LSU

School of Mechanical and Industrial Engineering

Ammonia swirl combustion research at LSU

S. Menon: Assistant Professor

V. Viswamithra, M. Gurunadhan: Graduate students

Department of Mechanical and Industrial Engineering

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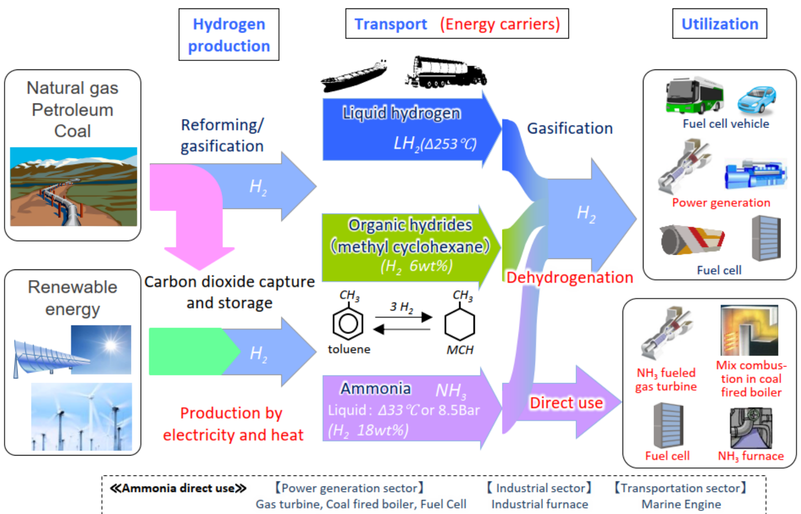
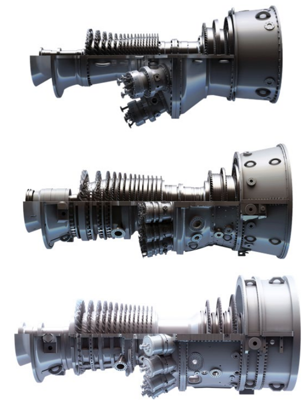
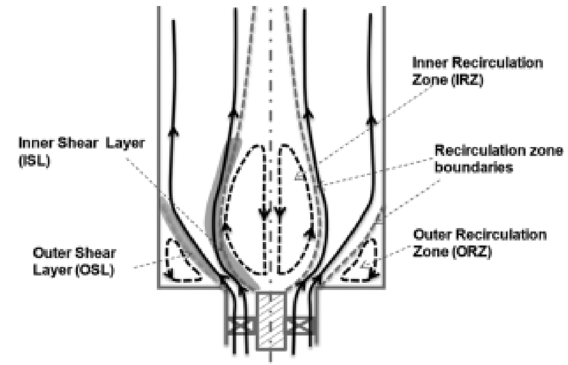
Ammonia swirl combustion







Fuel	NH_3	CH_4	H_2
LHV (MJ/kg)	18.6	50.2	120.4
Flammability limit	0.6-1.4	0.5-1.7	0.1-7.2
Maximum burning velocity	0.09	0.37	2.91
Ignition temperature	651	537	500
Adiabatic flame temperature	1750	1970	2120

https://www.ammoniaenergy.org/wp-content/uploads/2021/02/AEA-Imp-Con-01Nov18-Shigeru-Muraki-Keynote-Address.pdf
Bompelly, R. K., 2013, “Lean Blowout and Its Robust Sensing in Swirl Combustors,” Ph.D. thesis, Georgia Institute of Technology, Atlanta, GA.
https://www.ammoniaenergy.org/articles/ge-and-ihi-to-develop-100-ammonia-powered-gas-turbines/

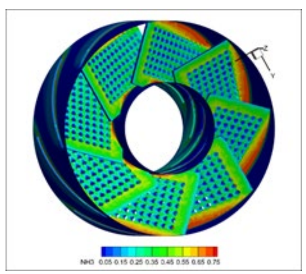
Ammonia swirl combustion strategies

NOx emissions
Combustor stability

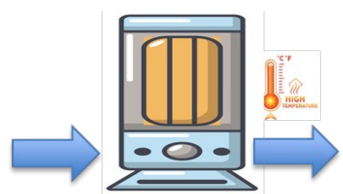
Methane addition

$$CH_4 + NH_3$$

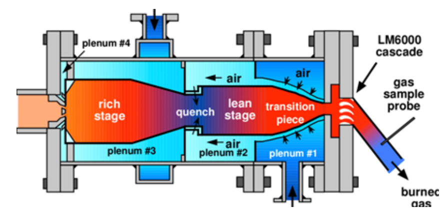
Air-fuel mixing



Inlet air preheating



Two-stage combustion



Feitelberg, A.S. & Jackson, M.R. & Lacey, M.A. & Manning, Kenneth & Ritter, A.M.. (1996). Design and Performance of a Low Btu Fuel Rich-Quench-Lean Gas Turbine Combustor.

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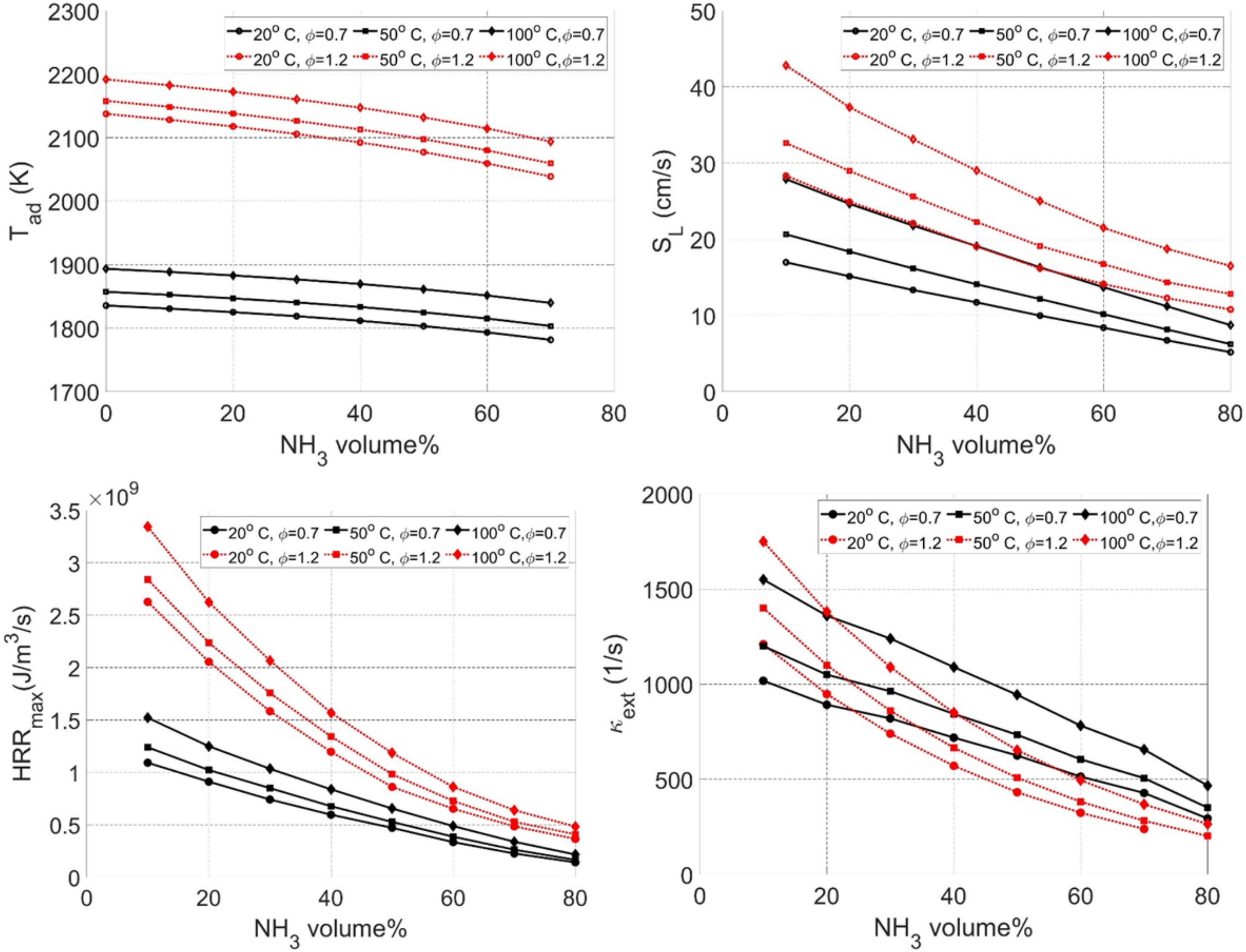
CH_4 addition and preheating effects



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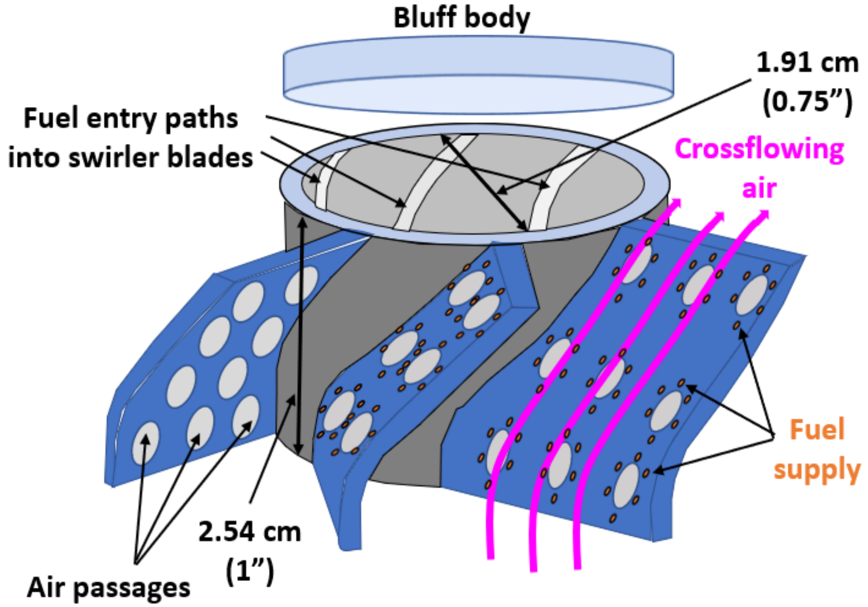
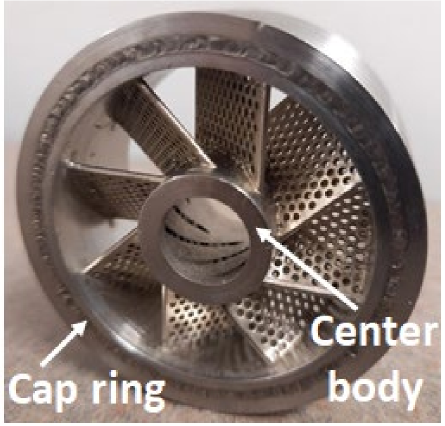
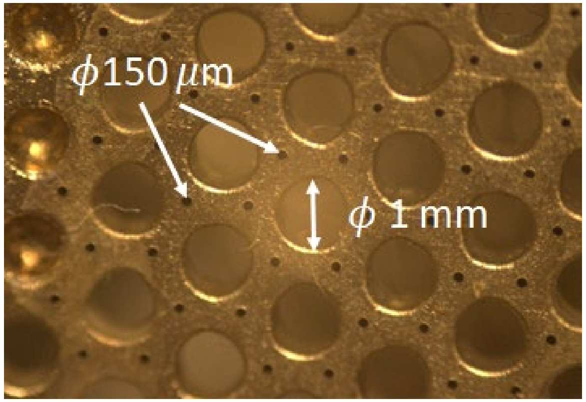
Distributed fuel injection







