The design and optimisation of a hydrogen combustor for a 100 kW micro gas turbine

UMONS
Université de Mons

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

fnrs
FREEDOM TO RESEARCH

Why a hydrogen **gas turbine**?

Compared to a piston engine:

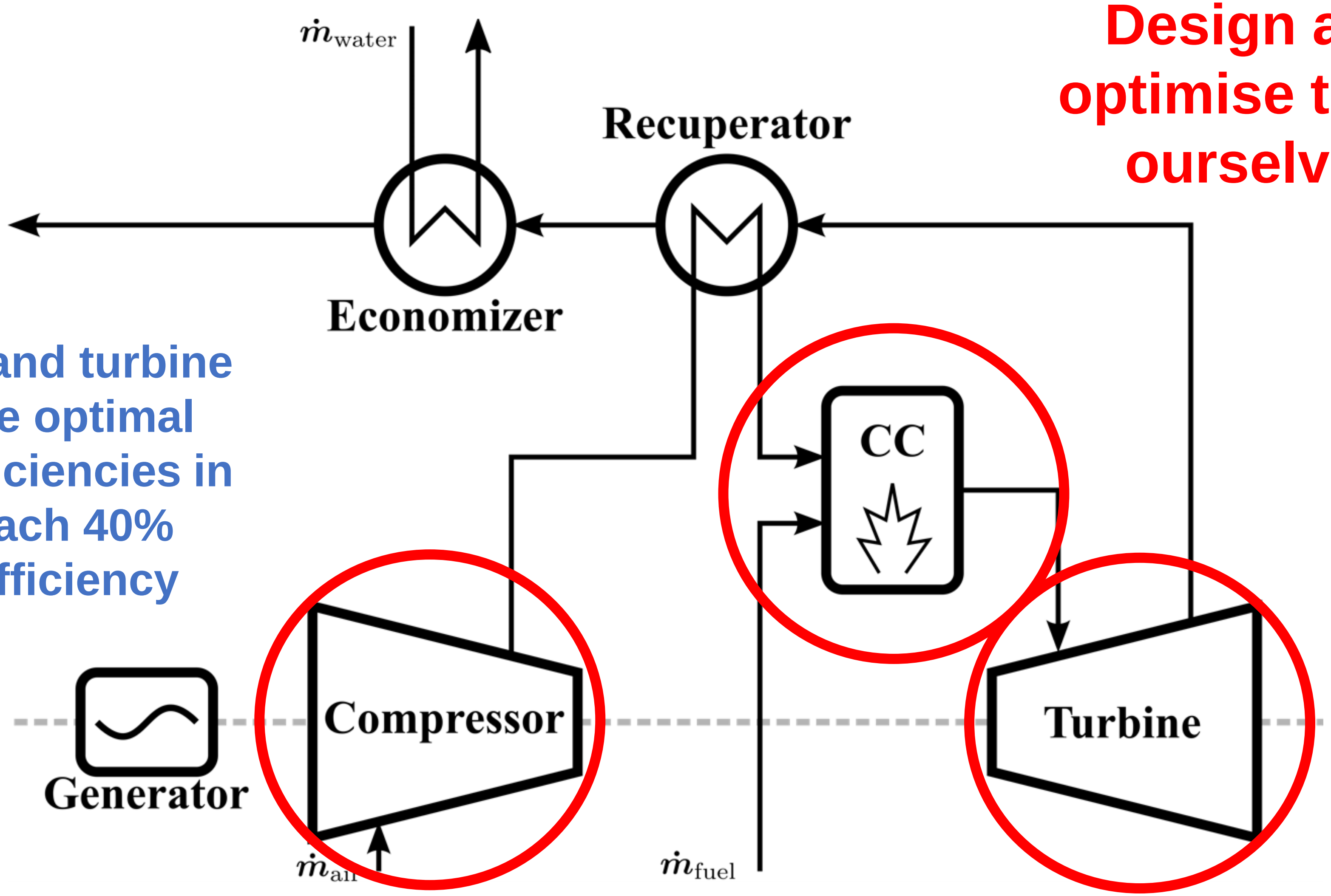
- (+) Only 1 moving part
  → **Reduced OPEX**
- (−) **Increased CAPEX**
- (−) **Reduced electrical efficiency**
  (35 - 40% vs 30% for 100 kW)

Compared to fuel cells:

- (+) **Increased power density**
  (by a factor of 3 - 4)
- (+) **Less pure hydrogen required**
- (+) **Increased service life**
  (40,000 hrs in continuous use, 2000 - 4000 hrs in variable use for PEM vs 60,000 for mGT)
- (−) **Reduced electrical efficiency**
  (50% vs 30% for 100 kW)

SOLUTION: **Higher Turbine Inlet Temperature** with a ceramic radial turbine rotor

IN THEORY: **40% electrical efficiency** for a 100 kW machine



Design and optimise these ourselves

Compressor and turbine need to have optimal isentropic efficiencies in order to reach 40% electrical efficiency

Compressor design

We developed our own 1-D calculation script based on the Cordier line

The most efficient compressor had:

