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NUMERICAL INVESTIGATION OF GAS TURBINE BURNERS OPERATING WITH HYDROGEN AND HYDROGEN-AMMONIA BLENDS

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"Gas turbines in a carbon-neutral society"

Outline

- Introduction
- Analysis scenario
- Model setup
- Results
- Conclusions

Introduction

Energy transition towards decarbonization → Green fuels (H_2, NH_3)

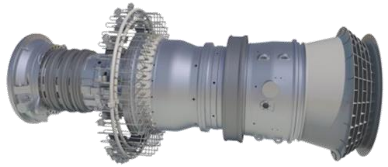
- Ammonia as a clean energy carrier and storage medium (experience and infrastructures already available)
- H_2 enhances combustion properties possibly enabling NH_3 combustion (H_2/NH_3 blends)

Great potential for H_2/NH_3 mixtures, provided the ammonia supply chain is consistently developed

Main challenges: NO_x emissions and flame stability

- Fuel-bound nitrogen: conventional lean-premixed combustors not effective in keeping low NOx levels
- Need of proper fuel definition and minimum set of design modifications of existing combustors.
- Retrofit is crucial (parallel growth of GT technology and NH_3 supply chain).

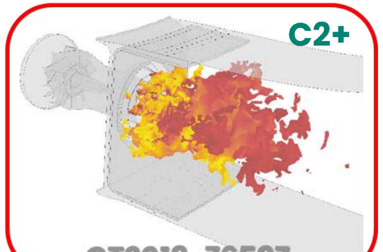
NovaLT16™
16.7 MW IGT



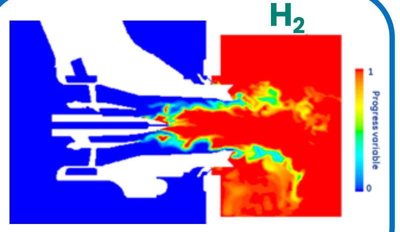
Experimental-modelling synergic effort

- **CFD based tools** developed at both burner and full combustor scale → NOx emission and flame stabilization with methane and non-conventional fuels (H_2, NH_3).
- Simplified **chemical kinetic models** (reactors network) for preliminary assessments and theoretical insigths.
- **Experimental assessment** on H_2 combustion at GT relevant pressure (NovaLT16™) for model validation.

GT2015-42730
GT2014-26906



GT2018-76587
GT2020-15575
GT2021-59215



GT2020-15432

Extended numerical natural gas and H_2 experience

Aim of the present work

- Definition of the **impacts on combustion system of the NovaLT16™ of a realistic ammonia supply scenario**

- Evaluation of a possible **operational profile** of the combustion system, based on a basic chemical reactor network analysis

- Evaluation of **NO_x emissions** through 3D computational fluid dynamic (CFD) model of the combustion system at gas turbine relevant conditions

Analysis scenario

Impacts of the ammonia blend into hydrogen gas turbine

- **Assumptions**
  - No changes to control strategy with respect to reference (pure hydrogen)
  - Same exhaust temperature as a function of pressure ratio
- **Operability impacts**
  - Hydrogen increased generated power and efficiency with respect to natural gas
  - Further increase in power and efficiency with respect to hydrogen
- **Combustion system development impacts**
  - Increased fuel supply pressure
  - Blend lower reactivity → poor flame stability
  - Fuel-bound nitrogen → significant NO_x emissions increase as ammonia content is increased (the impact of O_2 and H_2O in the exhaust affecting typical emissions correction at 15% O_2 is negligible)

		Pure H_2 (ref)	H_2-NH_3 blend	Pure NH_3
Fuel H_2 mole fraction	%	100	70	0
Fuel NH_3 mole fraction	%	0	30	100
P/P_0		1	1.09	1.12
η/η_0		1	1.03	1.04
$\dot{m}/\dot{m}_0$		1	1.03	1.04
Exhaust N_2 mole fraction	%	73.4	73.6	73.7
Exhaust O_2 mole fraction	%	14.8	13.3	12.9
Exhaust H_2O mole fraction	%	10.9	12.2	12.6
Exhaust CO_2 mole fraction	%	0.0	0.0	0.0
Exhaust Ar mole fraction	%	0.9	0.8	0.8