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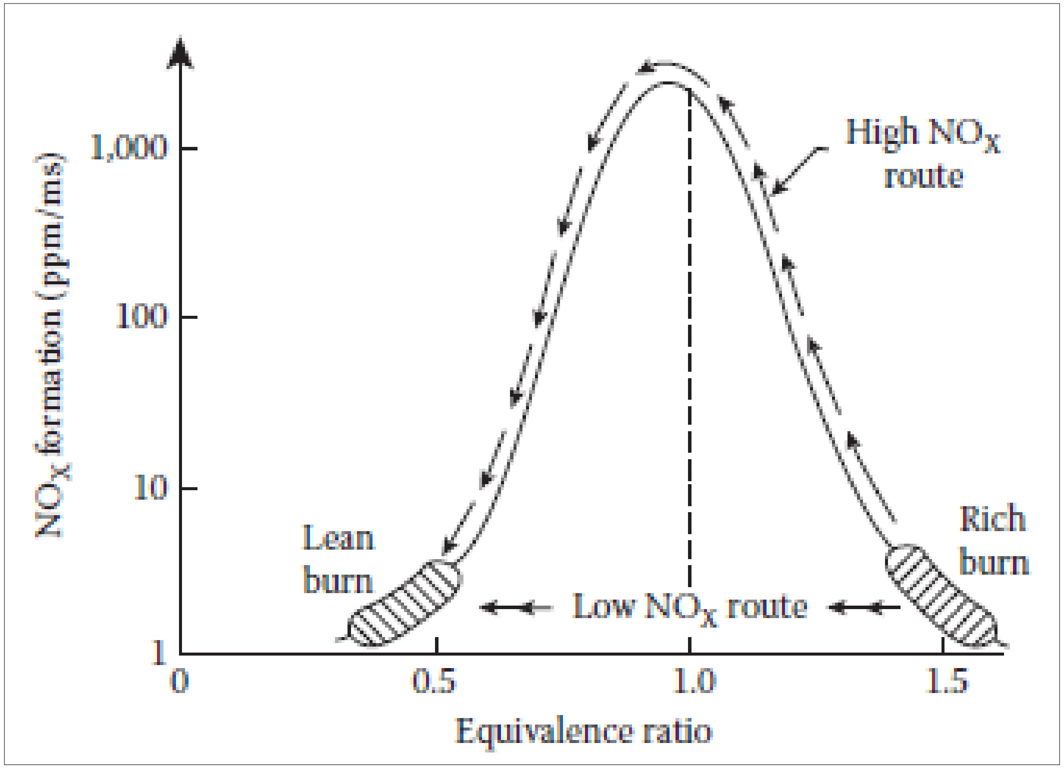
Two stage combustion

- Rich burn-Quick quench-Lean burn (RQL) strategy
- Secondary air injected to the second combustion chamber leading to rapid reduction of mixture temperature



Arthur H Lefebvre and Dilip R Ballal. Gas turbine combustion: alternative fuels and emissions. CRC press, 2010.

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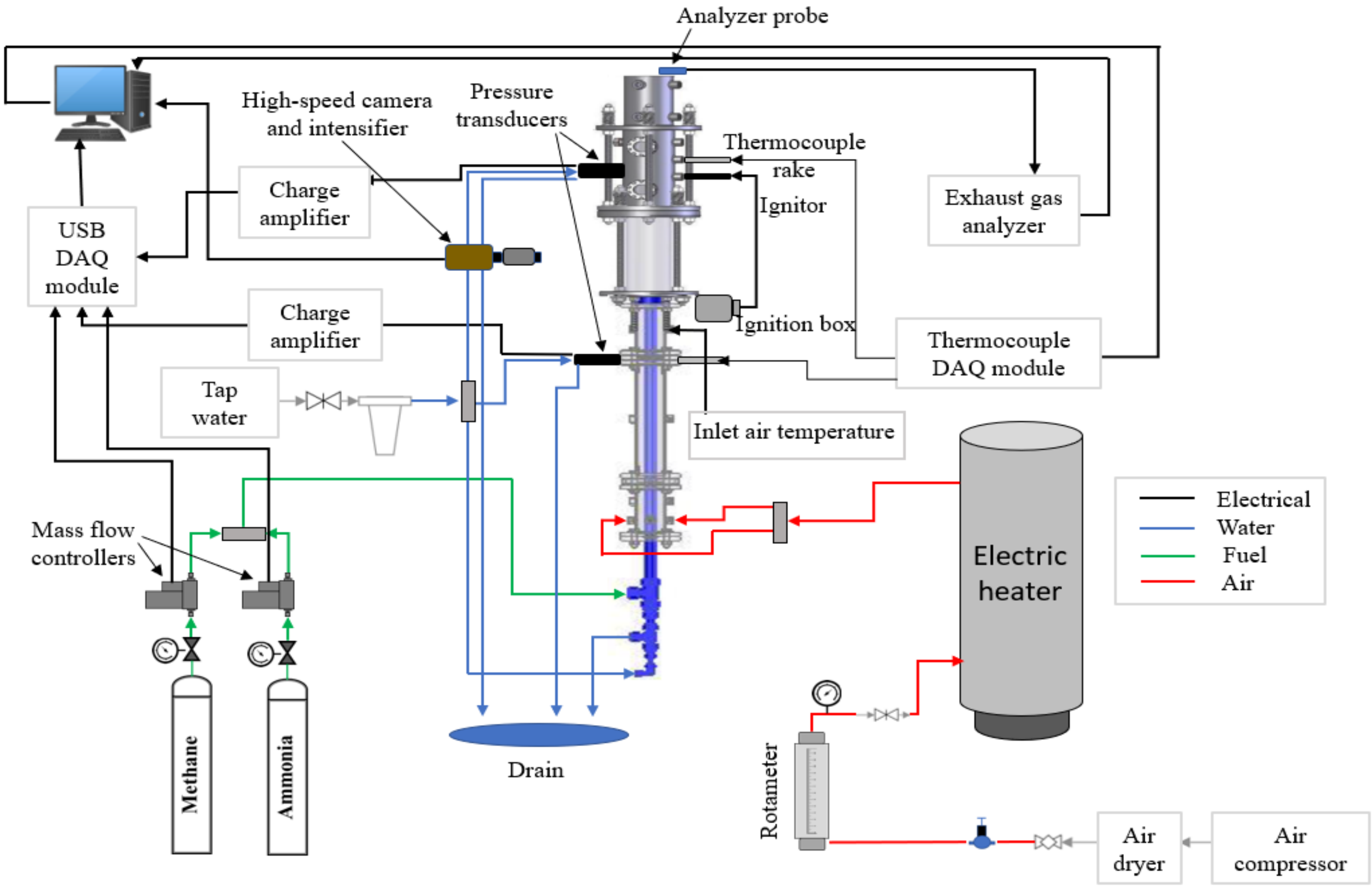
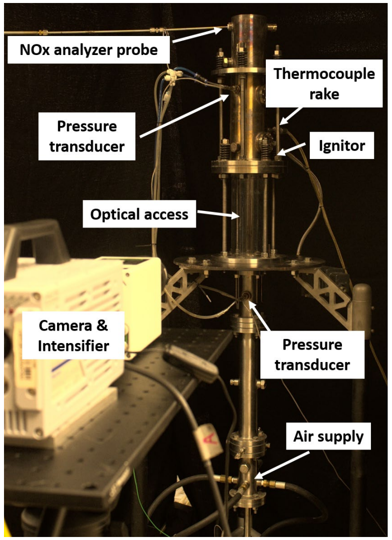
Experiments





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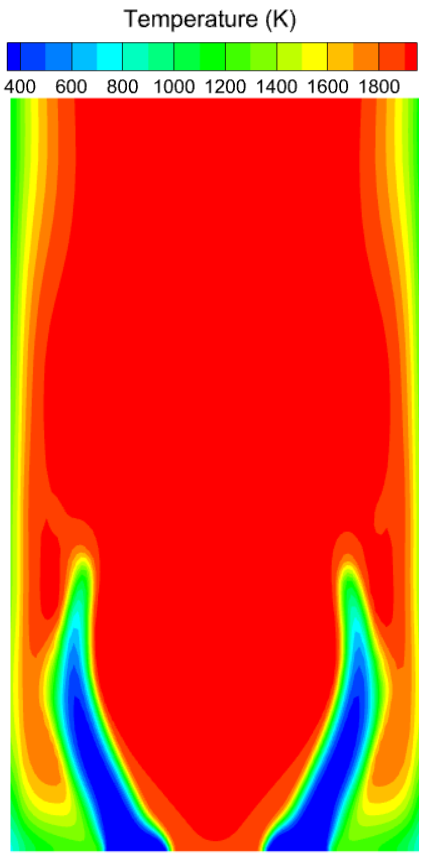
Diagnostics

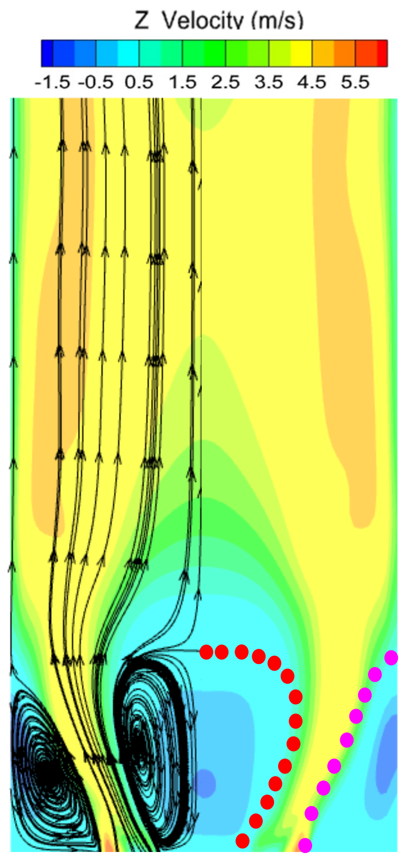
- Exhaust gas analyzer
  - Enerac M700
  - CO, CO_2, O_2, NO, NO_2, NH_3
- High-speed imaging and Chemiluminescence
  - Photron SA-3
  - UVi intensifier
  - Filters (OH*, CH*, NO*)
- Thermocouples
- Pressure sensors
  - Kistler water-cooled dynamic pressure sensors
- Particle Image Velocimetry (PIV)
  - LaVision 1-D, 2-Component
- Planar Laser Induced Fluorescence (PLIF)
  - Sirah dye laser pumped by Nd:YAG laser