Air mass flow rate = 0,8 kg/s

Rotational speed = 70.000 RPM

Same as Ansaldo T-100, so our calculation method is sound

We found an existing design for a 60.000 RPM synchronous generator, not one for 70.000

CAPEX of future mGT unit

We designed a **single stage centrifugal compressor** with:

Air mass flow rate = **0,8 kg/s**

Rotational speed = **60.000 RPM**

Lower RPM → lower CAPEX, typically the major weak point of existing mGTs (+)

Lower isentropic efficiency, compared to existing mGT compressors (−)

Turbine design

In order to compensate the lower isentropic efficiency of the compressor → Higher Turbine Inlet Temperature (TIT) → **TIT = 1300°C**

Ceramic turbine rotor

↓

We work towards **40%** electrical efficiency, but since a recuperated mGT is usually used in a CHP, **we must actually optimise overall efficiency** (electrical + thermal)

<u>And since</u>

1. Turbine RPM = Compressor RPM
2. Turbine mass flow rate ≈ Compressor mass flow rate

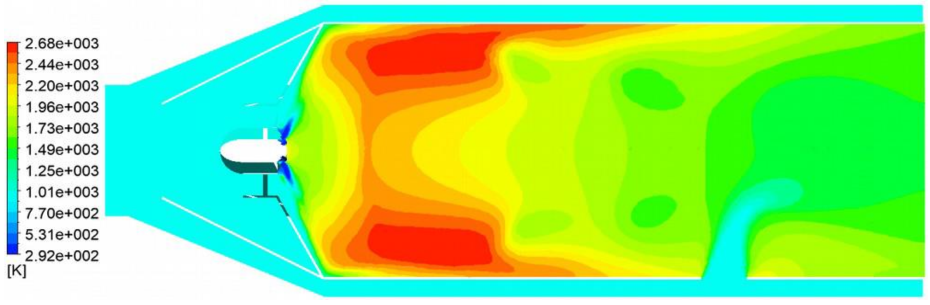
   (Hydrogen mass flow rate is very small)
3. Radial turbine = radial end blades

→ **Turbine design follows from compressor design**

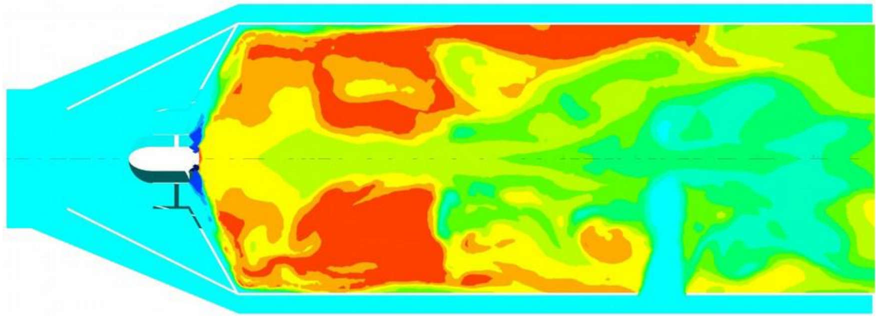
Focus on the combustor

Swozzle design gives too high NOx

Steady RANS



LES



LES gives finer flow contours, but overall results are the same:

NO_X at outlet = 1370 ppm

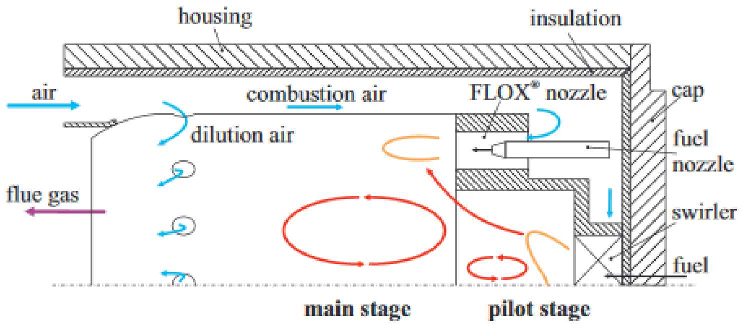
Combustor improvement – over to MICROMIX design

1. Improve the current single nozzle + swirler design with regards to:

- Outlet temperature homogeneity
- NO_X emissions

2. Compare improved current design to a "MICROMIX"-type combustor geometry of our own design:

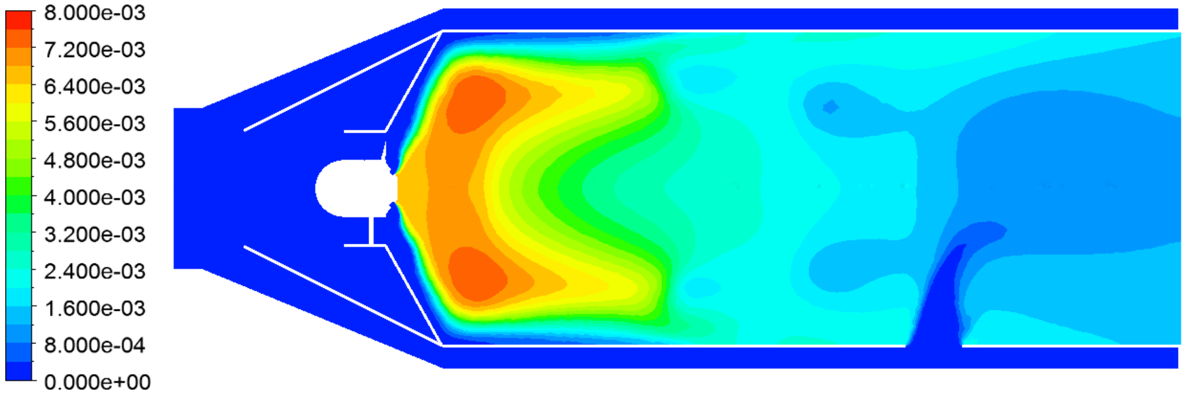
- Several smaller annular placed nozzles give a jet-stabilised flame
- Smaller flames → Air spends less time at a high T → thermal NO_X decreases



