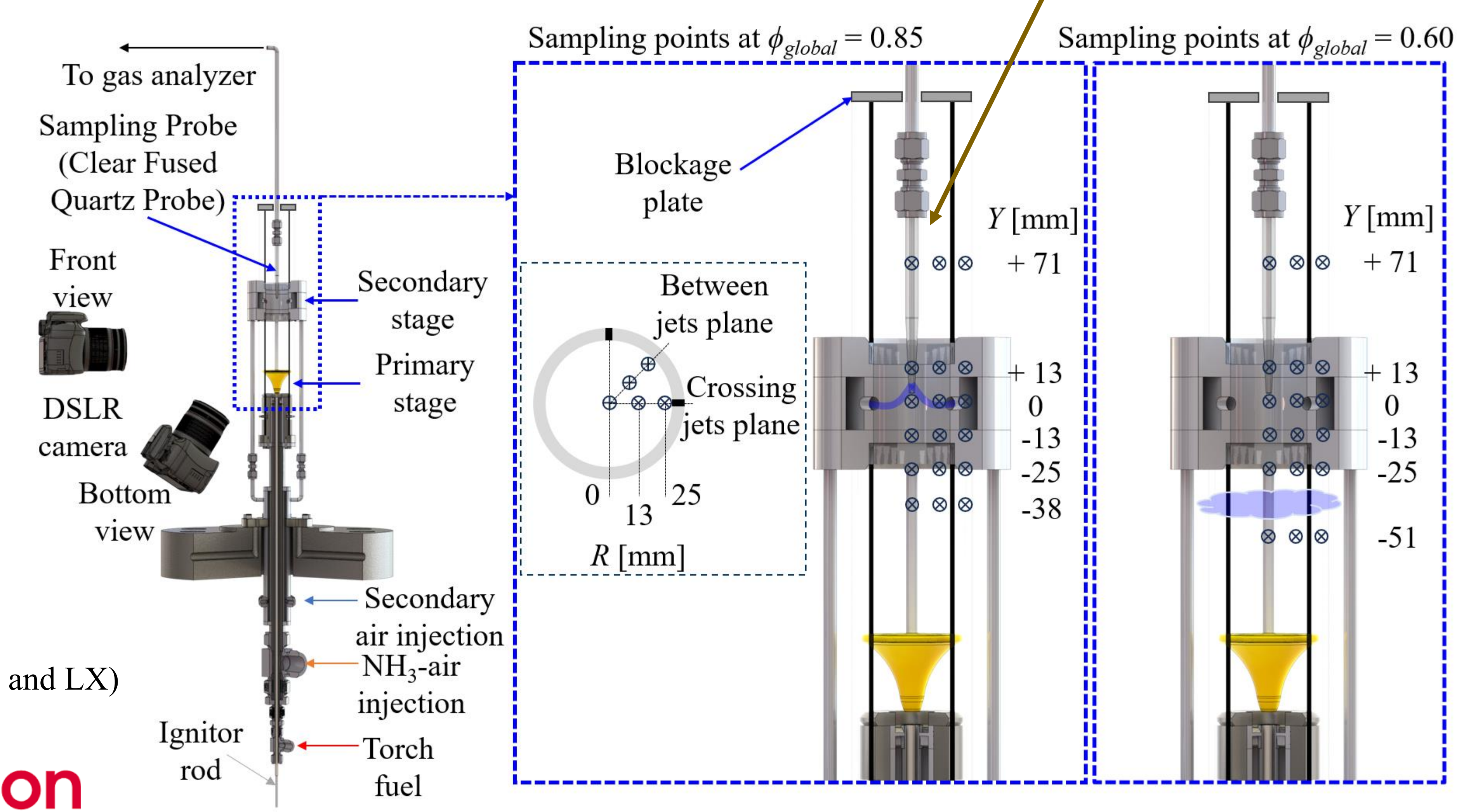
Experimental setup

Constant:
- $U_0 = 0.90$ m/s
- NH_3-air premixed flames
- $S_g = 1.1$ (straight 16 vanes)
- Quartz length = 178 mm
- Number of holes = 5
- Holes diameter = 4.1 mm