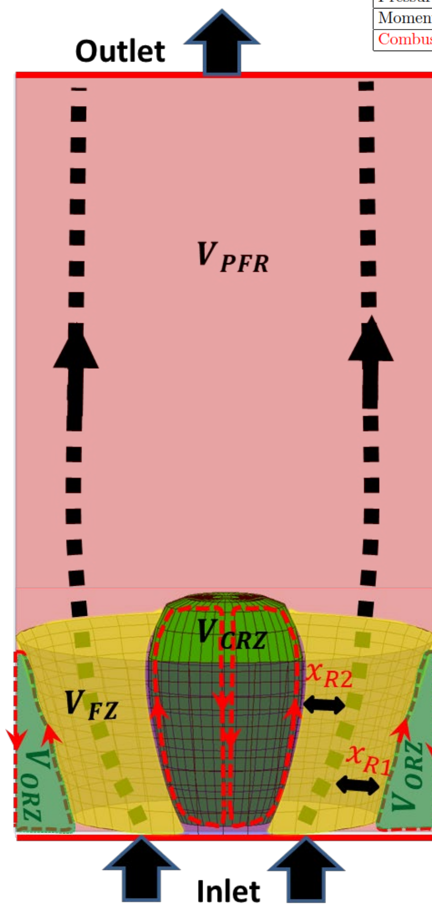
CFD modeling

Numerical aspect	Solution method
PV coupling	SIMPLEC
Turbulence	k-ϵ, Standard wall function
Gradient	Green Gauss Node based
Pressure	PRESTO!
Momentum, Energy, species	Second order upwind
Combustion	Arrhenius finite rate model with ISAT

- 3D simulations in Ansys FLUENT with detailed chemistry







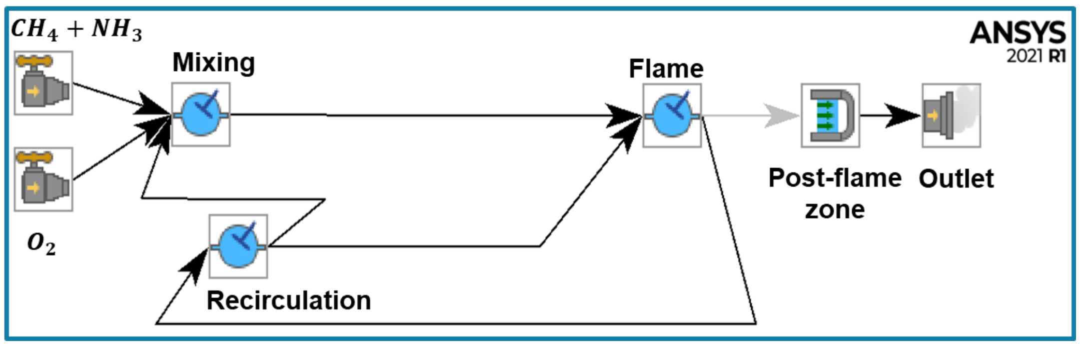
CH_4:50%;NH_3:50%, $\phi = 0.85$

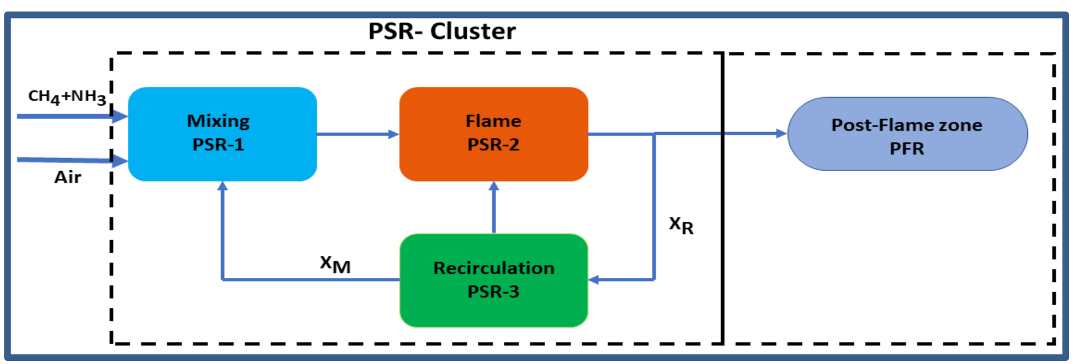
Reaction mechanism – Okafor; ~40 species and ~200 reactions

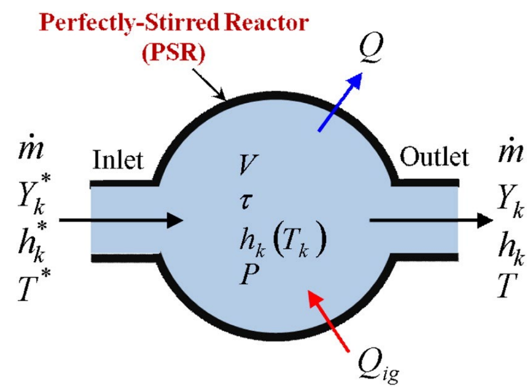
E. C. Okafor, K. K. A. Somarathne, R. Ratthanan, A. Hayakawa, T. Kudo, O. Kurata, N. Iki, T. Tsujimura, H. Furutani, H. Kobayashi, Control of nox and other emissions in micro gas turbine combustors fuelled with mixtures of methane and ammonia, Combustion and flame 211 (2020) 406–416.

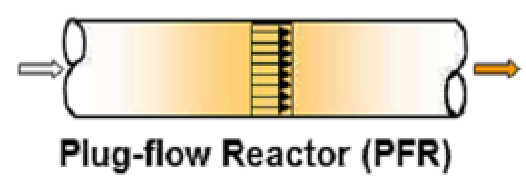
Reactor network modeling

- Perfectly stirred reactor (PSR): 0D component that acts as a mixing/reaction chamber
- Plug flow reactor (PFR): 1D reactor with no longitudinal mixing and known inlet composition
- Simulation time: 0D/1D chemical reactor network (~1hr) vs 3D reacting flow simulation (~48hrs)





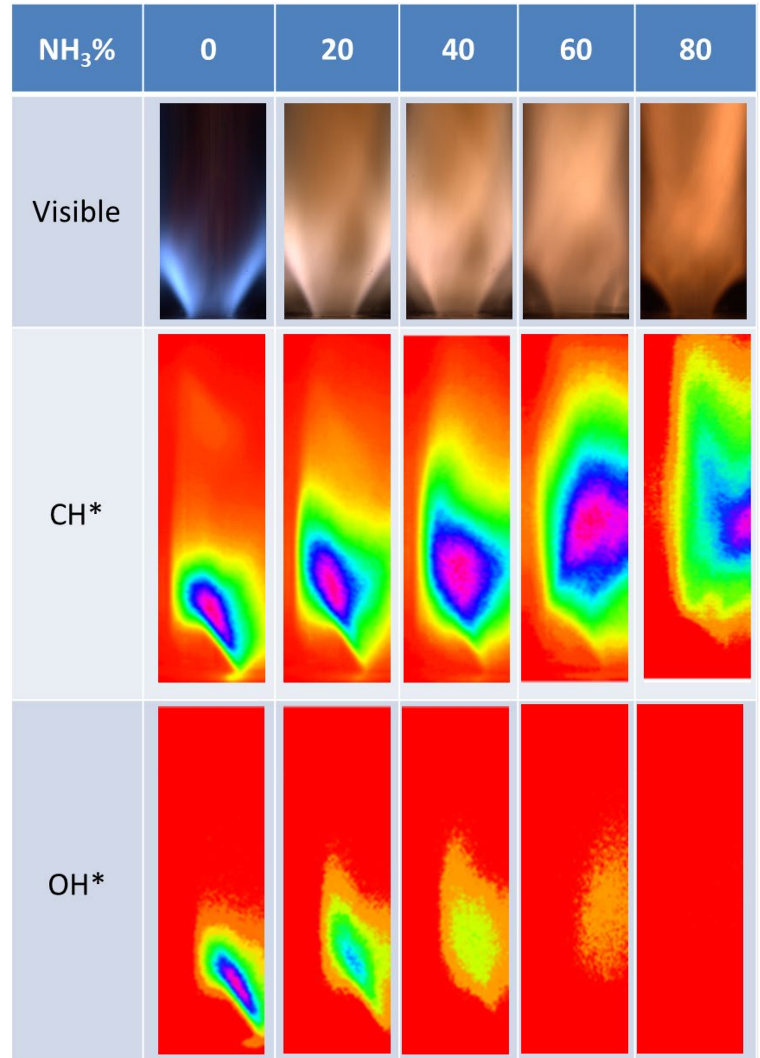




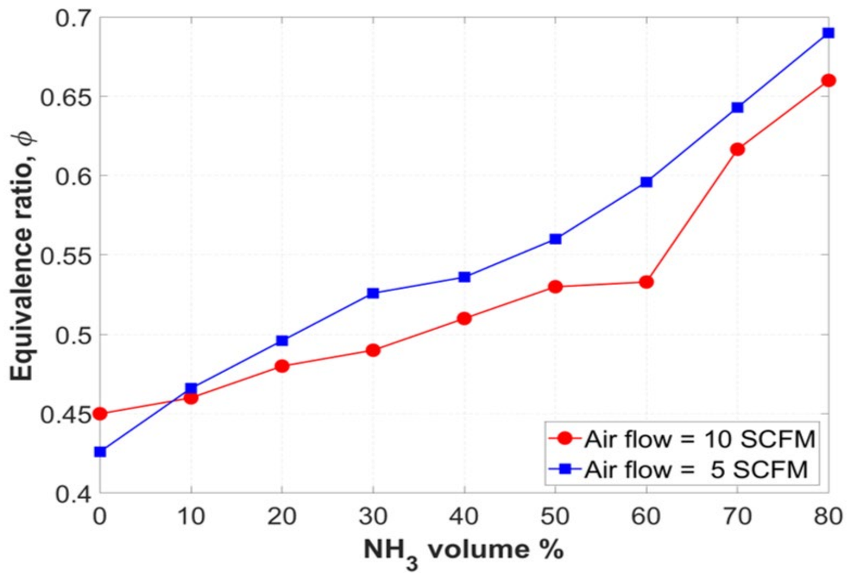
Input parameter	Set value
Volume $[cm^3]$	$V_{MZ} = 31$
	$V_{FZ} = 165$
	$V_{RZ} = 100$
	$V_{PFR} = 904 \quad (L = 10cm, D = 8cm)$
Recirculation mass fraction	$x_{RZ} = 0.09, \quad x_{MZ} = 0.05$