Timo Zornek, Thomas Mosbach et al. "Optical Measurements of a LCV-Combustor Operated in a Micro Gas Turbine With Various Fuel Compositions", ASME Turbo Expo 2018, GT2018-75481

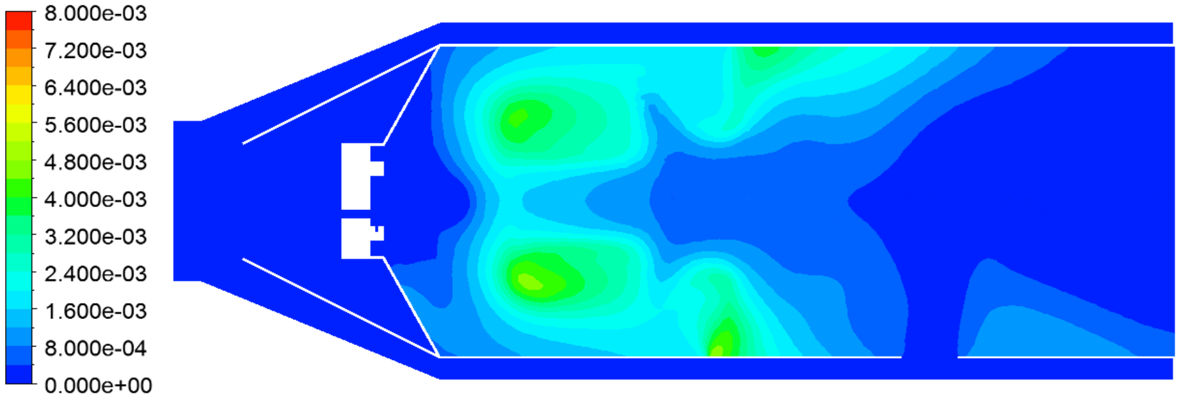
Micromix gives much lower NO_x

Contours of NO_X mass fraction



Steady RANS on single "**swozzle**" geometry

1370 ppm @ outlet