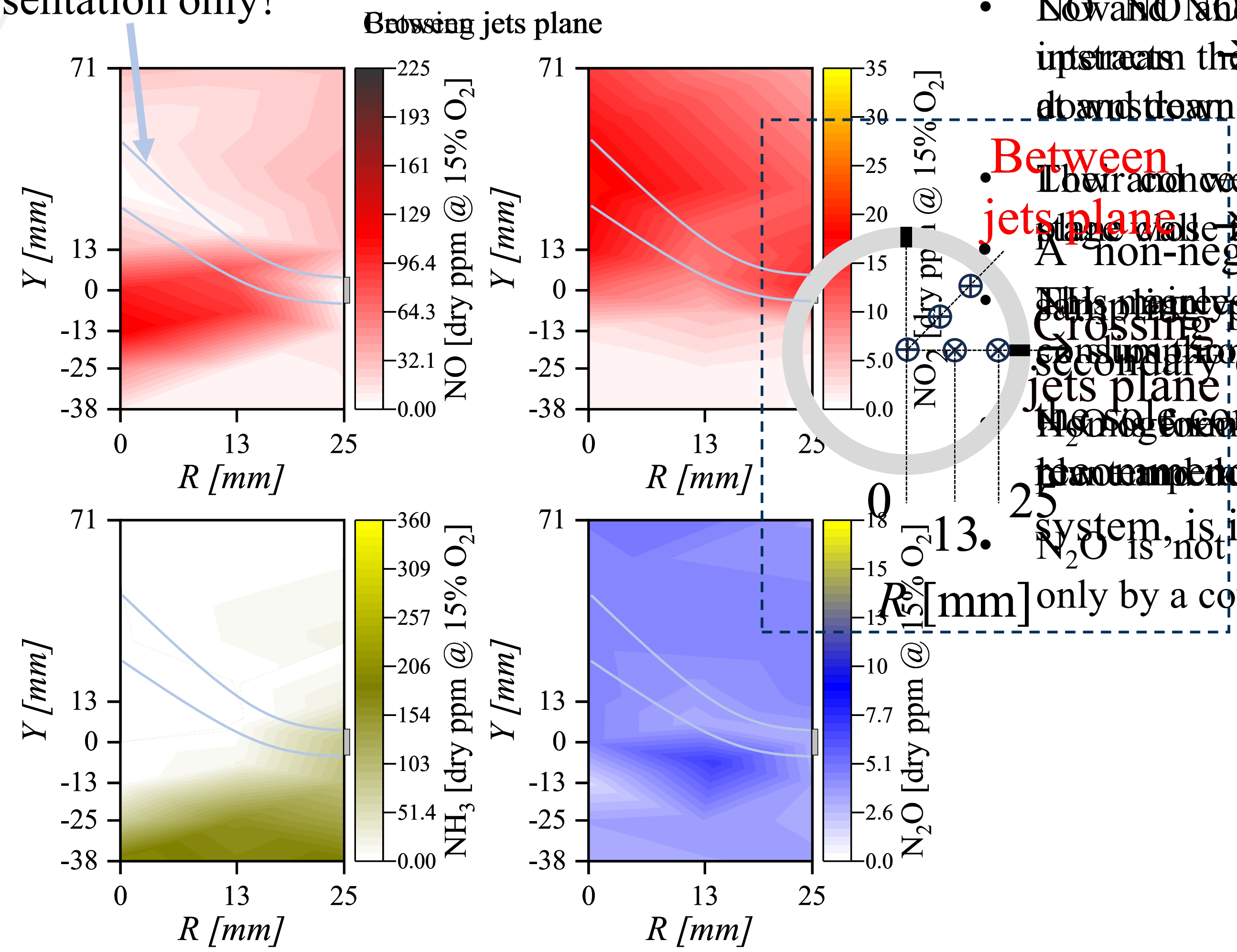
We varied:
- $\phi_{primary} = 1.13\text{-}1.15$
- $\phi_{global} = 0.85$ (diffusion-like)
  0.60 (premixed-like)
- Sampling position

We measured:
- Exhaust emissions
  $NO\text{-}NO_2$ (CLD50)
  $N_2O\text{-}NH_3\text{-}O_2$ (CAI 700 FTIR and LX)
- Flame images

Clear Fused Quartz Probe
2.3mm ID x 6.3mm OD x 100mm long tapered to a 1.5mm diameter opening on one end