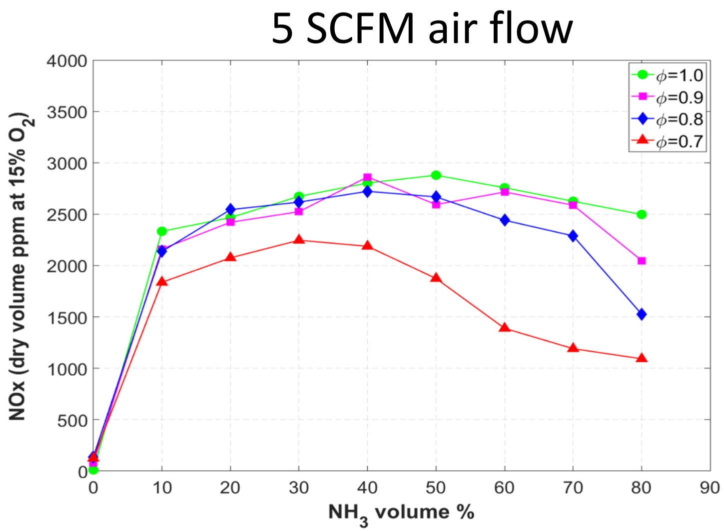
Flame imaging

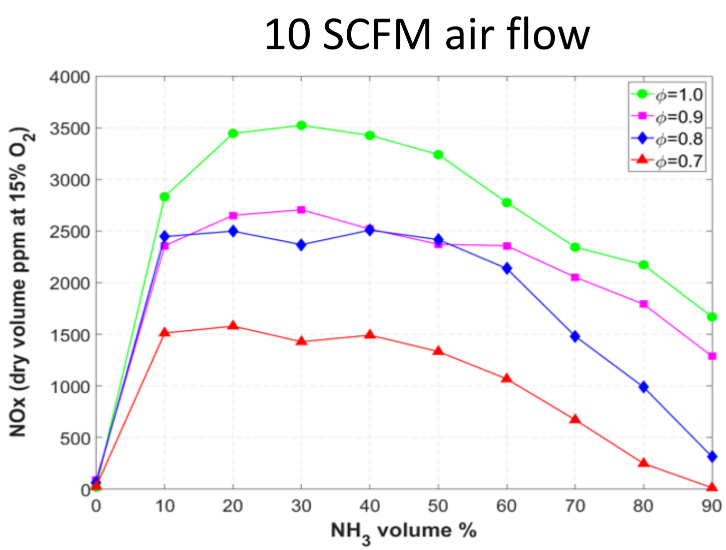
CH_4:100%;NH_3:0%, $\phi = 0.80$



Methane addition







$$C_{\text{adj}} = C_{\text{meas}} * \frac{20.9 - 15}{20.9 - \% O_2}$$

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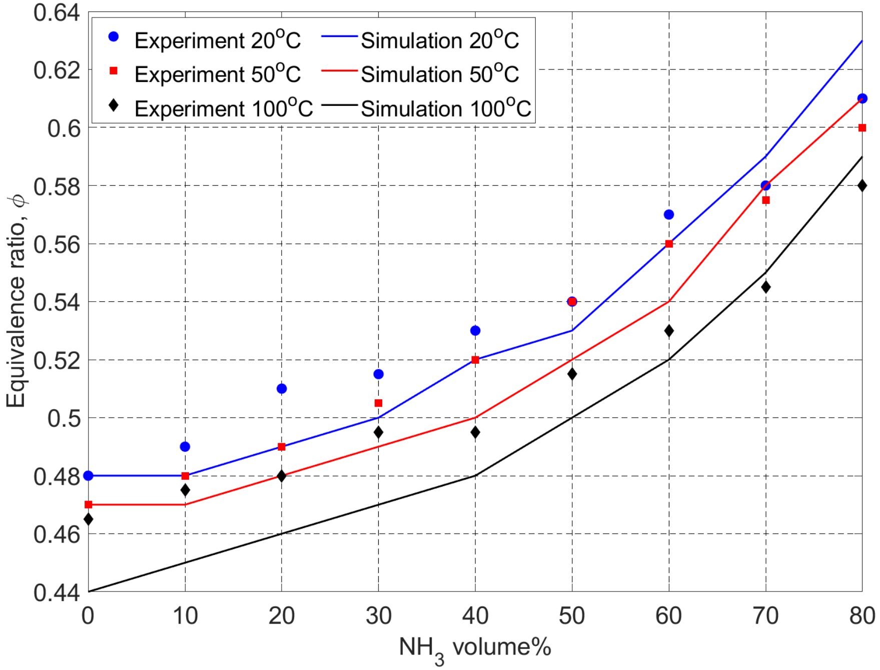
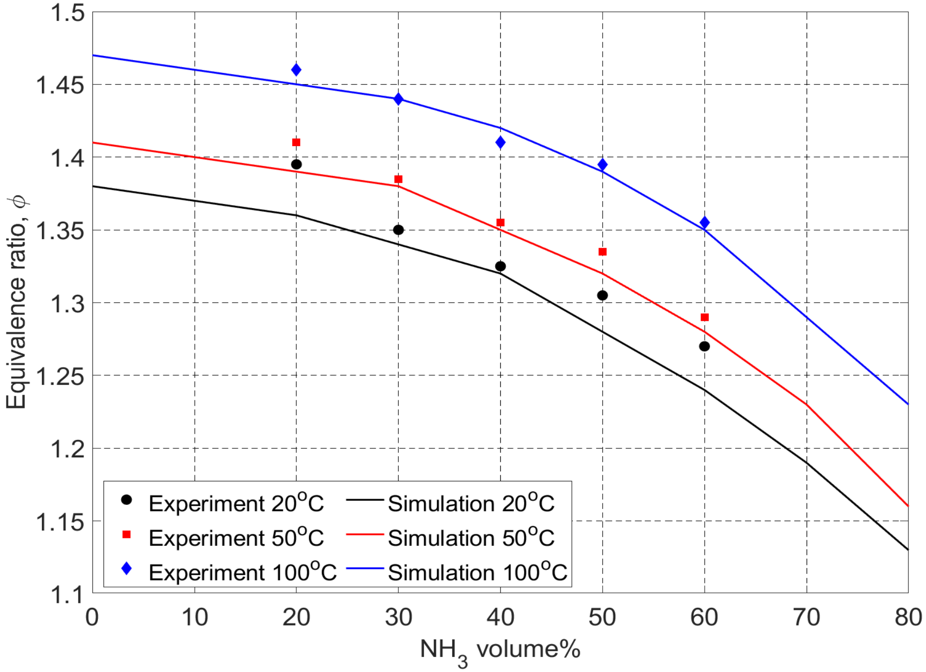
Methane addition and preheating