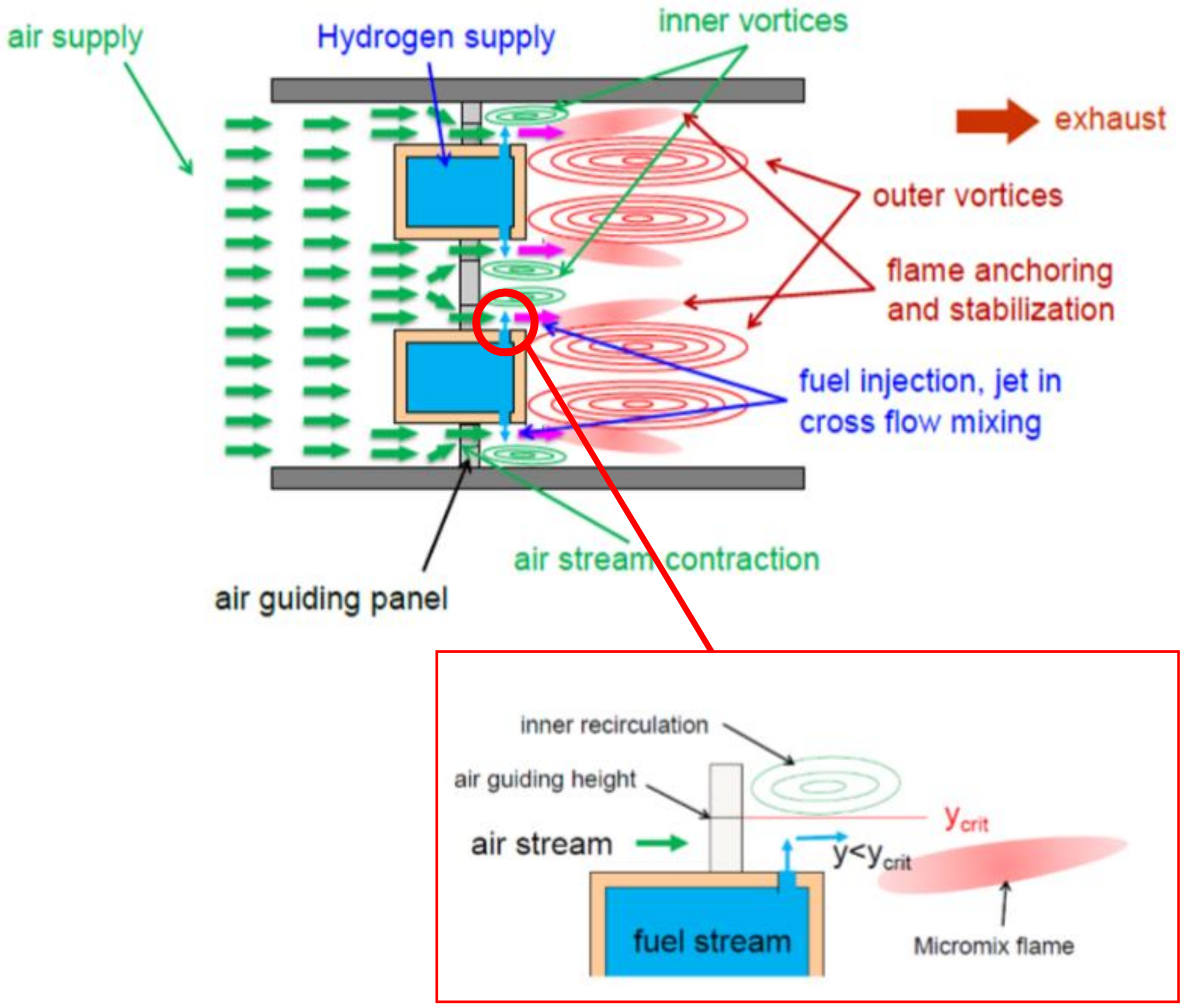
Steady RANS on "**micromix**" geometry

125 ppm @ outlet

Better, but still too high

H_2 injection depth is crucial

Finding the optimal injection depth

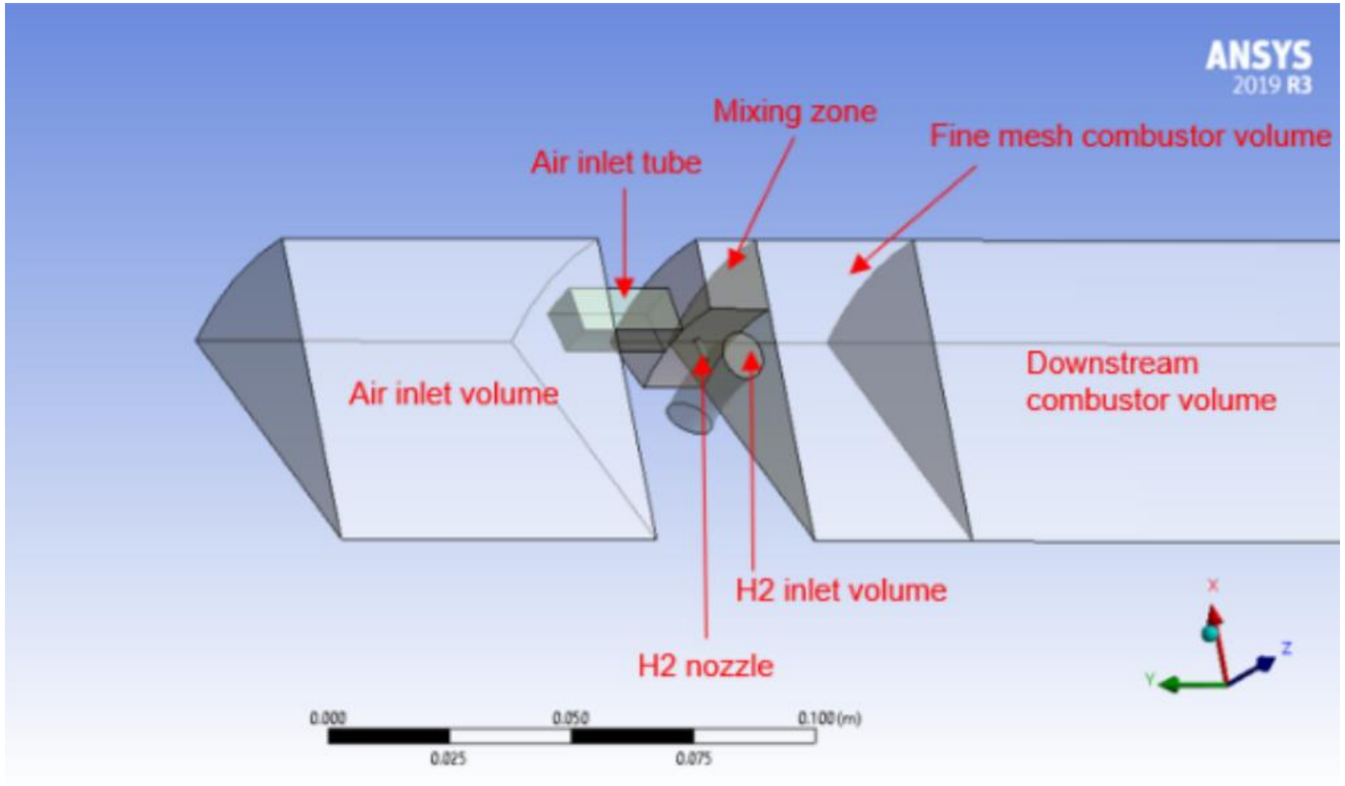


Perpendicular hydrogen injection into air supply causes a very turbulent flow → great mixing