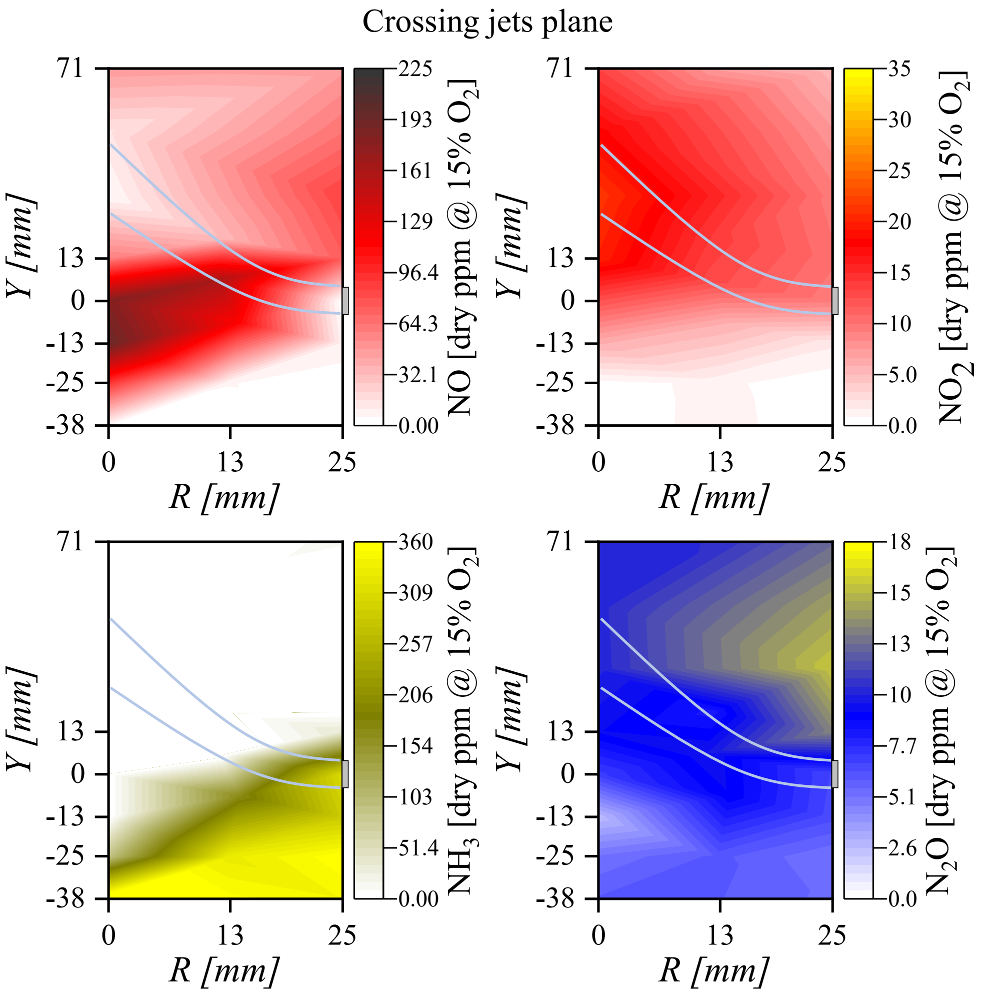
$\phi_{primary} = 1.13 - \phi_{global} = 0.85$


For representation only!

- [illegible] plane
- [illegible] ting zone)
- A non-neglig [illegible] NO_x (50% in some
- [illegible]
- [illegible] system, is imp
- N_2O is not high [illegible] ndary stage, increasing only by a couple ppm

[4] Sun et al. GT2024-123845
[5] Liu., et al. Chinese Journal of Aeronautics 37.4 (2024): 243-255
[6] Okafor – PROCI 2021