Lean blowout limits

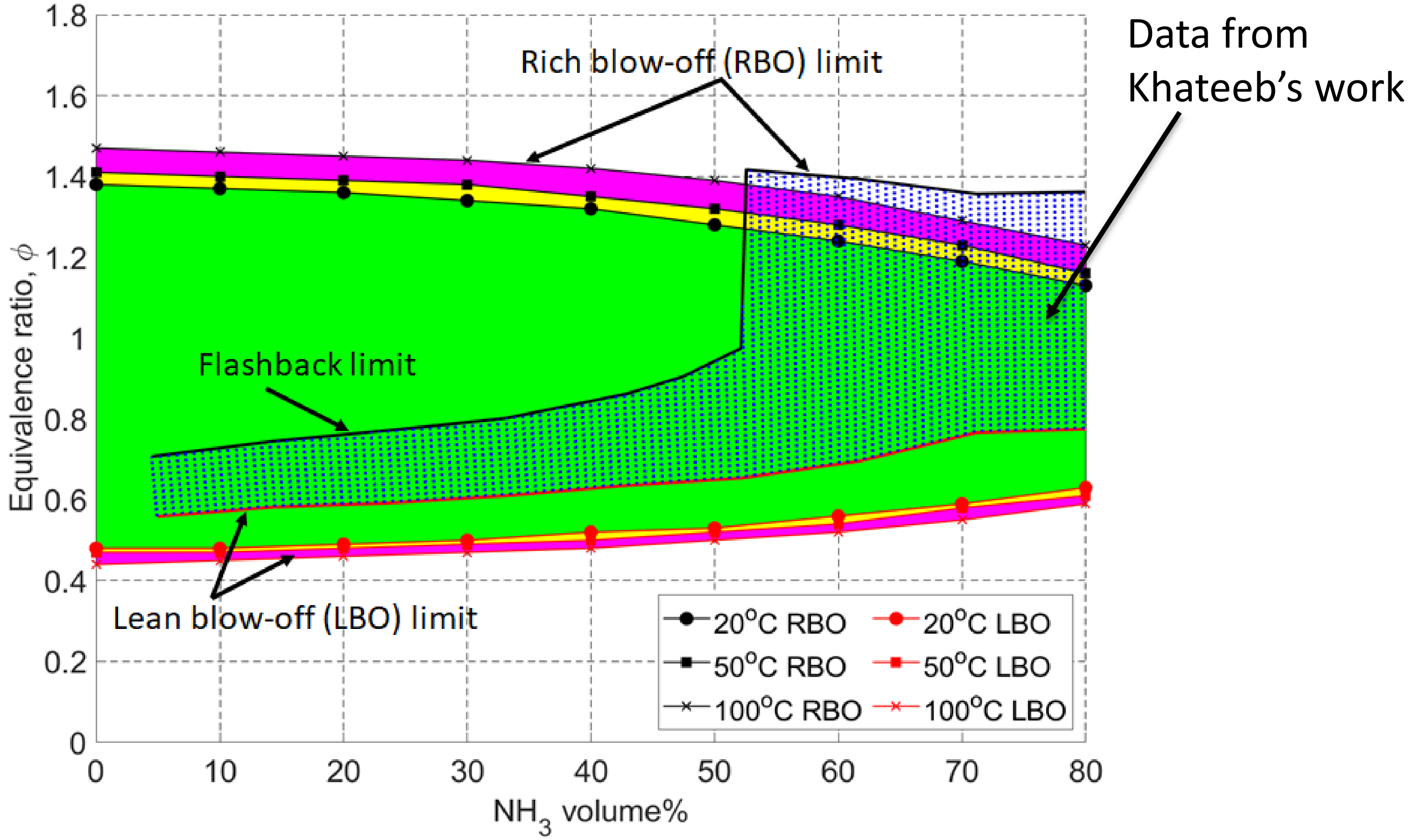


Rich blowout limits



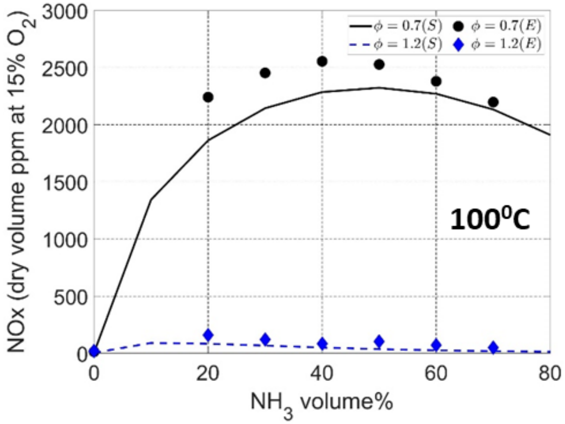
Air flow rate : 7 SCFM

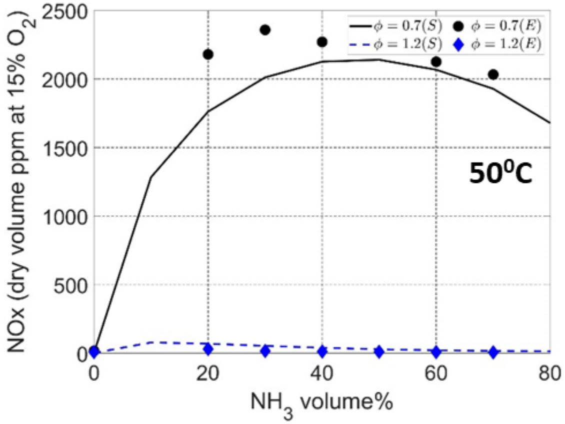
Combustor operability regime

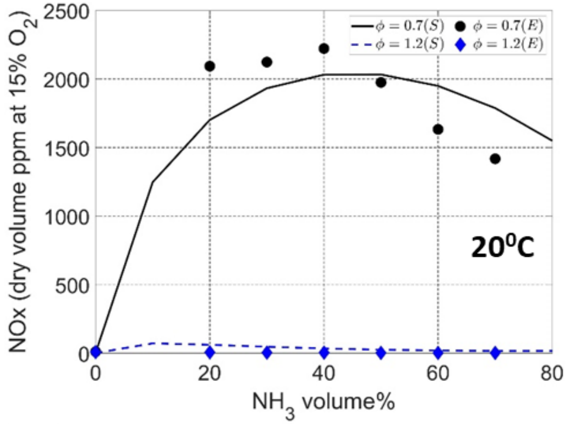


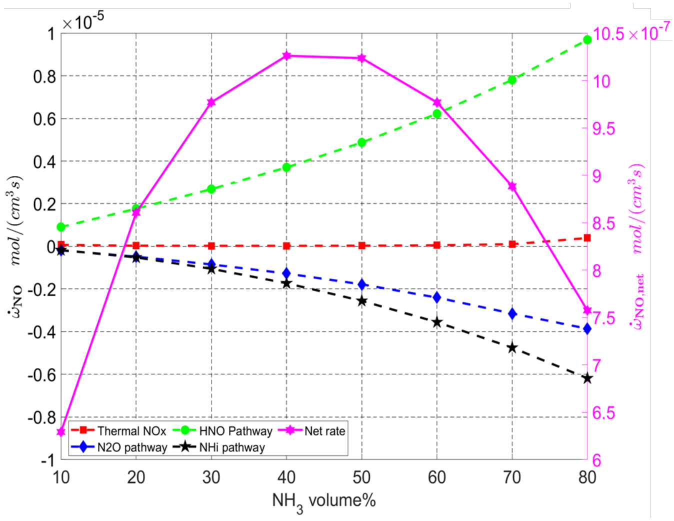
Khateeb, A. A., Guiberti, T. F., Zhu, X., Younes, M., Jamal, A., & Roberts, W. L. (2020). Stability limits and exhaust NO performances of ammonia-methane-air swirl flames. Experimental Thermal and Fluid Science, 114, 110058

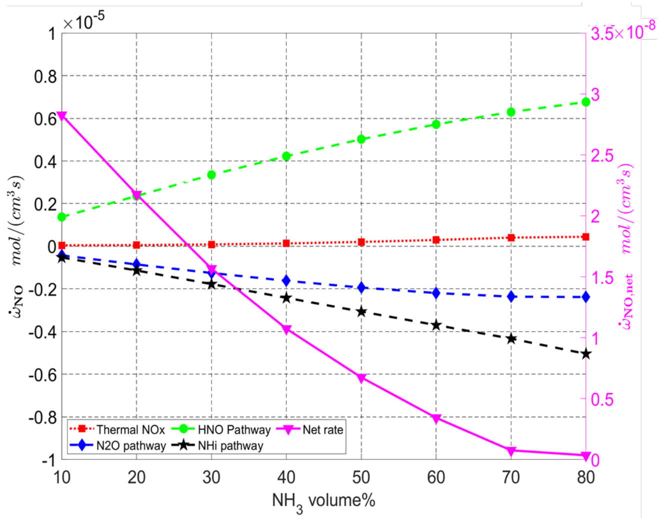
NOx emissions and production kinetics





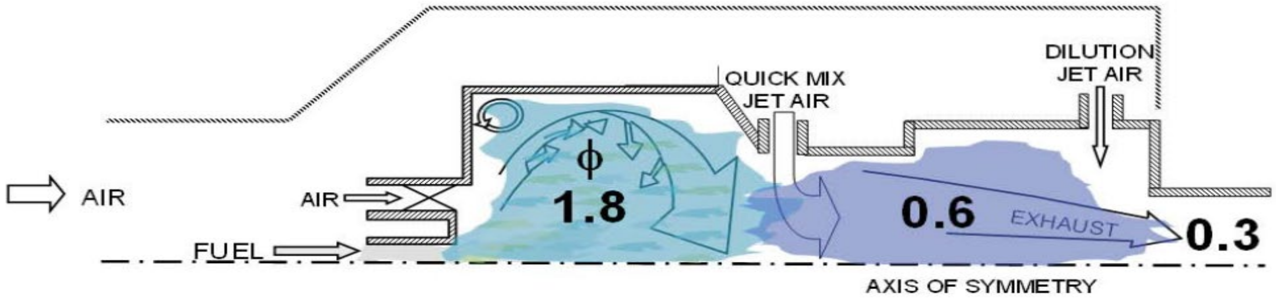


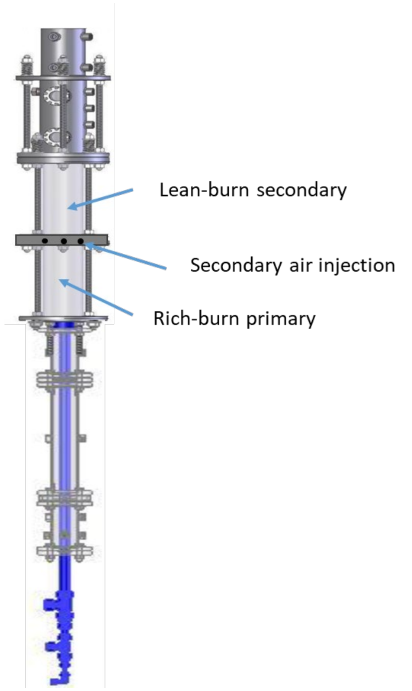


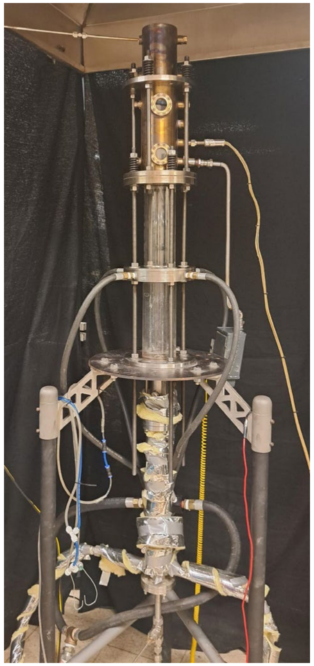


NO production pathway	Reactions
Thermal NOx	$N + OH \rightleftharpoons NO + H$
	$N + O_2 \rightleftharpoons NO + O$
	$N_2 + O \rightleftharpoons N + NO$
N_2O pathway	$N_2O + O \rightleftharpoons 2\,NO$
	$N_2 + H \rightleftharpoons NH + NO$
HNO pathway	$HNO\,(+M) \rightleftharpoons NO + H\,(+M)$
	$HNO + OH \rightleftharpoons NO + H_2O$
	$HNO + O_2 \rightleftharpoons NO + HO_2$
NHi pathway	$NH + O \rightleftharpoons NO + H$
	$NH + O_2 \rightleftharpoons NO + OH$
	$NH + NO \rightleftharpoons N_2 + OH$
	$NH_2 + NO \rightleftharpoons NNH + OH$
	$NH_2 + NO \rightleftharpoons N_2 + H_2O$

Two-stage combustion







Scott Samuelsen. Rich burn, quick-mix, lean burn (rql) combustor. The Gas Turbine Handbook, pages 227-233, 2006

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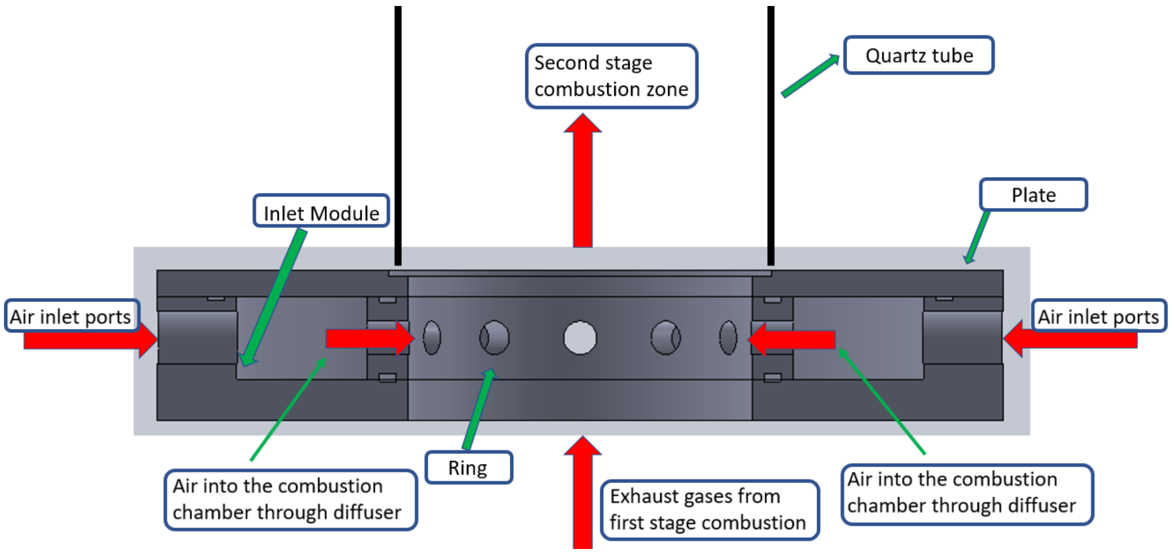
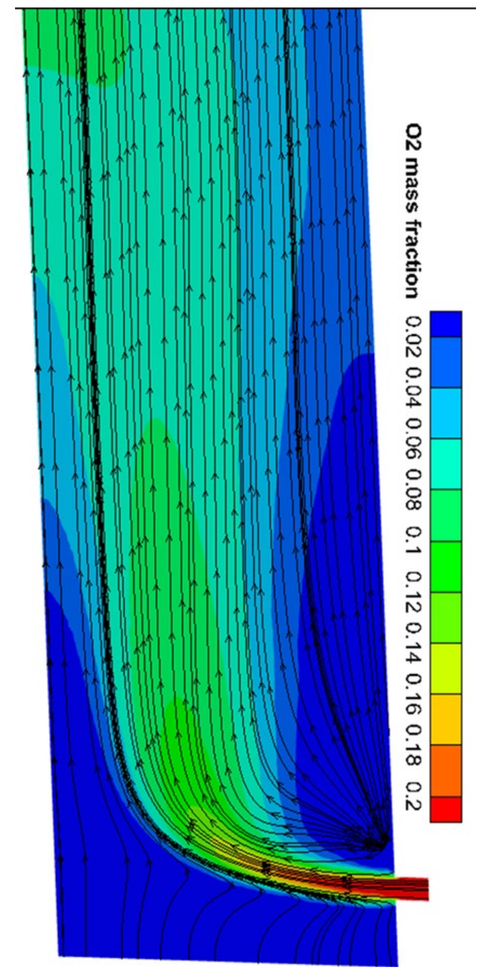
Second stage combustion setup