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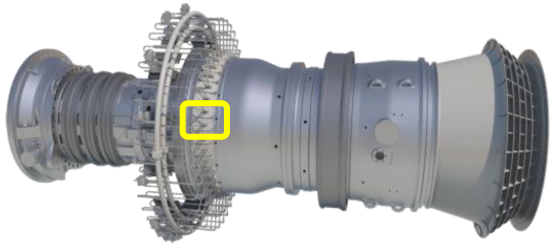
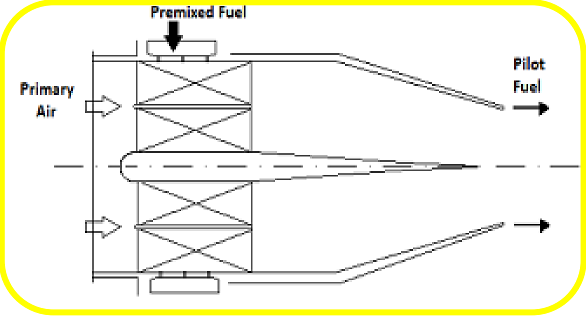


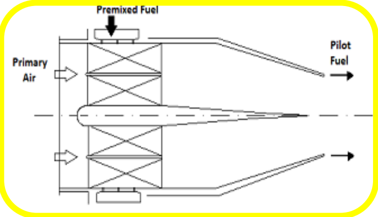


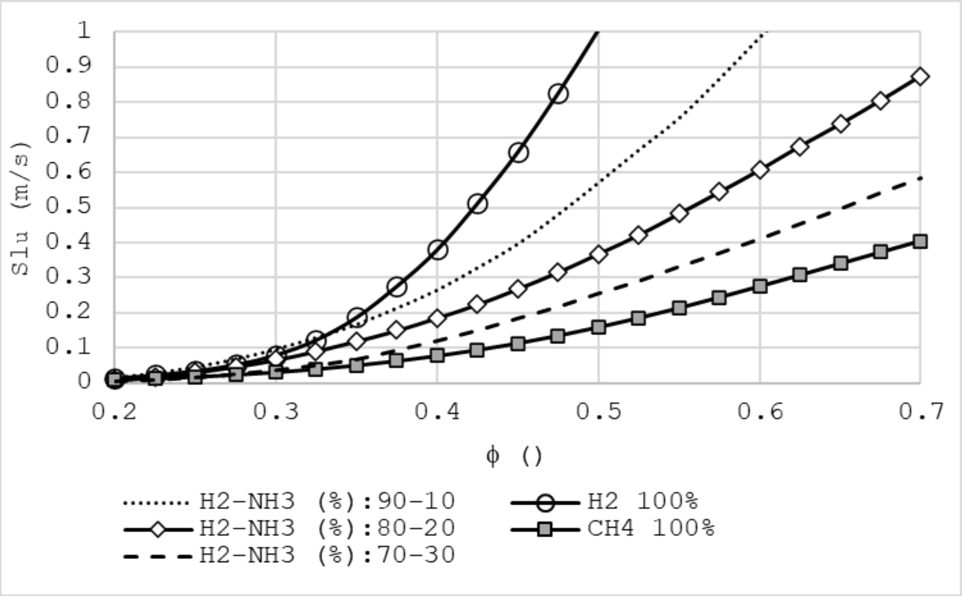
- **Adaptation is required to operate with significant NH_3 content**
- **Large differences in raw NOx emission expected for the real case geometry**