Injection depth is critical:

- Too small: not enough mixing
- Too large: penetration into the inner recirculation zone → increases residence time → NO_x ↑

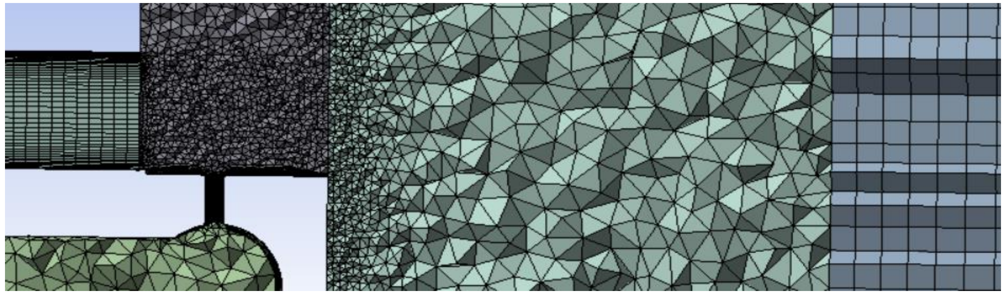
Single nozzle test geometry: Cold flow CFD



To investigate the **impact of increasing hydrogen injection pressure** and try to find an **optimum w.r.t NO_x emissions**

GOAL: Find the provisional optimal ΔP between hydrogen inlet and air inlet

Mesh



Models

Turbulence model: k-ω-SST

→ in order to better model the flame recirculation zones

Turbulence chemistry interaction: Eddy dissipation concept
(only for later hot flow simulations)

→ in order to incorporate the multi-step chemical reaction mechanisms

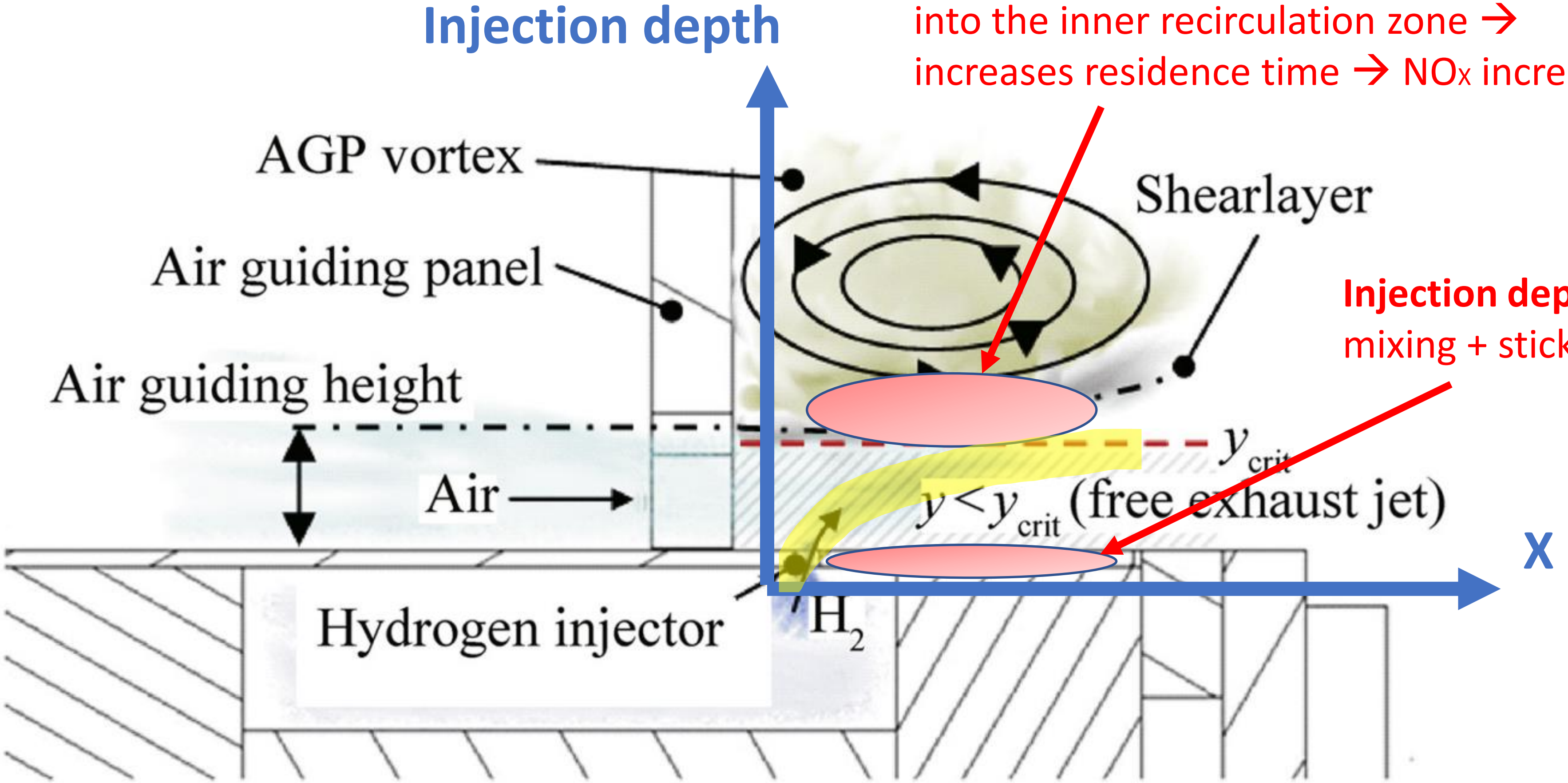
Combustion model: Burke mechanism with Zeldovich thermal NO_x modelling *(only for later hot flow simulations)*

