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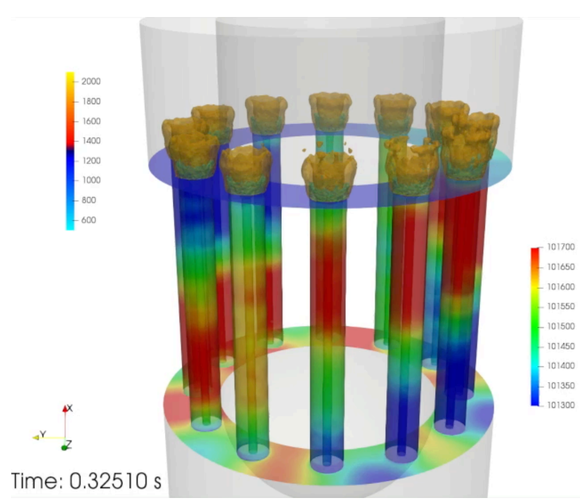
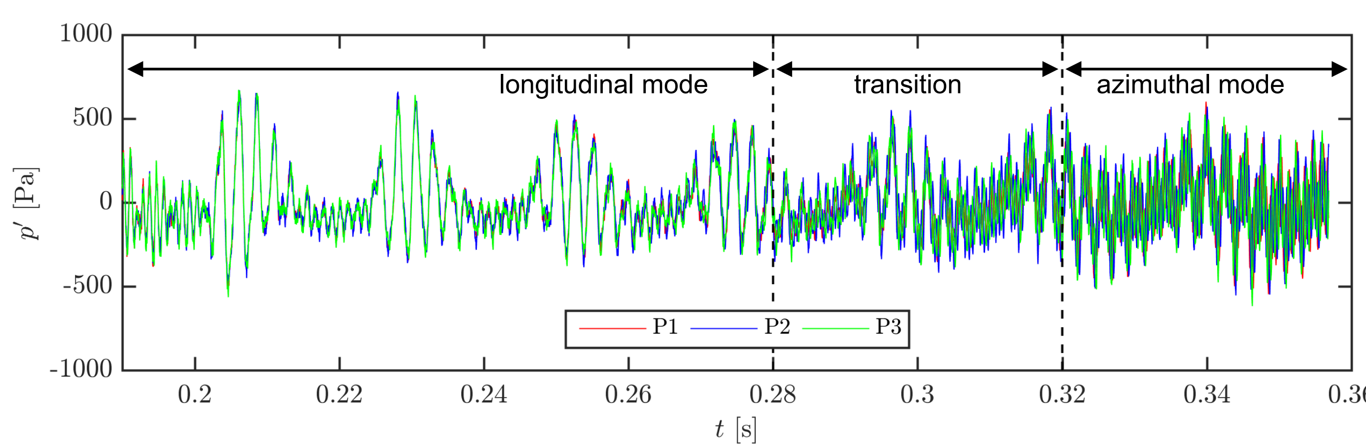
Large Eddy Simulation of Azimuthal Instability in a Model Annular Gas Turbine Combustor

Zhi X. Chen & N. Swaminathan

University of Cambridge

Department of Engineering





Outline

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- Background – thermoacoustic instabilities & azimuthal mode
- LES formulation and combustion modelling
- Simulation of a model annular combustor
  - Single sector – grid sensitivity and flame transfer function (ext. forcing)
  - 12 burner full annular – self-excited oscillations
- Summary and future work

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Thermoacoustic instabilities

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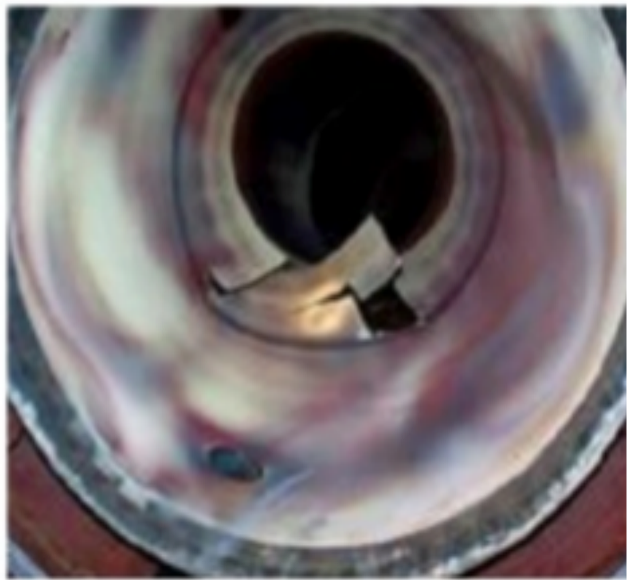
- Fuel lean combustion is prone to thermoacoustic instabilities in gas turbines.