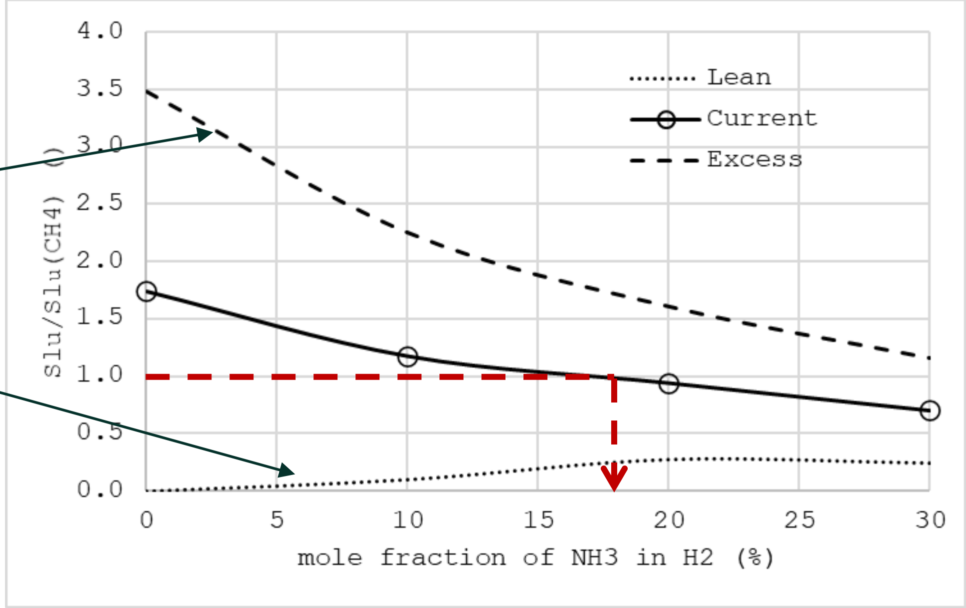
Analysis scenario

Blend assessment

- Comparison based on the unstrained laminar flame speed, Slu
  - Freely propagating conditions
  - GRI-Mech III
- Assumptions
  - Flame stability mainly driven by pilot injection
    - Constrained by the available fuel supply pressure
  - Well balanced premixed injection required
    - Minimize flashback risk
    - Ensure adequate stability
- Scenario summary
  - Average of two extreme cases
    - Pilot stabilizing at stoichiometric conditions
    - Premixed stabilizing with all the available air







- **~20% NH_3 in H_2 could provide similar stability characteristics of the CH_4 flame**
- **Short term realistic supply scenario**

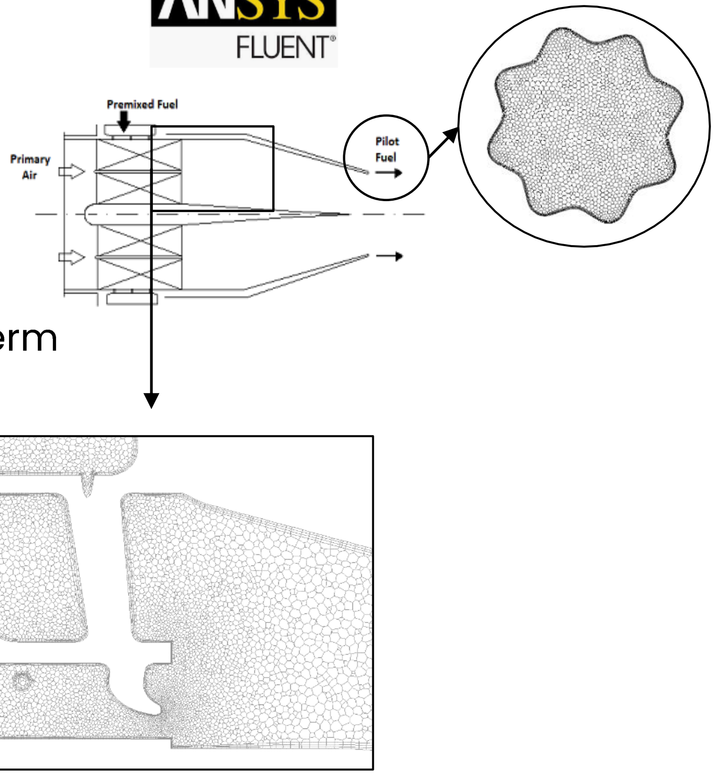
CFD model for NO_x assessment

Numerical setup

- **Domain and setup**
  - 17 million polyhedral mesh for one single sector of an annular combustor
  - LES with Smagorinsky-Lilly sub grid scale model

- **Combustion model (Flamelet Generated Manifold)**
  - Pre-Tabulated chemistry with Turbulent Flame Speed Closure for progress variable source term
  - Opposed diffusion flamelet
    - 100% H_2 cases: Chemical Mechanism from *Li et al.*
    - H_2-NH_3 blend cases: Chemical Mechanism from *Xiao et al.*
  - Unstrained laminar flame speed curves calculated using Cantera

