Direct numerical simulations of reheat combustor: pressure scaling of flame structure

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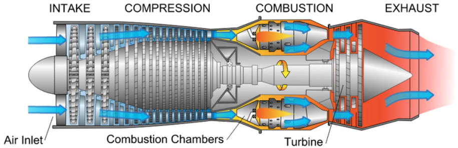
Stationary gas turbine

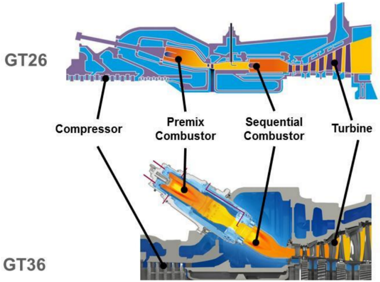
Features of an ideal gas turbine

- Fuel flexibility
- Low emissions
- High efficiency
- Wide range of operationality
- High power output



Source: energyeducation.ca

Gas turbine



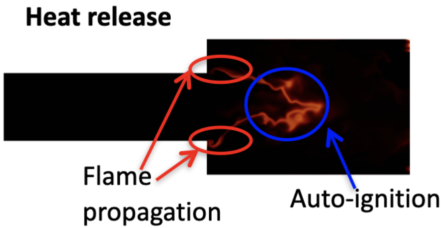
Source: Ansaldo

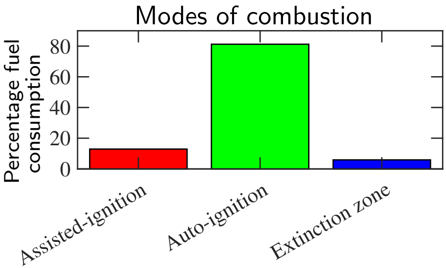
Current state of the art technology in gas turbine

- NOx EV burner
- Good fuel flexibility
- Constant pressure sequential combustion

Literature review

- *Güthe, F., Hellat, J. (2019), Ciani, A., et al. & Flohr, P. (2009), Bothien, M. R., et al. (2019)*: Used sequential combustion technology to achieve good fuel and operational flexibility
- *Aditya, K., et al. (2019)*: Explained reheat flame dynamics at 1 bar with the help of 3D DNS and along with intermittent autoignition and occurrence of flame propagation mode





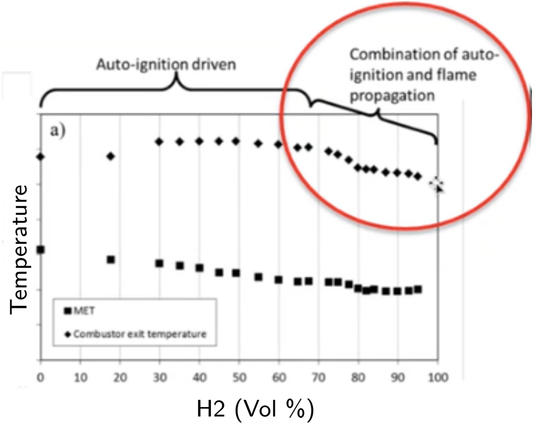
Literature review

- *Schulz, O., & Noiray, N. (2018)*: Investigated linear and non linear behaviour of heat release rate with respect to entropy waves in a sequential combustor by 3D LES
- *Gant, F., Scarpato, A., & Bothien, M. R. (2019)*: Explained unsteady behaviour of flame to temperature fluctuations with theoretical analysis and LES
- *Schulz, O., & Noiray, N. (2019)*: Discussed LES at pressures 1 and 10 bar to explain initial transients of reheat combustor for 3 different cases
- *Savard, B., et al. (2019)*: Explained mechanism of combustion mode transition from statistically planar premixed flame DNS

Challenges in staged gas turbine

- Currently its not possible to operate gas turbine with 100% hydrogen fuel without performance compromise

- Fuel blends are limited for gas turbine operation



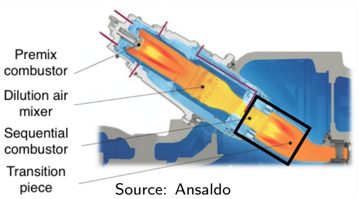
Decrease in combustor exit temperature as hydrogen fraction is increased in reactants[1]