[1]


[1]

Image sources: 1. W. Polifke, 2nd Colloquium on Combustion Dynamics and Combustion Noise Menaggio, Sept. 20-22, 2016
2. Altunlu et al., J. Eng. Gas Turbines Power 136 (2014) 051510.
3. N. Noiray, https://caps.ethz.ch/research/thermoacoustics.html.

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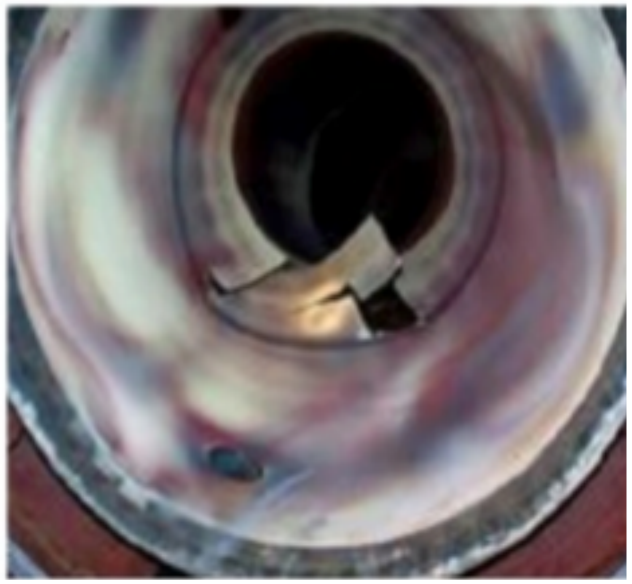

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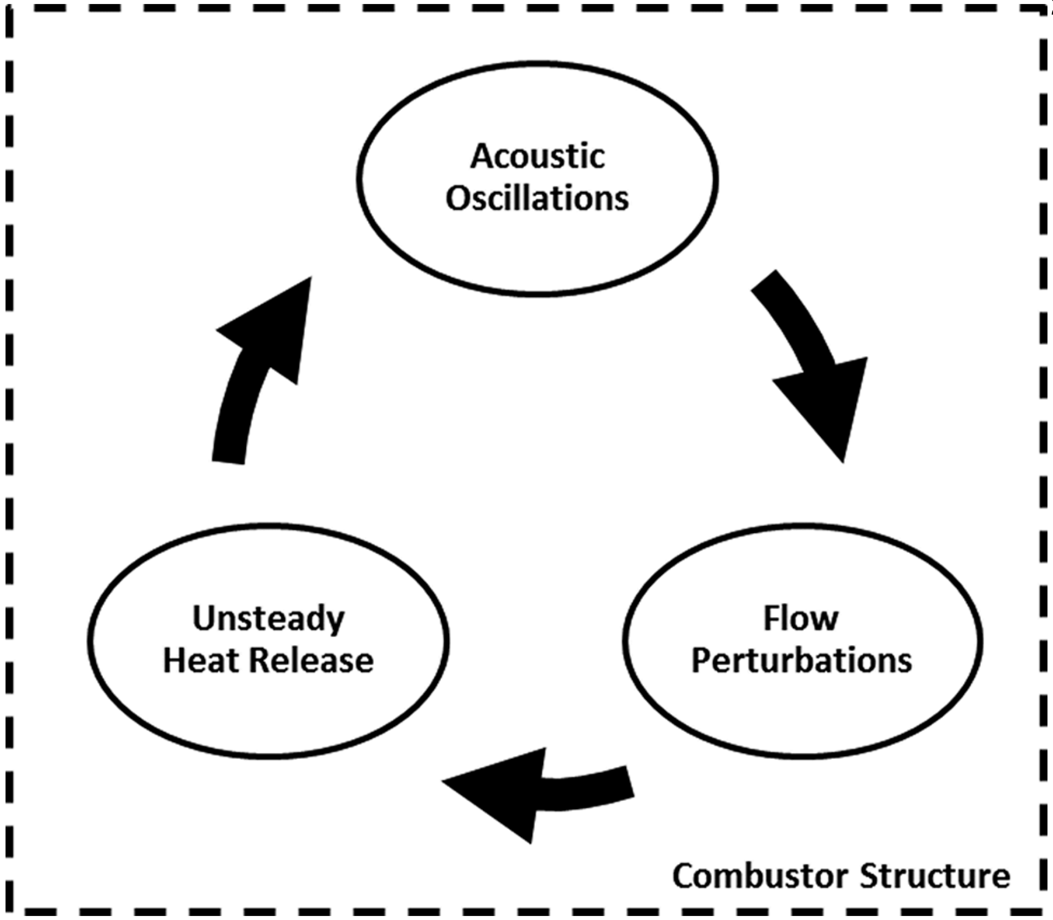