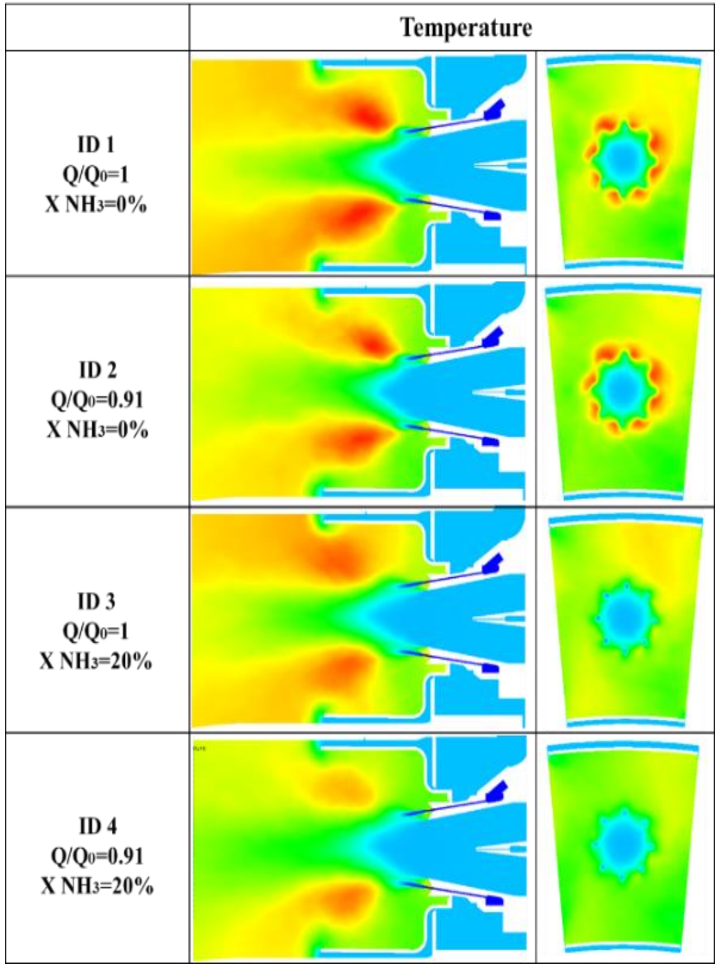
- **NO_x model**
  - The fuel bound NO_x (for NH_3) requires a non-conventional way to be calculated
  - The approach proposed by *Yadav et al.* has been used in this work
  - An **additional transport equation for NO** is considered
  - The NO net formation rate is calculated directly from the chemical mechanism and stored in a dedicated table
  - Other NO formation mechanisms like thermal and prompt are included as well

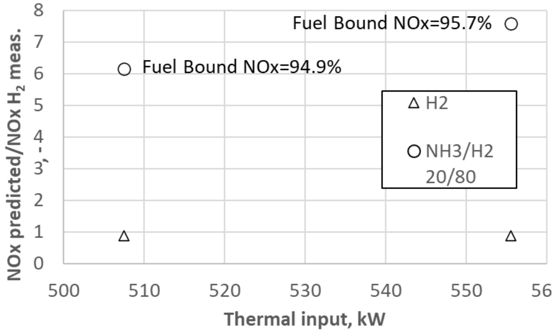


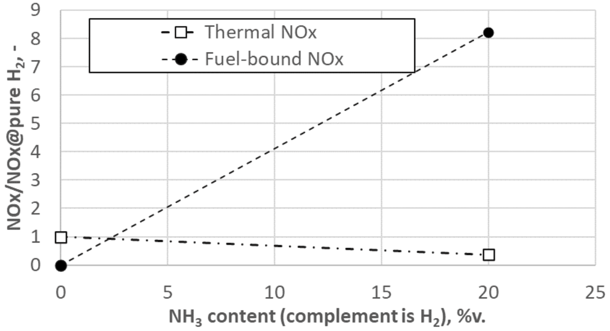
Computational Grid at the swirler location and at the burner exit

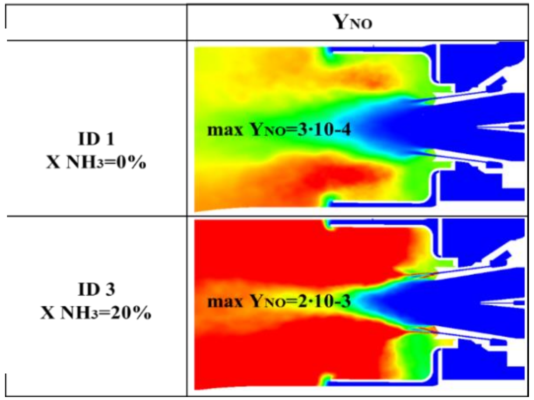
NO_x emissions assessment for pure diffusive combustion

- The CFD model seems to be able to reproduce the different NO_x formation pathways
- The trend of NO_x with the thermal power is captured









NO_x Formation Pathway

1. With pure H_2, NO_x formation mainly related to the hot regions
2. Introducing NH_3, the much higher NO mass fraction is due to fuel-bound nitrogen.