→ Compared with DRM.19 and Li + is state-of-the-art hydrogen combustion mechanism used

Burke, M.P., Chaos, M., Ju, Y., Dryer, F.L., and Klippenstein, S.J. Comprehensive h2/o2 kinetic model for high-pressure combustion. International Journal of Chemical Kinetics, 44(7):444–474, 2012. 34, 35

What we want

Injection depth too high = penetration into the inner recirculation zone → increases residence time → NOx increase



Injection depth too low = not enough mixing + stick to the wall

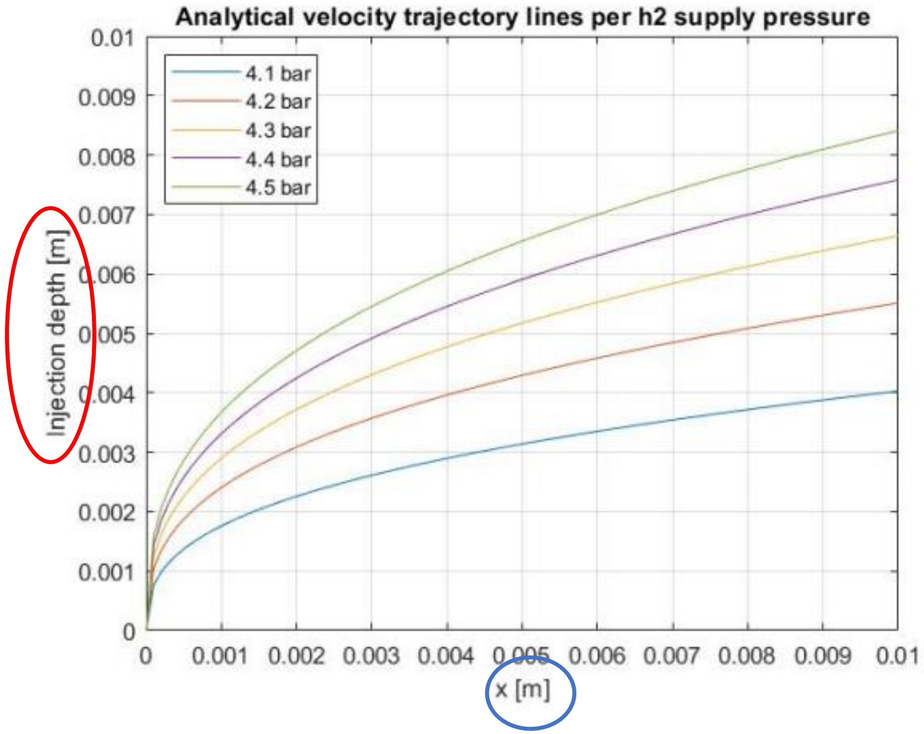
Ref.: A. Haj Ayed, K. Kusterer, H. H.W. Funke, J. Keinz, and D. Bohn. CFD based exploration of the dry-low-NOx hydrogen micromix combustion technology at increased energy densities. Propulsion and Power Research, 6(1):15–24, 2017. vi, 4