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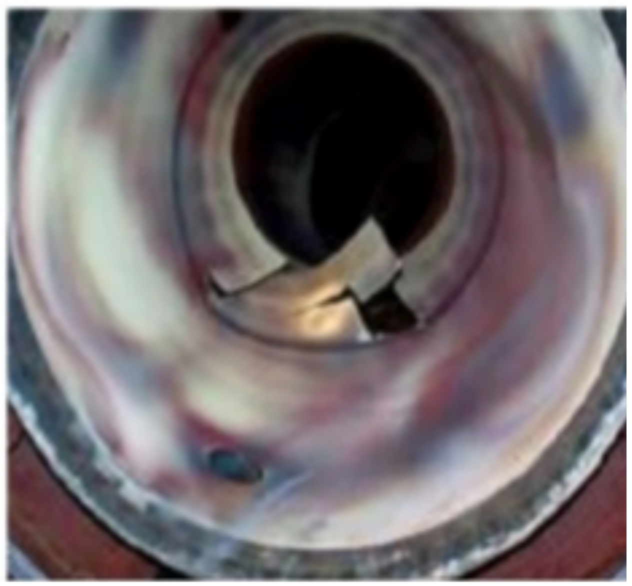
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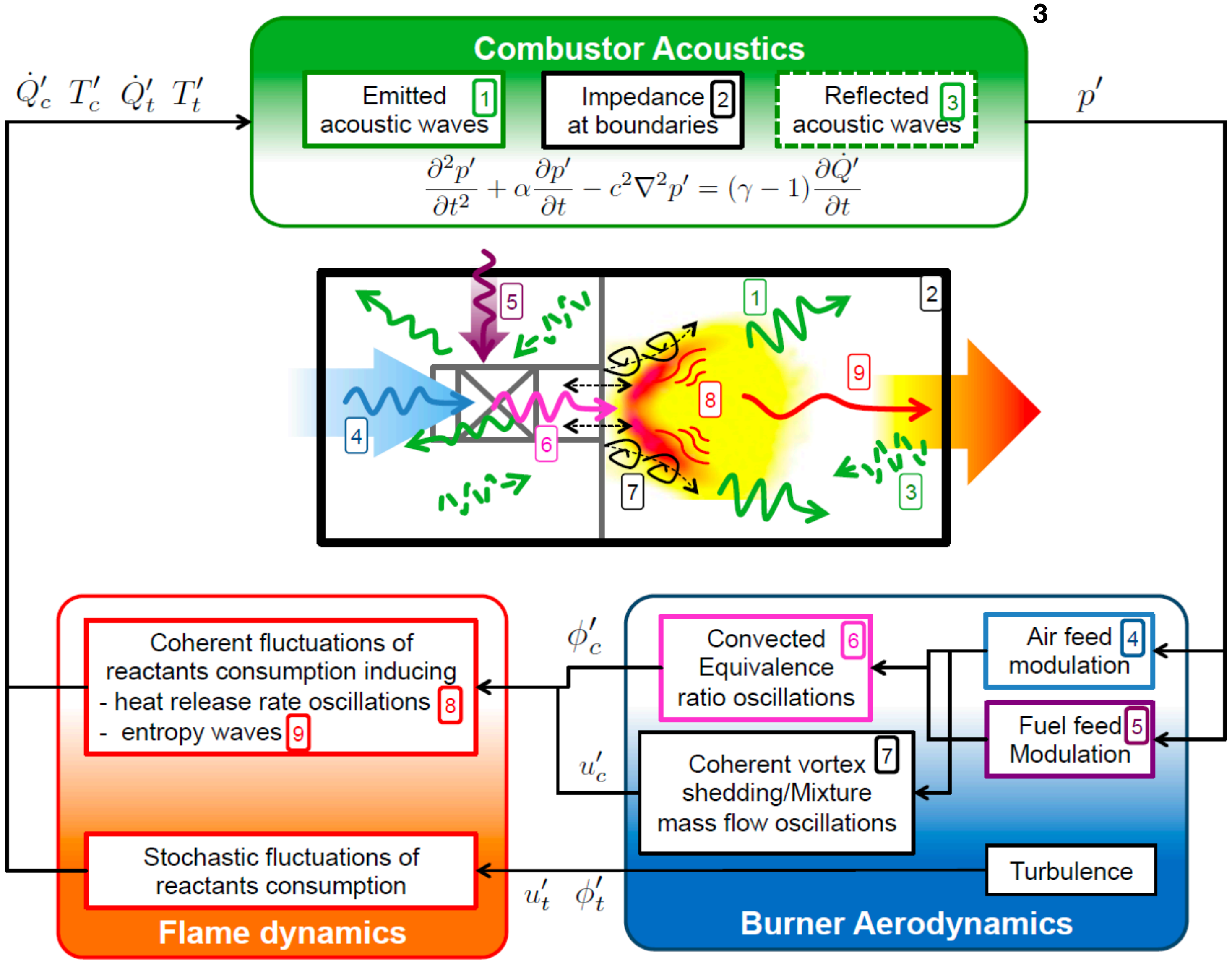