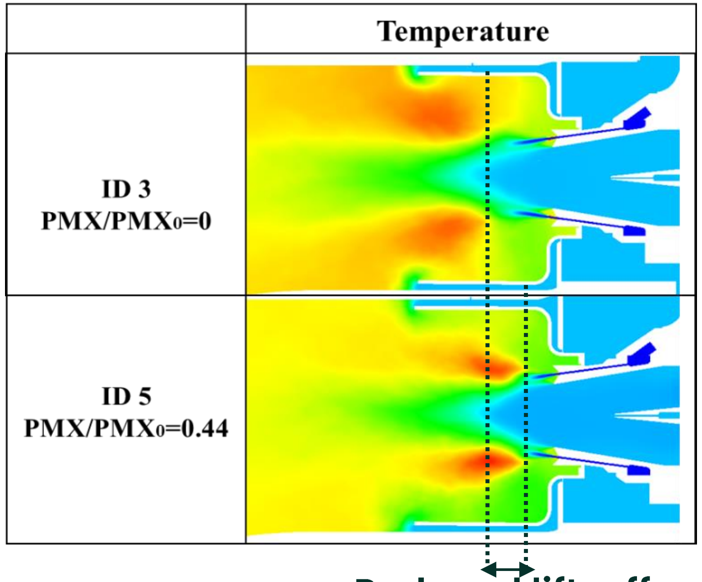
Thermo-Fluid Dynamic Impact

Blending hydrogen with ammonia allows:

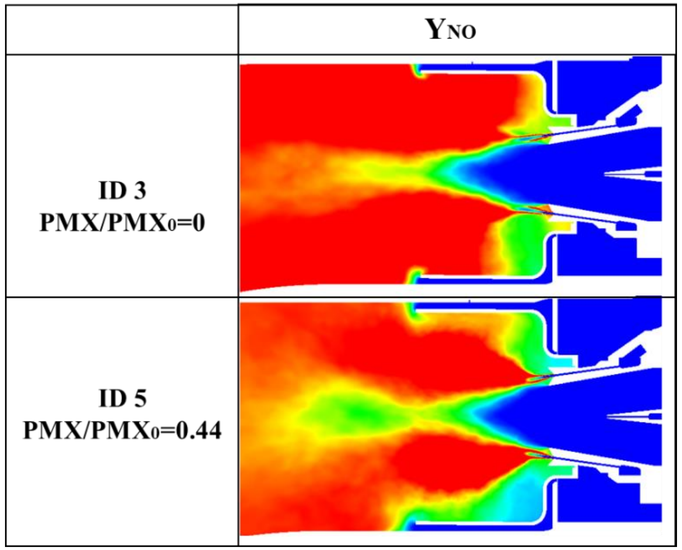
1. a consistent reduction of temperature peaks
2. a moderate shift of the flame front.

Impact of the partial premixing mode onto NO_x emission

Additional case (ID5), at optimal pilot split → evaluate the impact of the partially premixed mode onto NO_x.



Reduced lift-off height



- Lower pilot exit velocity
- Reduced flame lift
- Higher temperature peaks
- Reduced extent of high temperature regions
- Lower residence time responsible for thermal NO_x production.

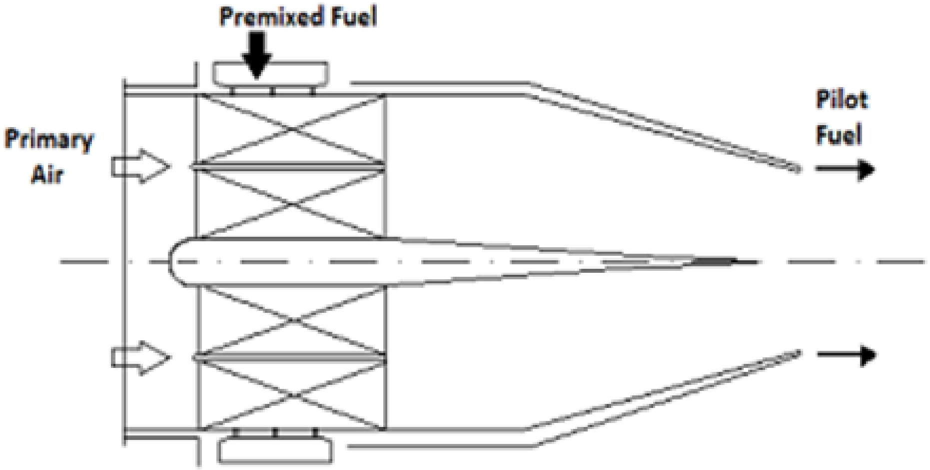
The fuel-bound nitrogen mechanism remains the dominant one → the reduction of NO_x is negligible.