Parameter	Value
Jet diameter	8 mm
Jet Re	200-1800
Crossflow diameter	3.25”



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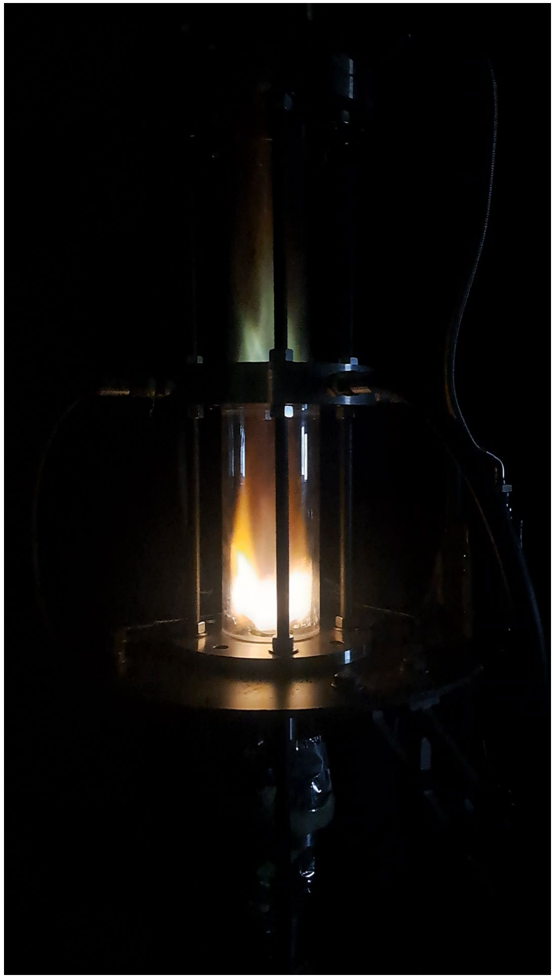
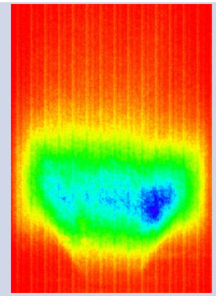
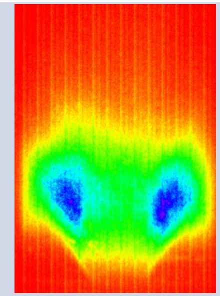
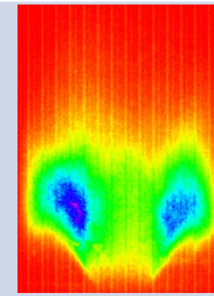
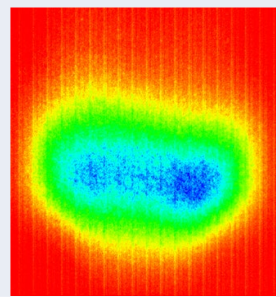
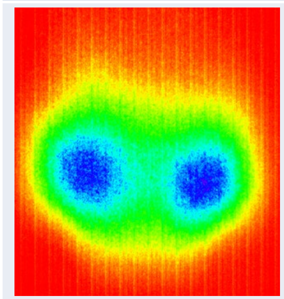
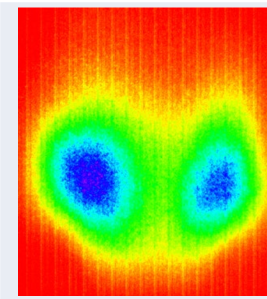
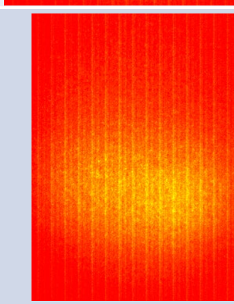
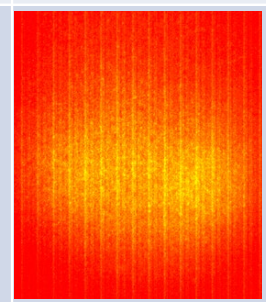
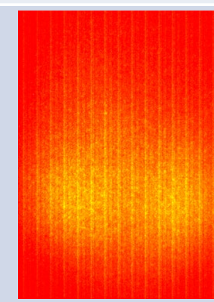
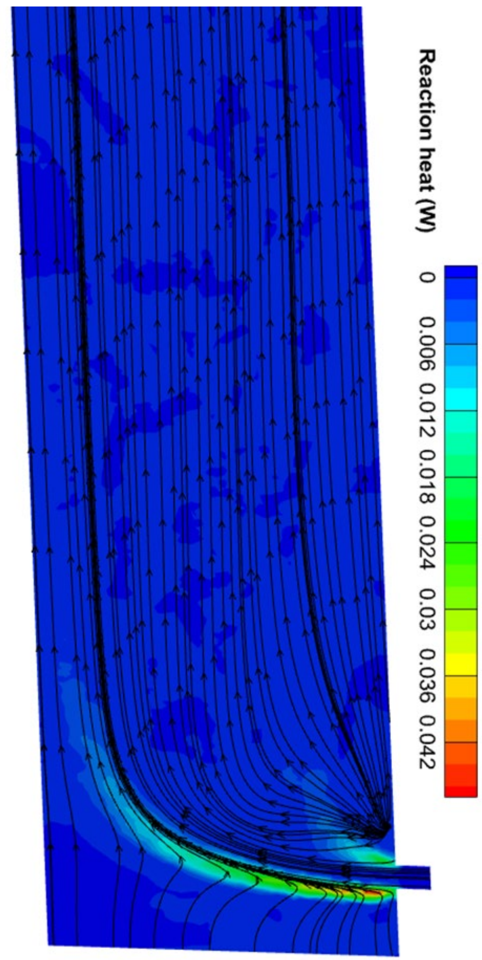
Flame imaging and chemiluminescence



CH_4: 40%; NH_3: 60%, ϕ_p =1.15,
$\phi_{overall} = 0.75$, 3 SCFM air flow

	$\phi_p = 1.05$	$\phi_p = 1.15$	$\phi_p = 1.25$
CH*			
OH*			
NO*			

Flame structure



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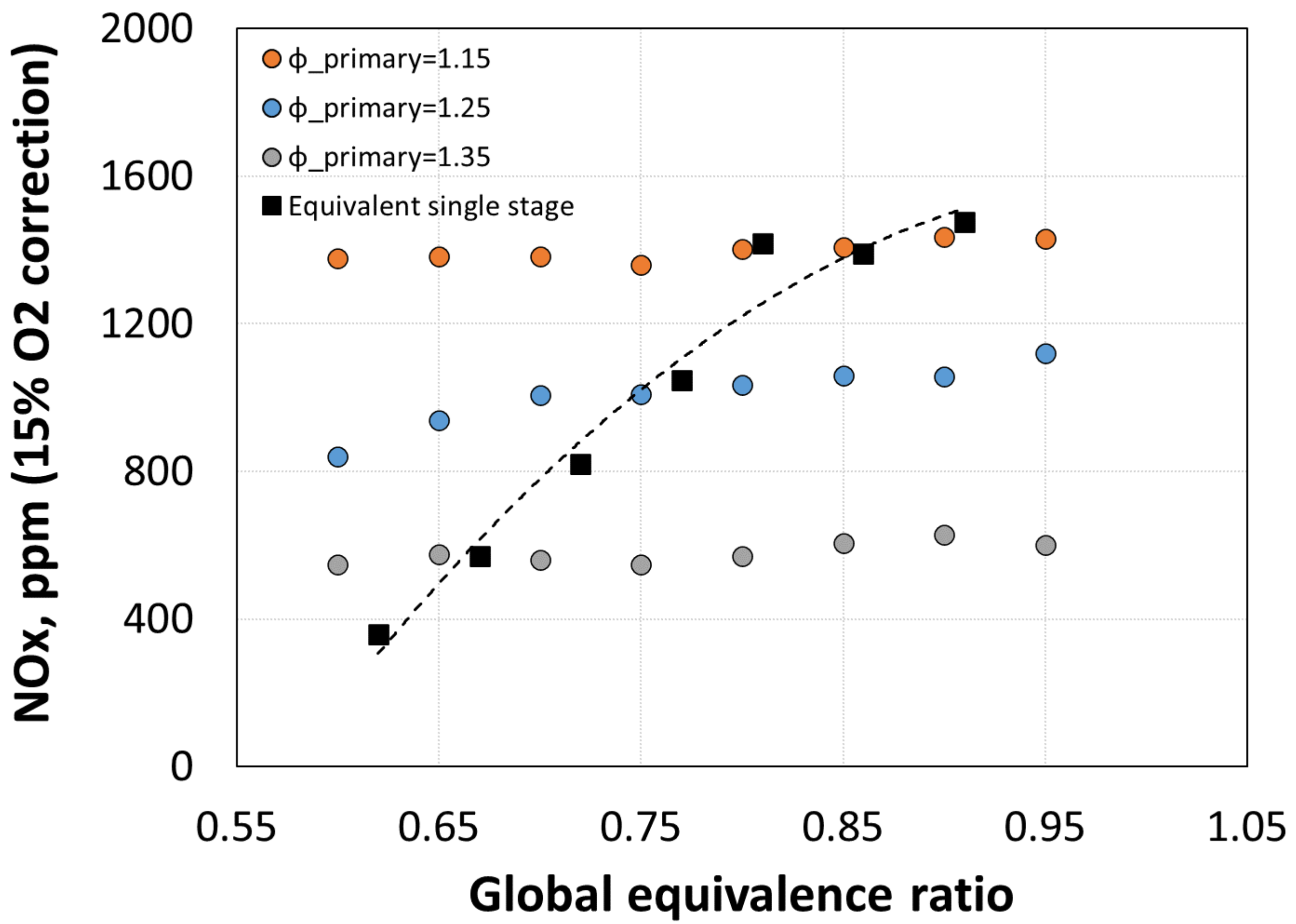
NOx emissions