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Azimuthal mode

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- Azimuthal mode instabilities are more complex, damaging and <u>not yet well understood</u>.

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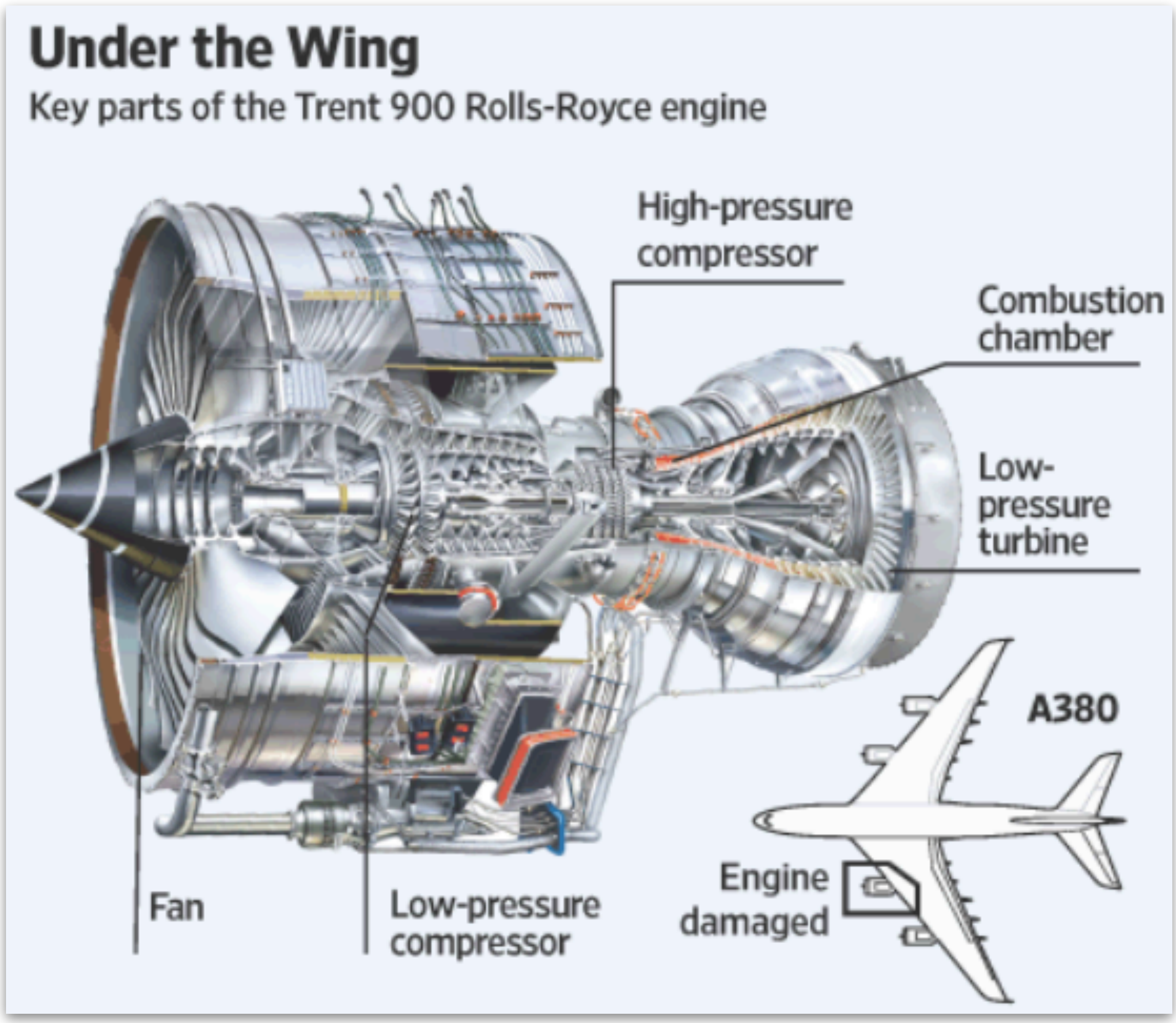