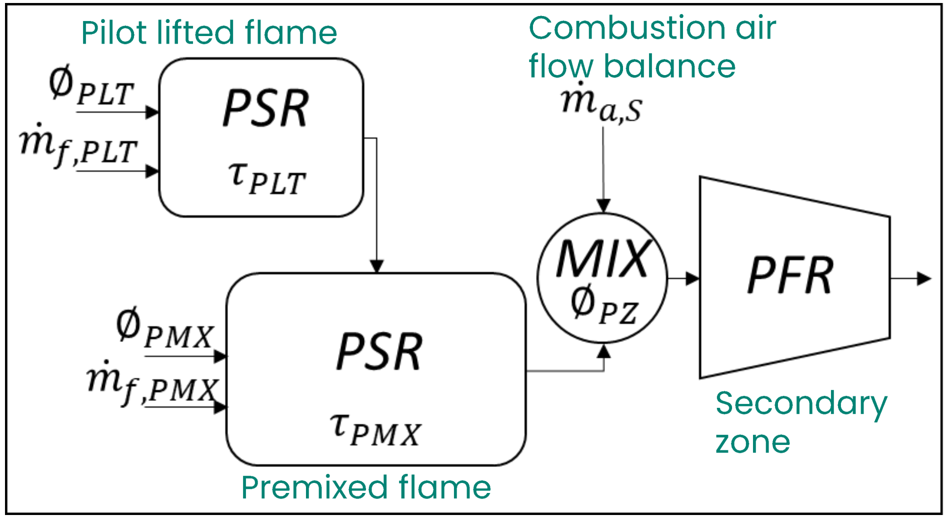
The portion of the fuel which is burnt in lean conditions is being converted via peculiar reaction pathways that imply high OH concentrations, promoting the oxidation of fuel-bound nitrogen to NO_x.

Chemical reactors network for NO$_x$ assessment

Simple series of chemical reactor (Perfectly Stirred Reactors + Plug Flow Reactor)

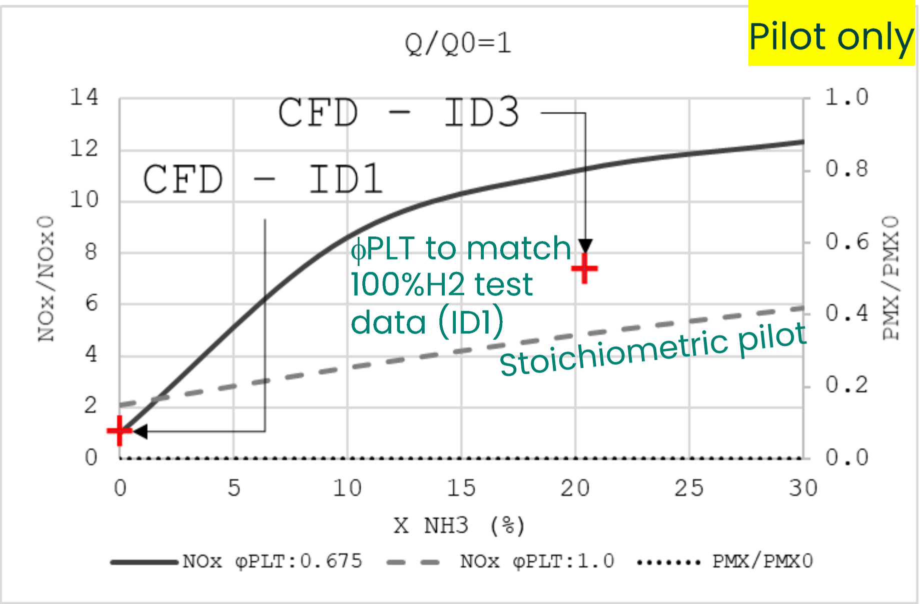
Pilot fuel injection plays a fundamental role in the stabilization of the piloted premixed flame front, due to the low swirl induced by the counter-rotating swirler.