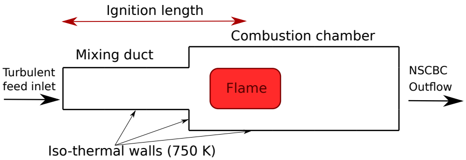
[1]Mirko R. Bothien, et al. (Journal of Engineering for Gas Turbines and Power 2019)

Objective

- Two dimensional direct numerical simulation of reheat combustor at various pressures
- Study the flame structure scaling with pressure
- Quantify the distribution of fuel consumption rate between the two modes of combustion
  - Autoignition
  - Flame propagation

Simulations



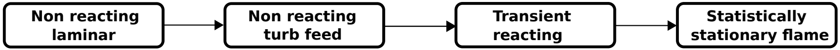


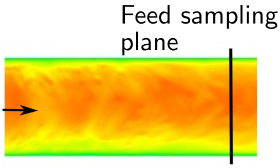
- Configuration has two parts: mixing duct and combustion chamber
- Conditions at inlet are such that flame is at a desired location (ignition length) in combustion chamber
- **S3D-multiblock[2]:** 8th-order central difference schemes for spatial derivatives
- Explicit 6-stage, 4th-order Runge-Kutta method for time advancement
- CHEMKIN and TRANSPORT libraries: compute thermo-chemical and transport properties

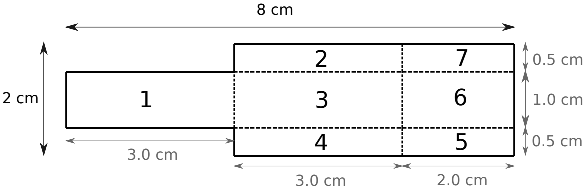
[2] Chen, et al. (Computational Science & Discovery 2009)

Simulation setup

- Detailed chemistry with 9 species and 21 reactions by Li[3] et al. 2004
- Fully developed channel flow DNS is used for turbulent feed inlet
- Turbulent velocity feed inlet and non-reflecting Navier-Stokes characteristics boundary condition outflow
- Isothermal walls (750K) with no slip condition







[3] Li, et al. (International journal of chemical kinetics 2004)

Simulation parameters

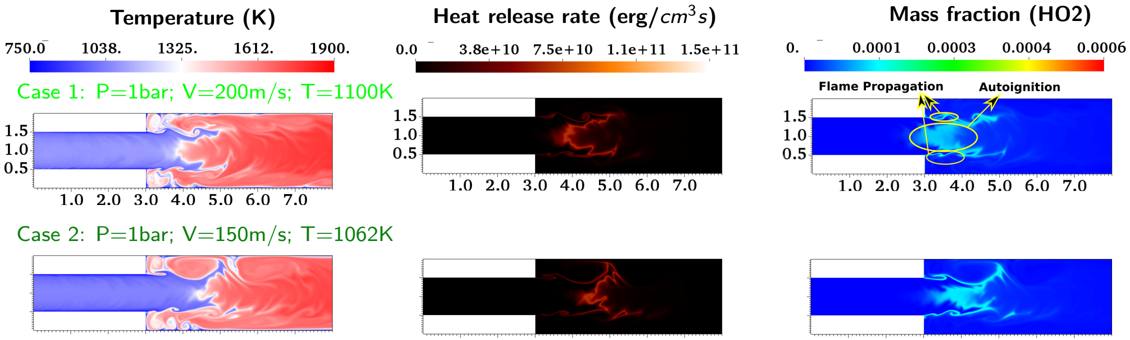
- 2D simulations were performed on SahasraT (IISc, India) and FRAM (Norway)

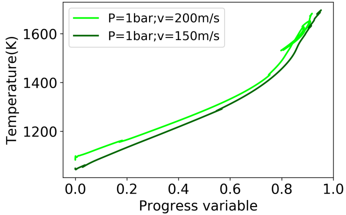
Case	Pressure	T_{inlet}	U_{bulk}	Grid resolution	Grid points	Reynolds number
1	1 bar	1100K	200 m/s	22.22 μm	2,308,500	7150
2	1 bar	1062K	150 m/s	22.22 μm	2,308,500	5700
3	5 bar	1132K	150 m/s	8.33 μm	16,560,000	25500
4	10 bar	1182K	150 m/s	5.00 μm	45,600,000	47500

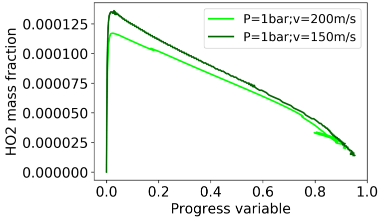
Case 3: P=5bar; $V_{inlet} = 150$m/s; $T_{inlet} = 1132$K video