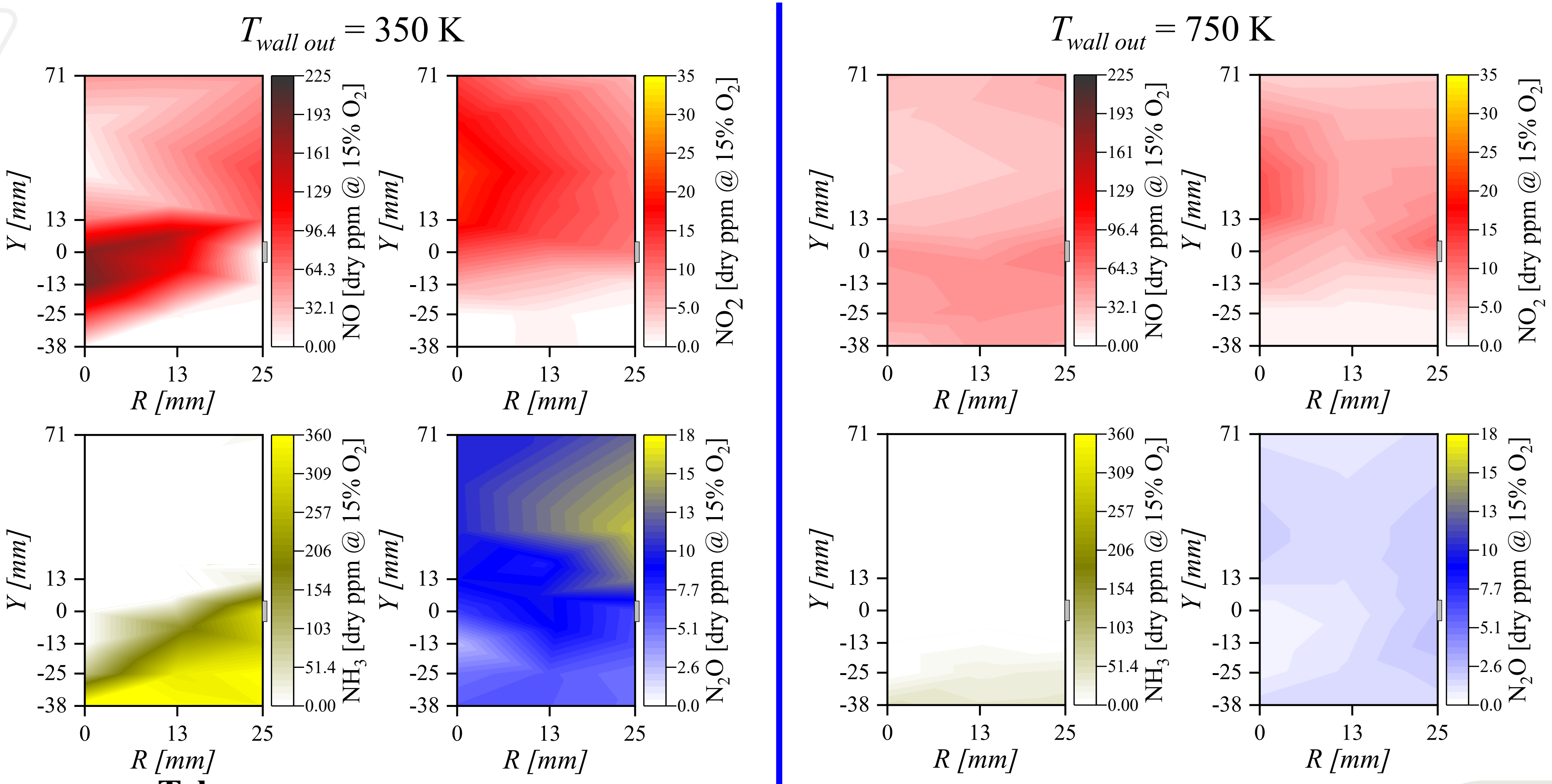
$\phi_{primary} = 1.15 - \phi_{global} = 0.85$


Crossing jets plane

- Same trends for NO and NO_2 for both sampling planes
- NO_x concentration leaving the burner is around 40% higher
- Much higher NH_3 concentration reaching the secondary stage (about 100%)→ increasing fuel NO_x pathway
- N_2O emissions are much higher at the downstream region, with the higher concentration region close to the walls
- In agreement with the simulations by [4] and [5], N_2O is formed in the Leeward side of the jets → related to NH_3 chemistry

[4] Sun et al. GT2024-123845
[5] Liu., et al. Chinese Journal of Aeronautics 37.4 (2024): 243-255

$\phi_{primary} = 1.15 - \phi_{global} = 0.85$



Takeaway:

- Lower wall heat losses increase NH_3 cracking → less NO_x production in SS

Conclusion

- Inverse diffusion-like combustion (ϕ_{global} = 0.85) is not desirable →
  - High NO and NO_2 production upstream the jets plane and post-secondary flame, respectively.
  - NH_3 and N_2O may slip through the walls between jets
- Lower overall exhaust emissions with premixed-like (ϕ_{global} = 0.60) combustion in the secondary stage →
  - Therefore, more desirable for low NO_x control with low N_2O emissions and zero NH_3 slip
- A non-negligible portion of total NO_x (50% in some sampling positions) is composed of NO_2 after the lean secondary combustion zone. Therefore, considering NO as the sole constituent of total NO_x for NH_3 combustion is not recommended if a staged strategy, such as the RRQL system, is implemented
- NO_x production in the secondary stage is higher for $\phi_{primary}$ = 1.15 compared to $\phi_{primary}$ = 1.13 → higher NH_3 concentration available from the primary stage
- Reducing the wall heat losses reduces the unburned NH_3 concentration drastically → enhancing the overall exhaust emissions with sub-10 ppm N_2O concentrations

Takeaway

Simultaneous tuning of primary and secondary stages; high jets' momentum flux (low enough ϕ_{global}) to produce premixed-like combustion in the secondary lean stage and reducing wall heat losses are key parameters for an adequate NH_3-RRQL system design in terms of exhaust emissions

St. George D: Novel Energy Systems (1K03) – 10:15

"*Influence of wall heat losses and secondary stage geometry on exhaust emissions of an NH_3 RRQL system*, R. Cole, et al."

Summary

- Primary zone geometry and flame shape mostly impacts the optimum primary zone equivalence ratio
  - Residence time effects
  - Wall interactions
- Important to tune primary zone equivalence ratio with secondary zone geometry
  - Avoid inverse diffusion flames
- NO generated in primary zone, burns/converts to NO2 in secondary
- Cold walls promote ammonia and N2O slip along walls between secondary jets

Questions?

Publication List:

S. Gubbi, R. Cole, B. Emerson, D. Noble, R. Steele, W. Sun, T. Lieuwen, Air quality implications of using ammonia as a renewable fuel: How low can NOx emissions go?, *ACS Energy Lett.*, 8 (10) (2023) 4421–4426.

R. Cole, S. Gubbi, D. Wu, B. Emerson, D.R. Noble, R. Steele, W. Sun, T. Lieuwen, Rich ammonia flame shapes and NO relaxation: Facility development and characterization, *ASME Turbo Expo: Power for Land, Sea, and Air*, GT2024-87943, V03AT04A012 (2024).

S. Gubbi, R. Cole, B. Emerson, D. Noble, R. Steele, W. Sun, T. Lieuwen, Evaluation of minimum NOx emission from ammonia combustion, *J. Eng. Gas Turbines Power*, 146 (3) (2024).

R. Cole, C.D. Avila Jimenez, D. Wu, T. Lieuwen, B. Emerson, Carbon monoxide emissions from combustion of non-carbon-containing fuels, *Combust. Flame*, 273 (2025) 113913.

S. Gubbi, R. Cole, C.D. Avila Jimenez, B. Emerson, D. Noble, R. Steele, W. Sun, T. Lieuwen, Investigation of minimum NOx emissions for cracked ammonia combustion, *Combust. Flame*, 274 (2025) 114005.

C.D. Avila Jimenez, R. Cole, J. Parnell, M. Peckham, D. Wu, B. Emerson, Exhaust emissions point measurements on the secondary stage of an NH3-RRQL system, *Proc. Combust. Inst.*, 41 (2025) 105791.

R. Cole, C.D. Avila Jimenez, D.R. Noble, R. Steele, D. Wu, B.L. Emerson, T.C. Lieuwen, Towards the development of an NH3-RRQL system Part 1: Swirl pattern effect on exhaust emissions and chemiluminescence distribution for NH3-air premixed swirl flames, *ASME Turbo Expo: Power for Land, Sea, and Air*, GT2025-1527, (2025).

C.D. Avila Jimenez, R. Cole, D.R. Noble, R. Steele, D. Wu, B.L. Emerson, T.C. Lieuwen, Towards the development of an NH3-RRQL system Part 2: Effects of the primary combustion zone length and secondary stage number of holes on stability and emissions, *ASME Turbo Expo: Power for Land, Sea, and Air*, GT2025-88780, V03AT04A015 (2025).