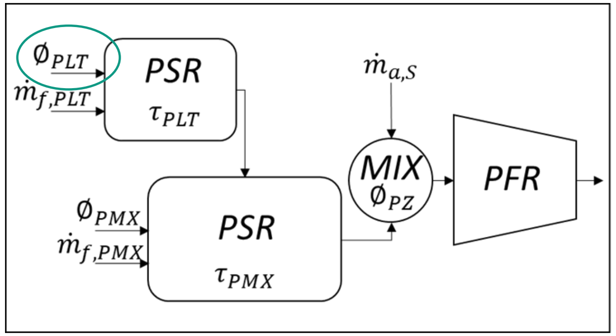


The simple 1-D model was used for preliminary emission assessment of the investigated combustion system.

Reactors network results compared to CFD

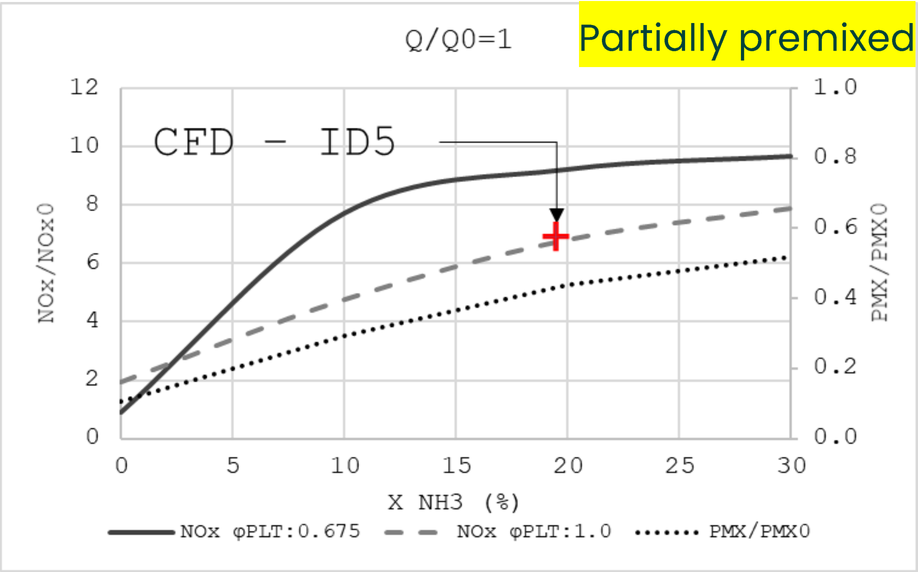


Pilot equivalence ratio is one of the most impacting parameters on NO_x formation.



Increasing **ammonia** content: leaner case (solid line) provides a significant rise in NO_x emissions w.r.t. stoichiometric case (dashed line).

Flame lift (ϕ<1) is lowering the thermal NO_x contribution, but **fuel-bound nitrogen plays again a major role** in the result.



Premix line activation → smaller spread between the two curves

CFD prediction still within the range (aligned with the assumption of stoichiometric conditions at pilot fuel discharge; same assumption not able to match the emissions with pure H_2).

- **Models' setups can be considered adequate to describe the main trends**
- **Expected benefit from future experimental data for validation and further developments.**

Conclusions

- An overview of **potential impacts of hydrogen-ammonia fuel blends on the performances and the pollutant emissions of an existing gas turbine combustion system** has been provided thought this study.

- The analysis scenario has been properly selected to **minimize the impact on the fuel supply pressure system, and the flame stability**. Flame stability as a function of both the fuel blend and the equivalence ratio has been evaluated through the laminar flame speed, leading to the **definition of the optimal operating conditions for each blend**.

- **NOx predictions** at relevant gas turbine operating conditions from a **chemical reactor network** model have been compared to **3D CFD** outcomes. Models have been calibrated on the available **data from full scale annular combustor rig test operated with pure hydrogen**.

- Models are aligned in ascribing to the **fuel-bound NOx the dominant role in the production of pollutant emissions**. Nevertheless, a validation would be required before the extensive use for real combustion systems design development.

- Despite the development needed, **the proposed models are able to capture main physical trends, allowing the numerical screening of viable design options** to reduce the scope of dedicated test campaigns, thus revealing proper tools for high hydrogen and hydrogen-ammonia burner design and development.

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Thank you for your attention!

Feel free to contact us:

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