- CH_4: 40%; NH_3: 60%, 3 SCFM air flow



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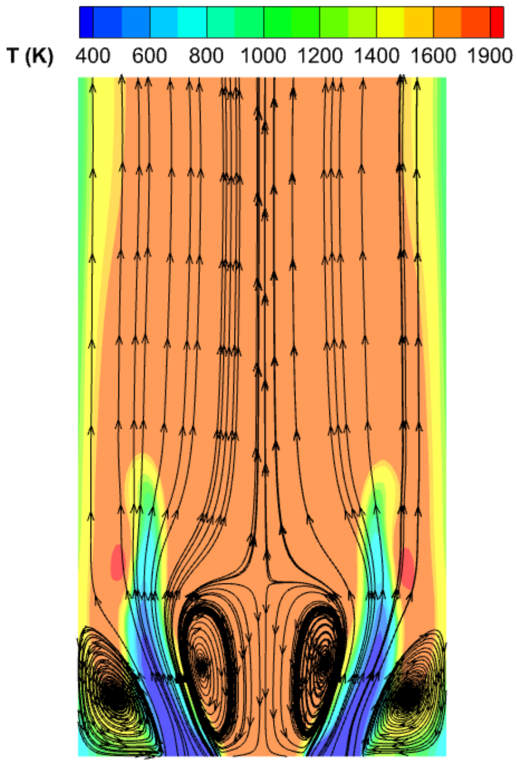
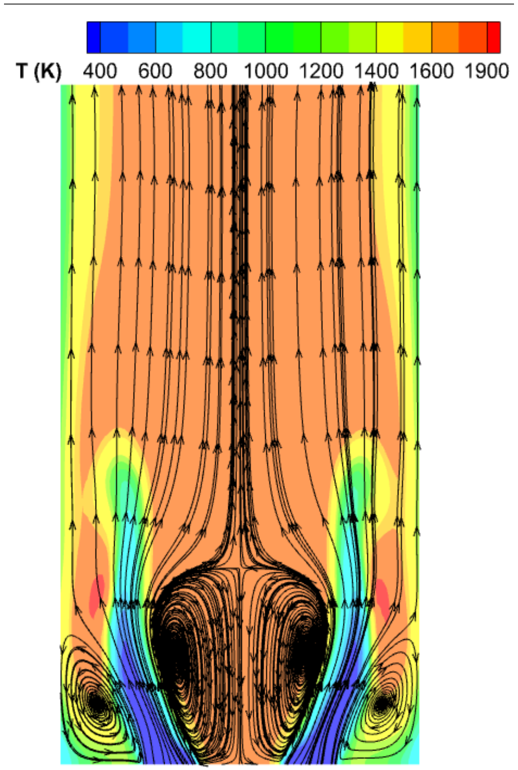
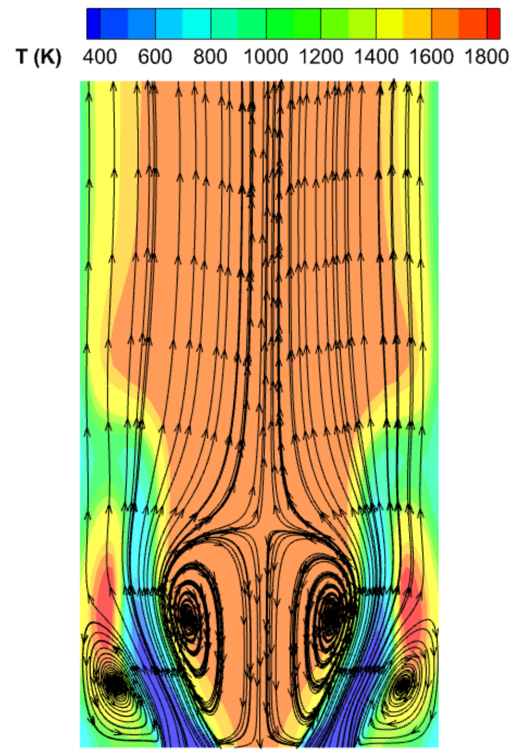
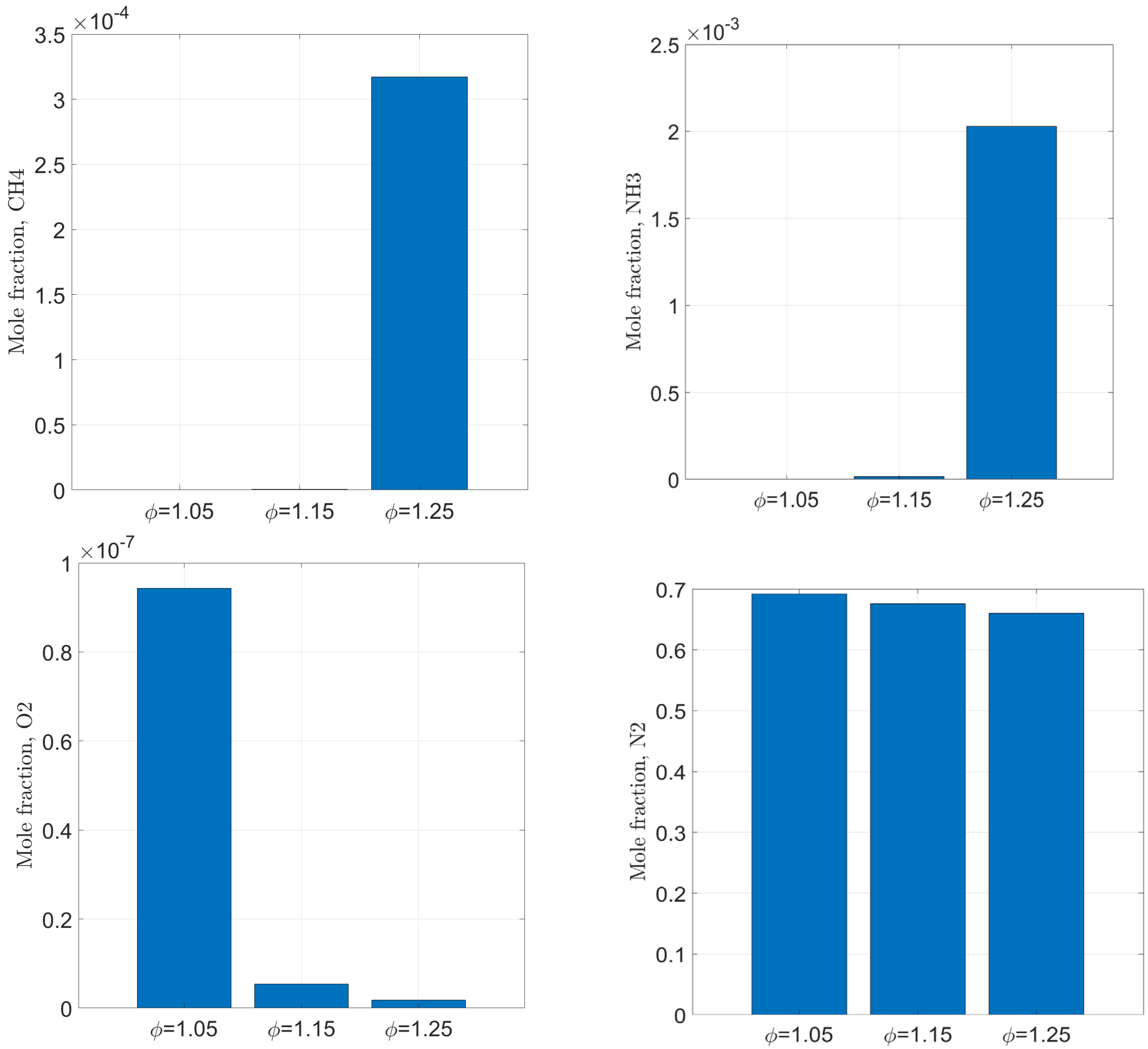
Primary stage flowfield