Finding the optimal ΔP between H_2 and air

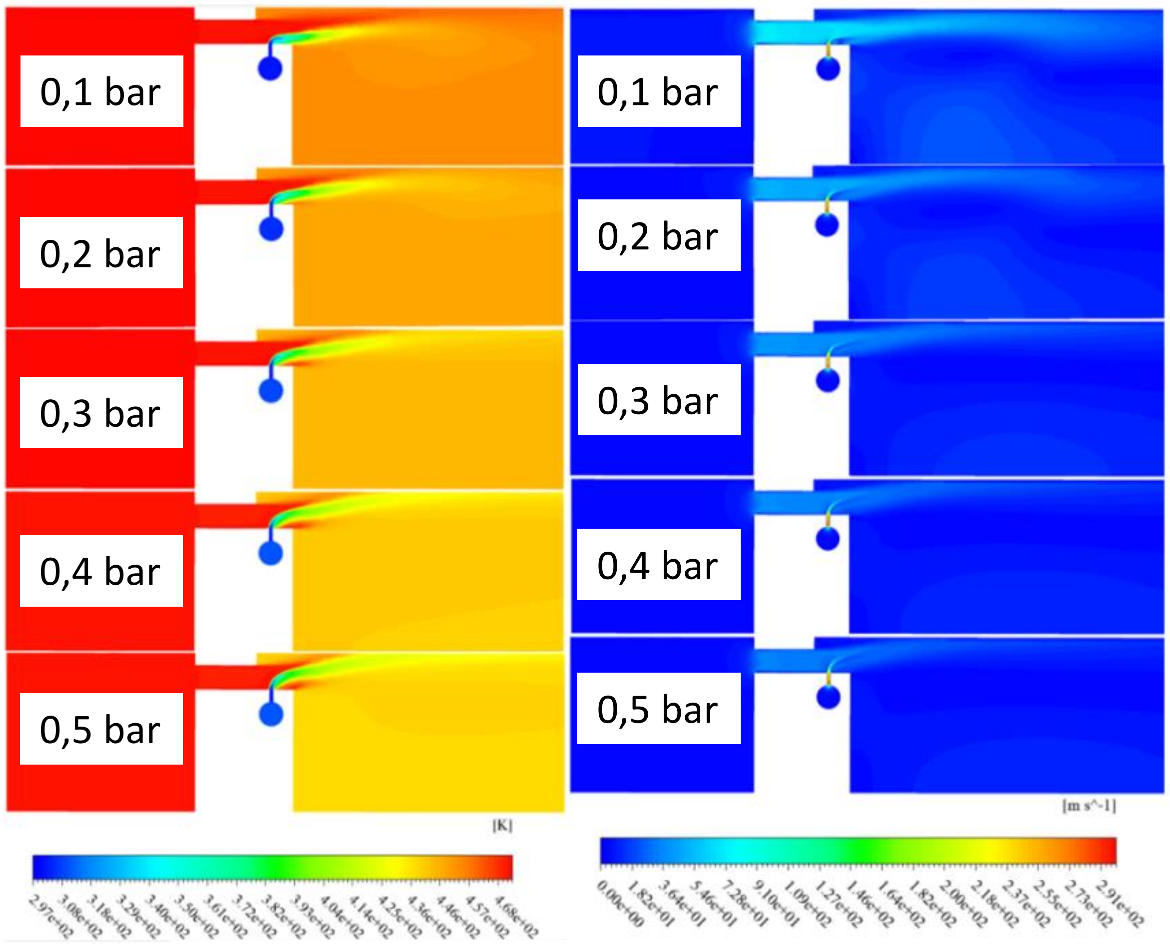
Using the Holdeman empirical relation

$$\frac{Z_v}{D} = 0.89 J^{0.47} \left(\frac{X}{D}\right)^{0.36}$$

$$J = \frac{2(P_j - P_\infty)}{\rho_\infty v_\infty^2}$$

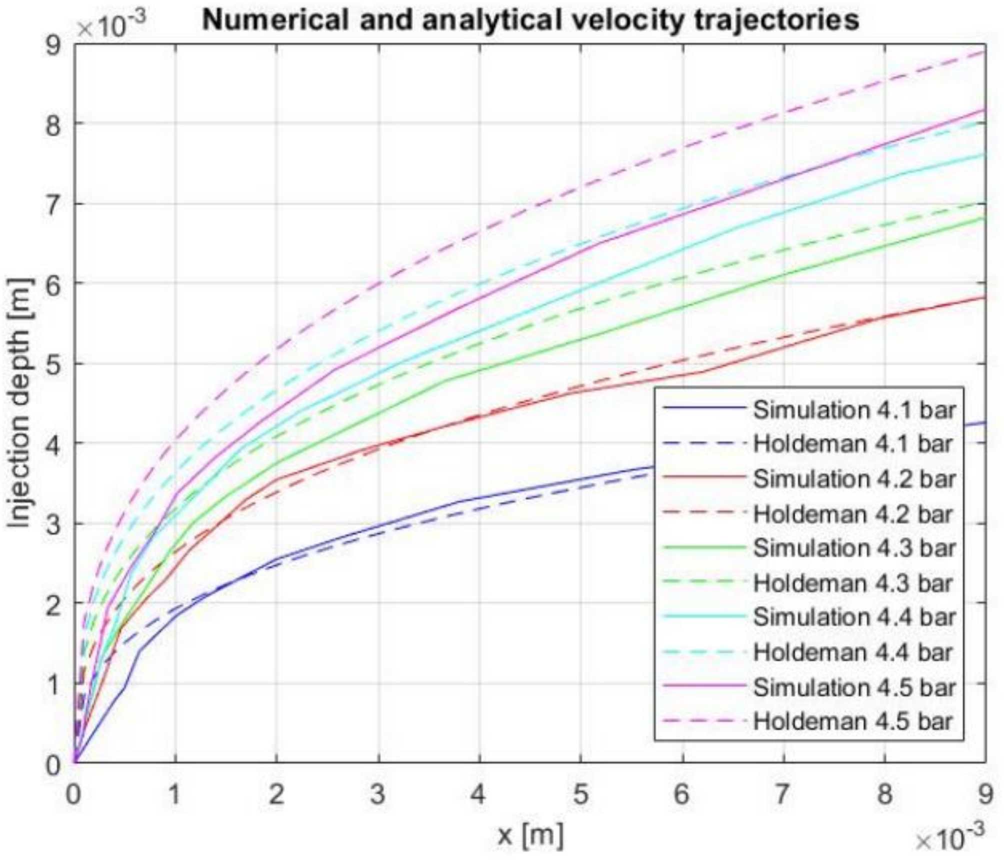


Using our simulations (cold flow)