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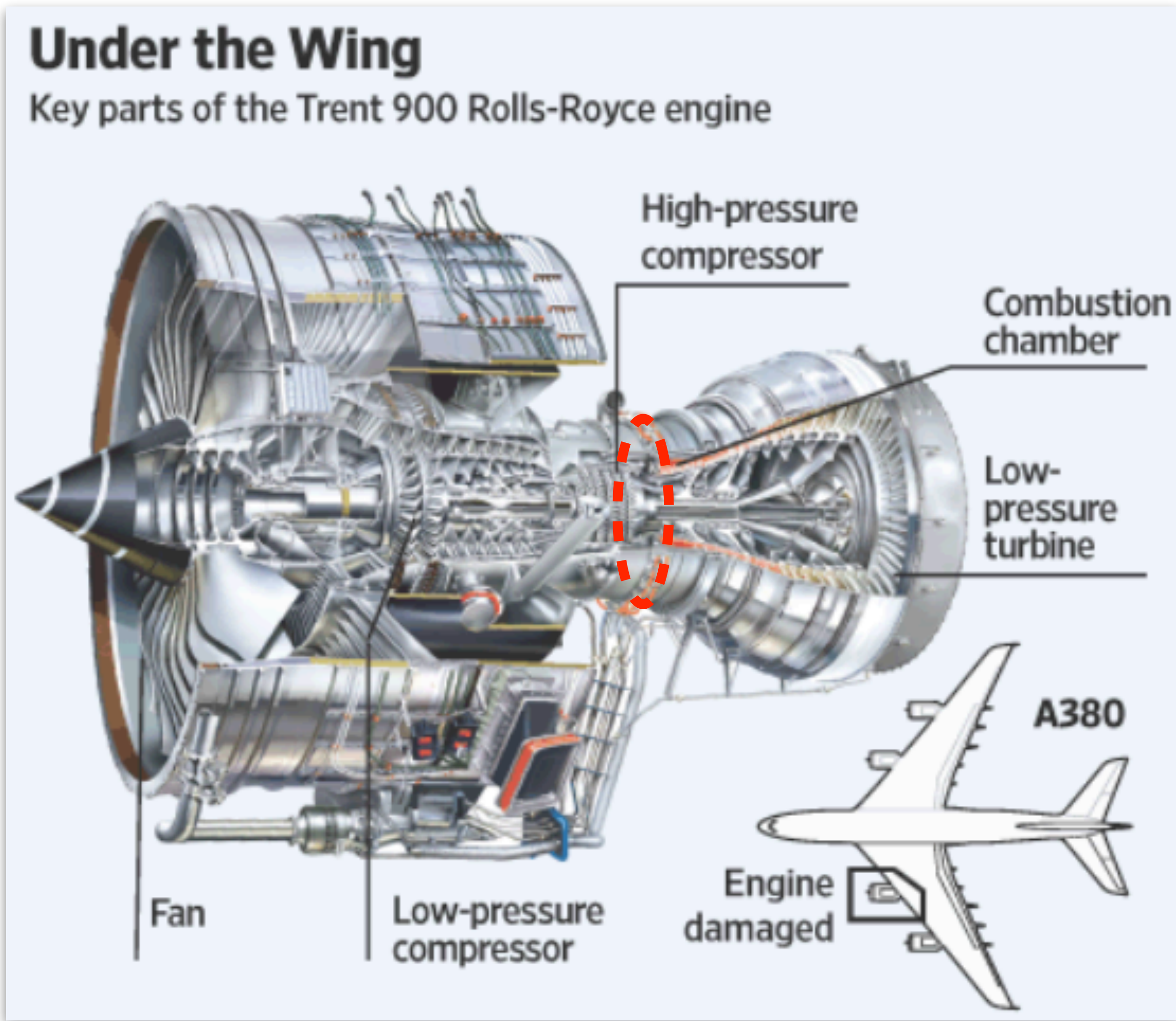