- Temperature contours

Effect of residence time on flame structure

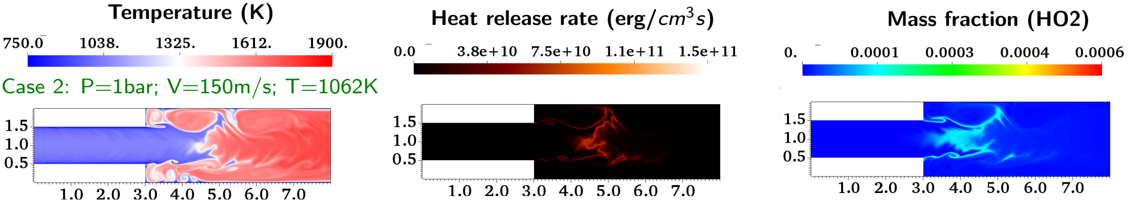




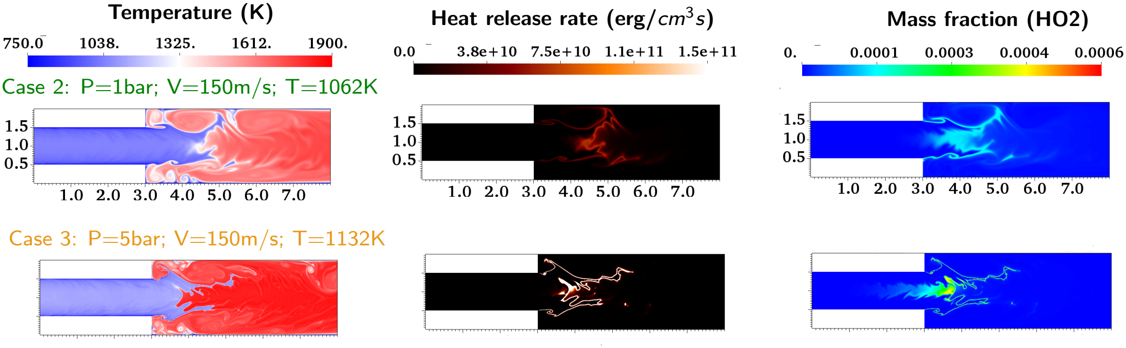


Pressure scaling

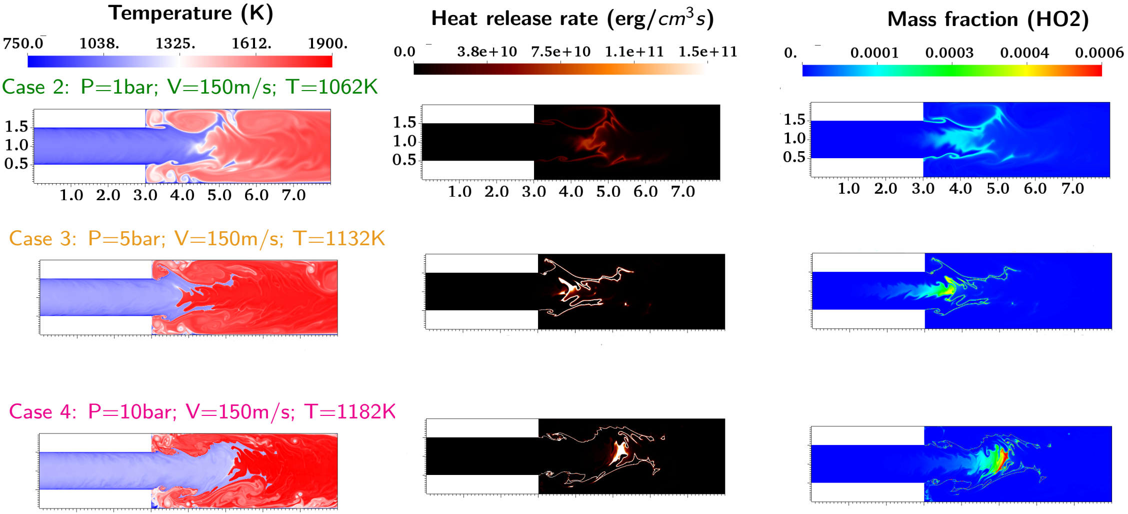
Case 2: P=1bar; V=150m/s; T=1062K



Pressure scaling

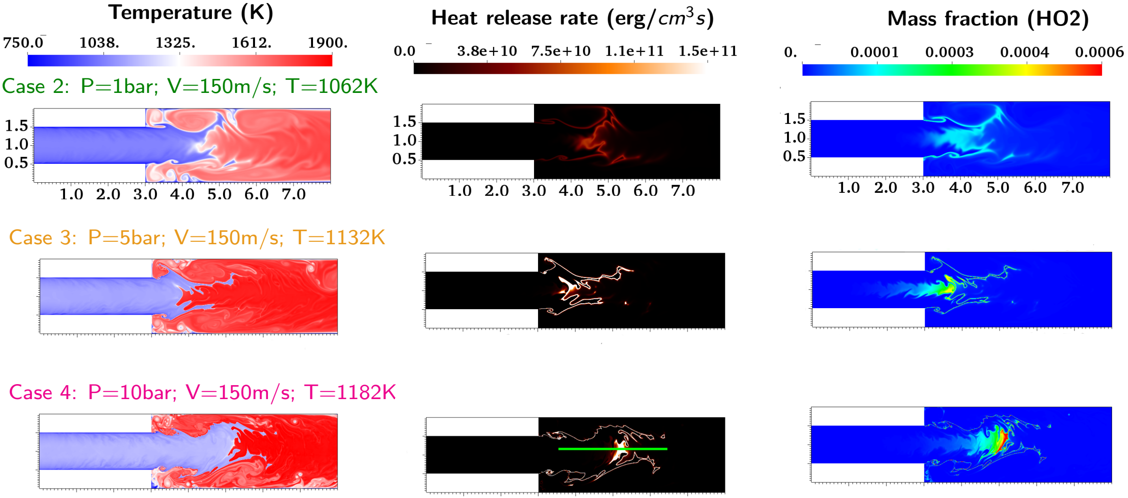


Pressure scaling