Temperature **Velocity**

Comparison of empirical and simulation results



Good agreement at lower hydrogen injection pressures
Less agreement at higher pressures

→ Due to impact of wall (and opposing jet in the real combustor case) compared to the jet in free air in Holdeman case

Optimal H2 injection pressure range

- **The lower limit**

→ Because jet separates from lower surface

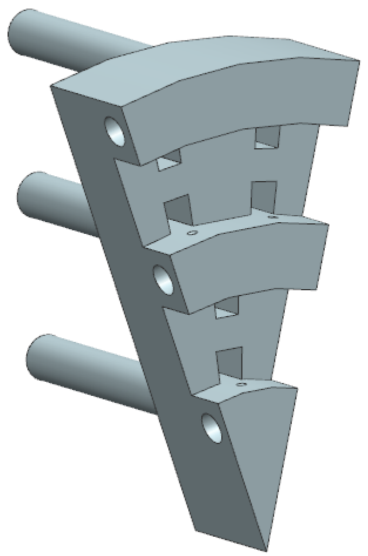
- **Upper limit**

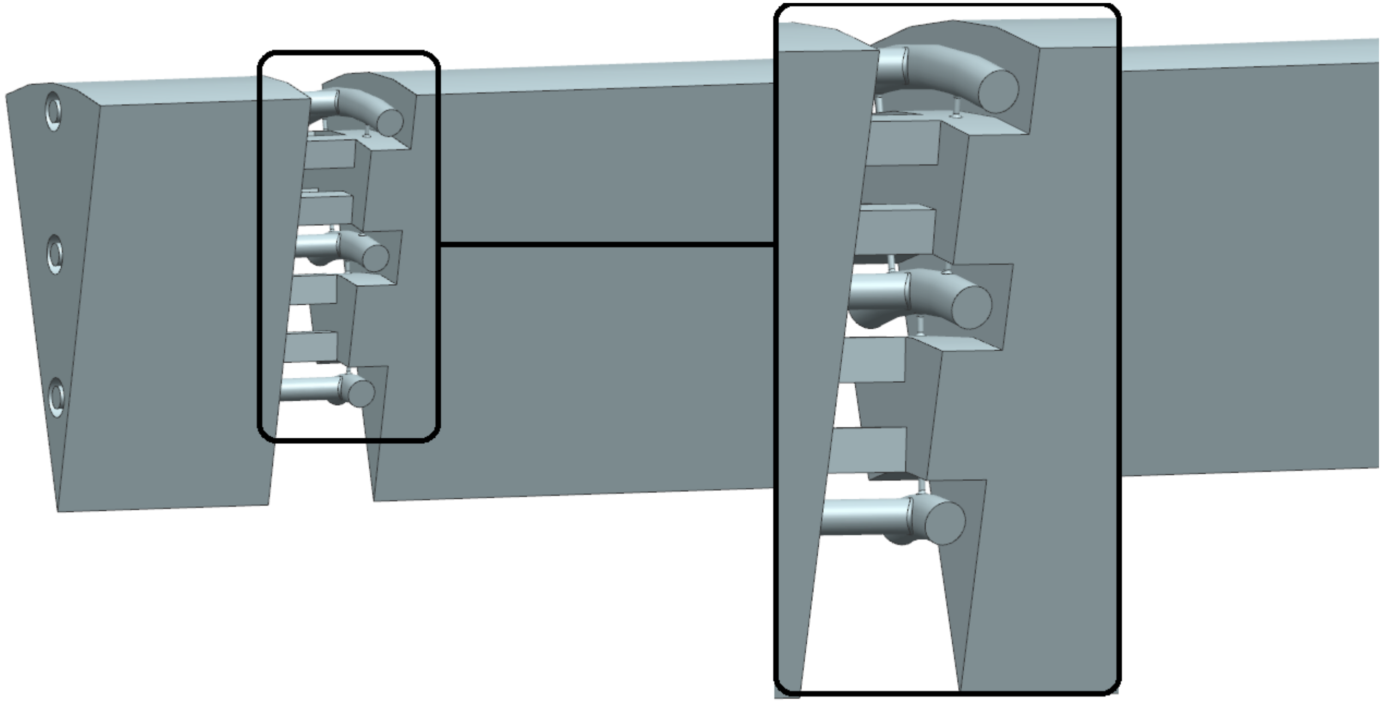
→ Because jet penetrates into upper vortex

Tentative optimum from cold flow simulations

New multi-nozzle combustor geometry

Six injection pairs per slice; “multi-nozzle pizza slice model”





Conclusions and future work

Current conclusions

Tentative optimal inlet hydrogen pressure from cold flow simulations in single nozzle geometry

Future work

Adding secondary air flow, downstream dilution holes and the combustor liner, for **conjugate heat transfer simulations**

Comparing the optimum H_2 inlet pressure with previous cold flow results

Finding optimum split between primary and secondary air flows

Find final exhaust NO_x emissions at homogeneous combustor outlet temperature of 1300°C

The design and optimisation of a hydrogen combustor for a 100 kW micro gas turbine