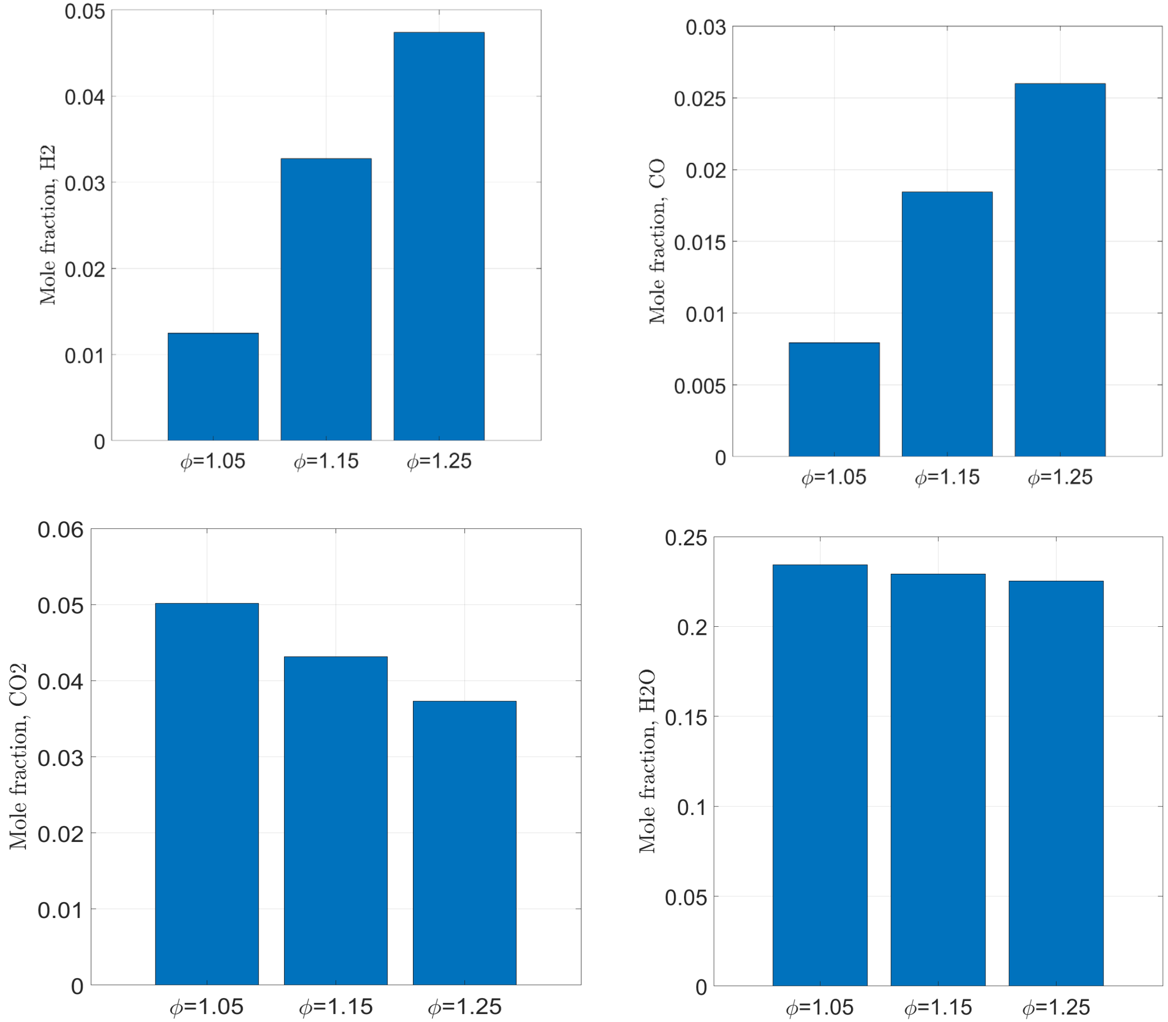




Primary stage products

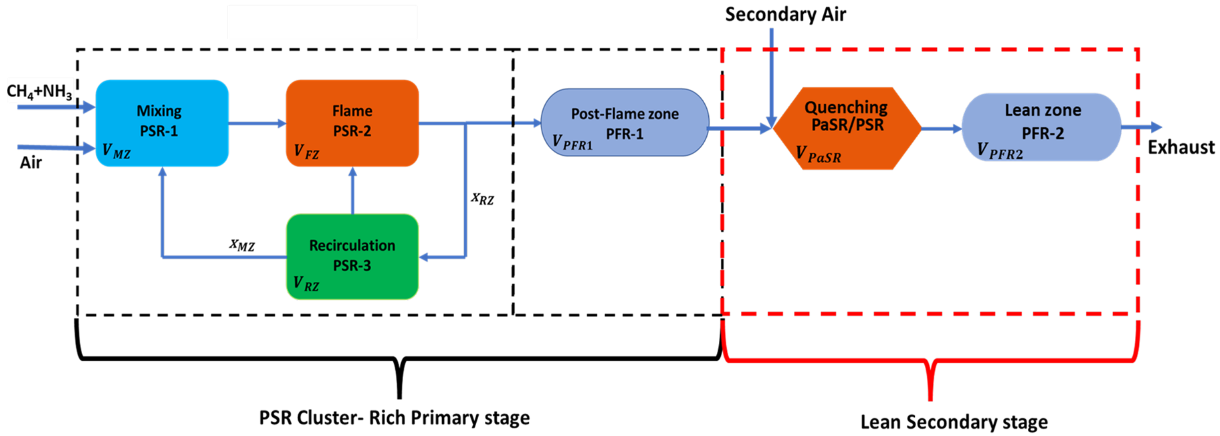


Primary stage products



Ongoing work

- Reactor network simulations for two-stage combustor



- PIV and PLIF diagnostics
- Secondary stage mixing characterization
- Extend to higher pressure (1-3 bar)

- *Where and how is NOx formed?*
- *Where and how is NH3 consumed?*

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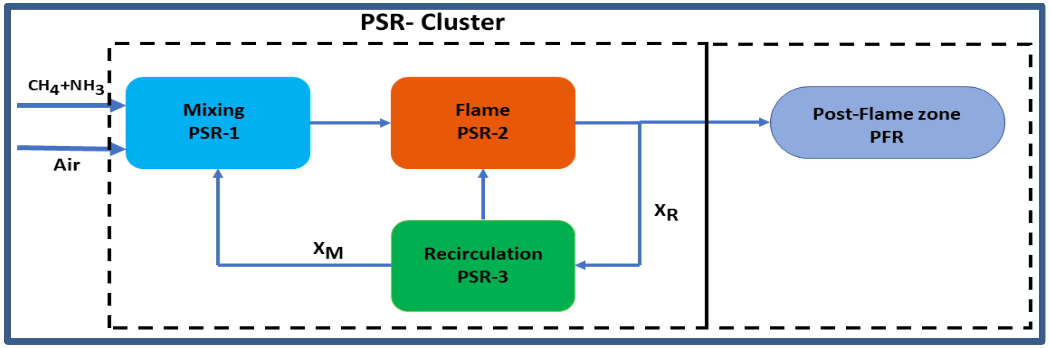
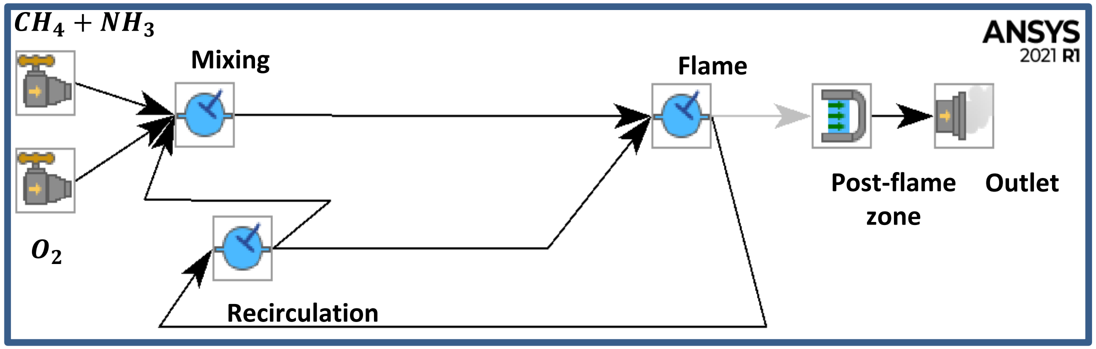
Publications

- Viswamithra, V., Gurunadhan, M., & Menon, S. (2023). Expanding swirl combustor operability on methane-ammonia-air mixtures using a distributed fuel injection technique and inlet air preheating. *International Journal of Hydrogen Energy*, 48(3), 1189-1201.
- Viswamithra, V. N., & Menon, S. K. (2022). A Distributed Fuel Injection Approach to Suppress Lean Blow-Out and NOx Emissions in a Methane-Ammonia-Fueled Premixed Swirl Combustor. *Journal of Engineering for Gas Turbines and Power*, 144(6), 061015.

Chemkin 0D/1D model description and key features





Residence time of reactor j,

$$\tau_j = \frac{\rho V_{PSR,j}}{\dot{M}_{in,j}}$$

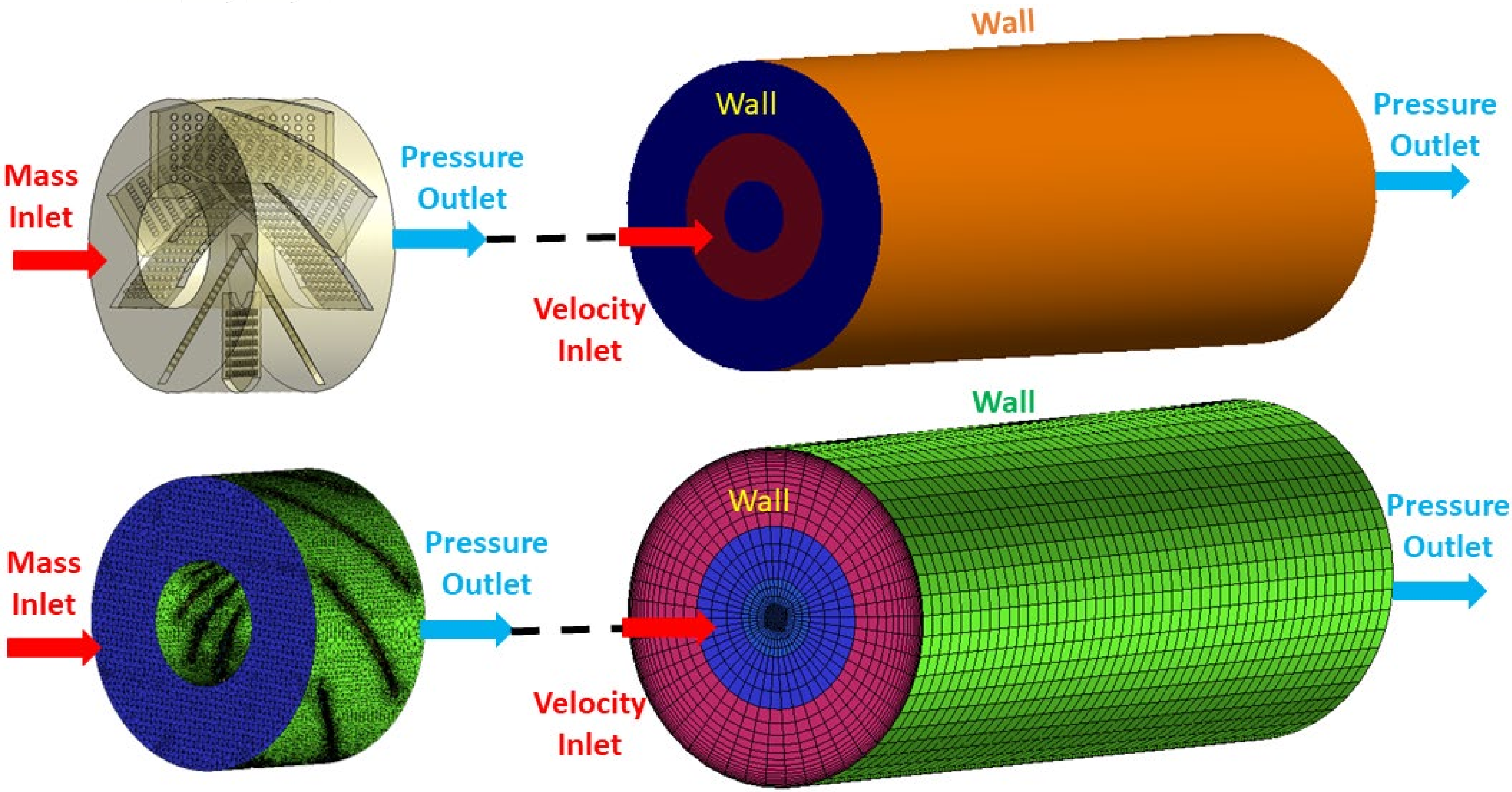
$V_{PSR,j}$: Volume of PSR reactor j,
$\dot{M}_{in,j}$: Total inlet mass flow rate to the reactor.

$V_{PSR,1}$= 0.2 V_{tot} , $V_{PSR,2}$= 0.6 V_{tot}
$V_{PSR,3}$= 0.2 V_{tot}

V_{tot}: Expected total inner volume of the combustor/ test rig.

PSR: Perfectly Stirred Reactor
PFR: Plug Flow Reactor

Reacting flow field problem setup



MFI swirler

Cylindrical combustor