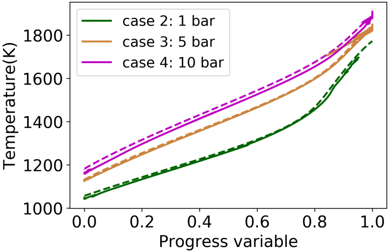
- Thinner flames and enhanced heat release rate at high pressure

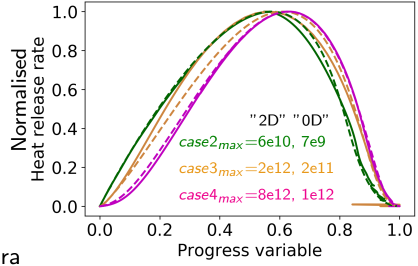
Pressure scaling



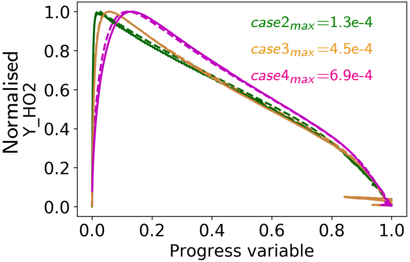
- Thinner flames and enhanced heat release rate at high pressure

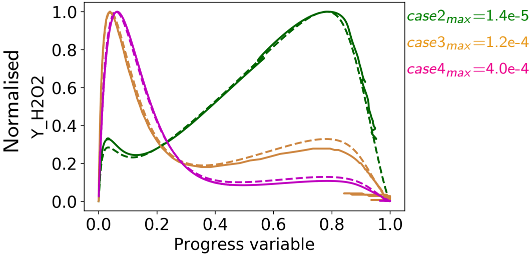
Comparing autoignition from 2D-DNS and 0D-cantera





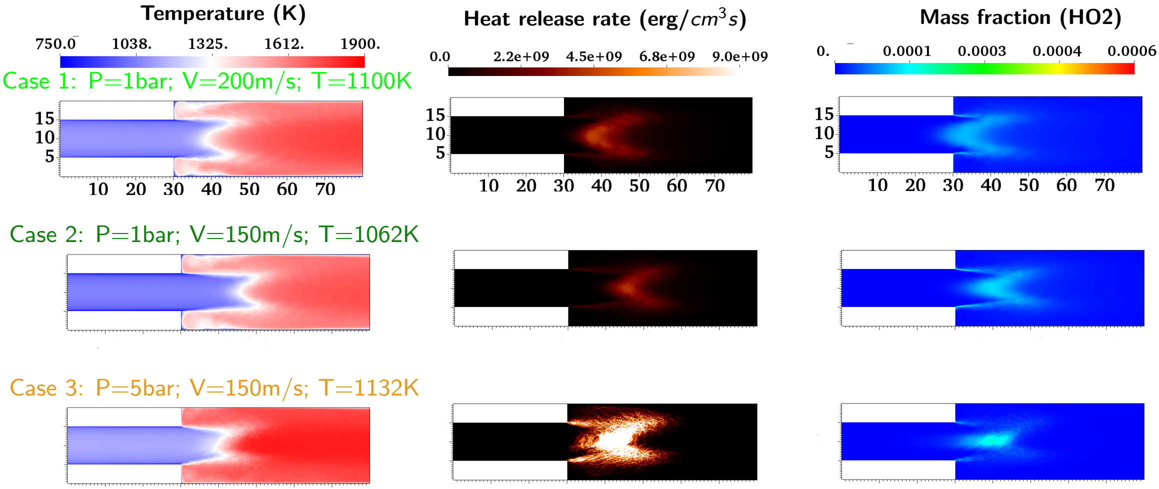
'—': 2D DNS
'- -': 0D Cantera





- Change in chemical pathway with pressure increase

Time averaged plots



- Thicker flame brush and greater heat release rate at high pressure

CEMA: Chemical explosive mode analysis[4]

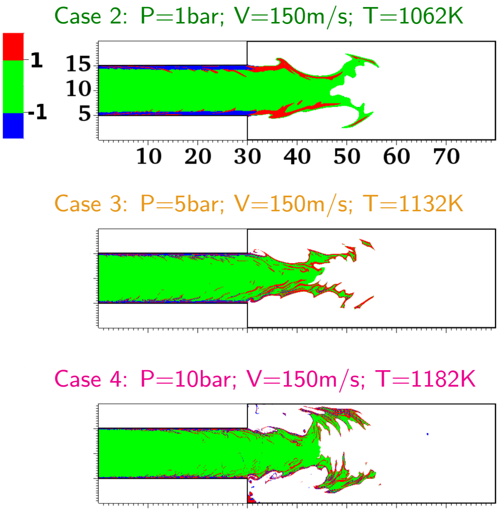
- CEMA is based on eigen-analysis of the Jacobian of the local chemical source term in the governing equation of a reacting flow
- Projected chemical source term $\phi_\omega = \mathrm{b} \cdot \omega(\mathrm{y})$
- Projected non-chemical source term $\phi_s = \mathrm{b} \cdot \mathrm{s}(\mathrm{y})$
- Ratio $\alpha = \phi_s/\phi_\omega$: scalar variable to distinguish between different modes of combustion

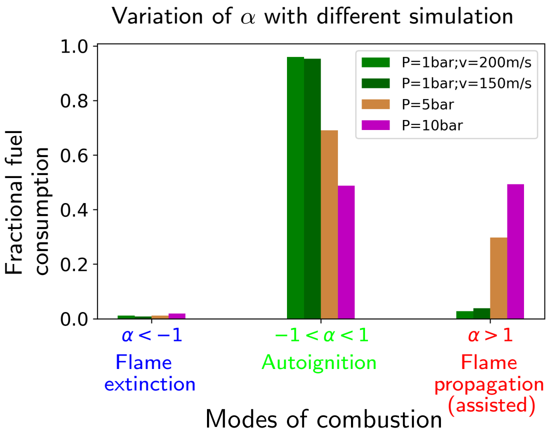
$$\alpha \simeq \frac{\text{diffusion source term}}{\text{reaction source term}}$$

- $\alpha <$ -1: flame extinction
- -1 $< \alpha <$ 1: autoignition
- $\alpha >$ 1: flame propagation

[4]Chao, et al. (Proceedings of the combustion Institute 2019)

Fuel consumption: autoignition vs flame propagation





- Significant reduction in fuel consumption by autoignition mode as pressure increased from 1 bar to 10 bar

Conclusions

- Performed 2D DNS of reheat combustion at different pressures
- Investigated the flame structure for autoignition and flame propagation modes
- Significant increase in heat release rate and temperature at high pressure
- At high pressure significant reduction in fuel consumption by autoignition
- Further investigation on pressure scaling of flame structure and fuel consumption is being carried