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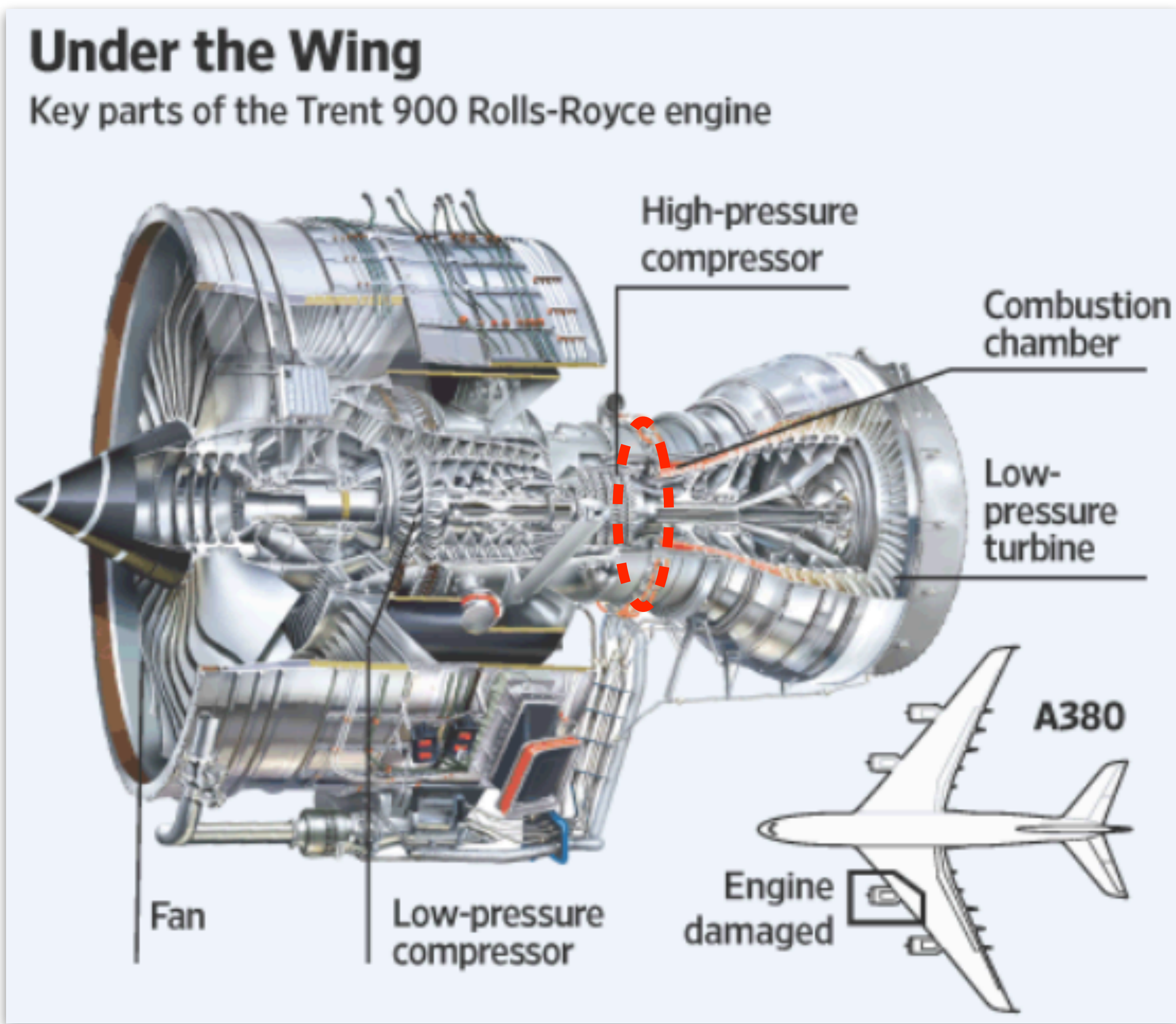
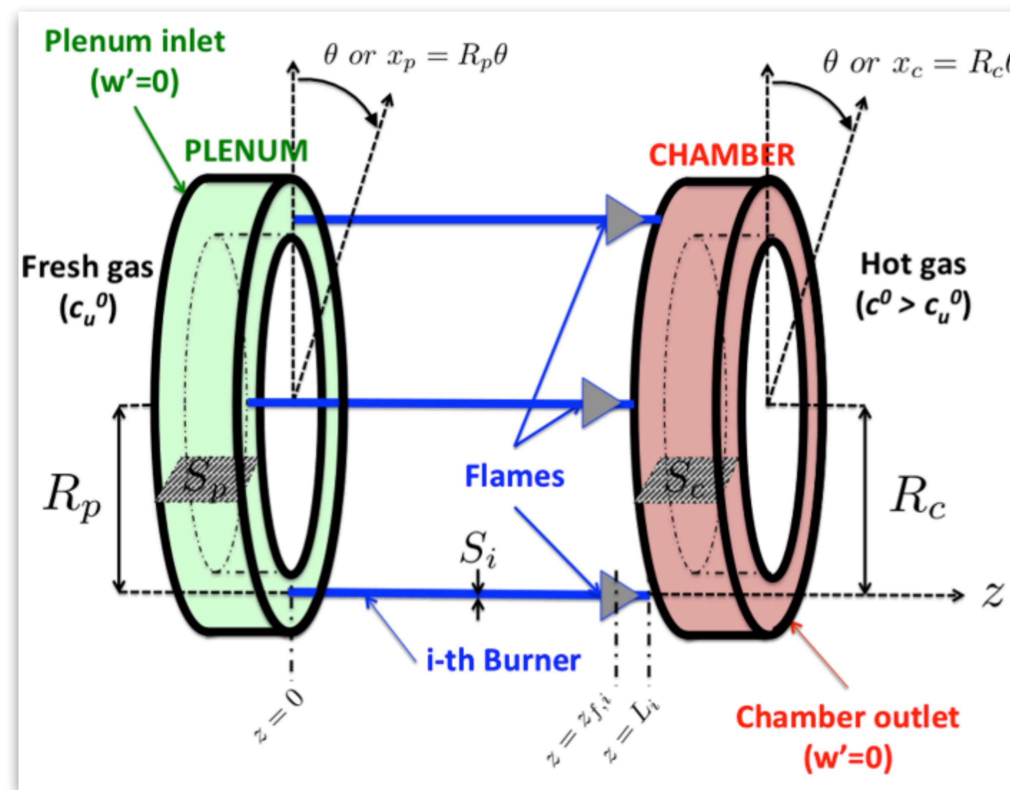


Smaller acoustic length compared to longitudinal modes

[2]



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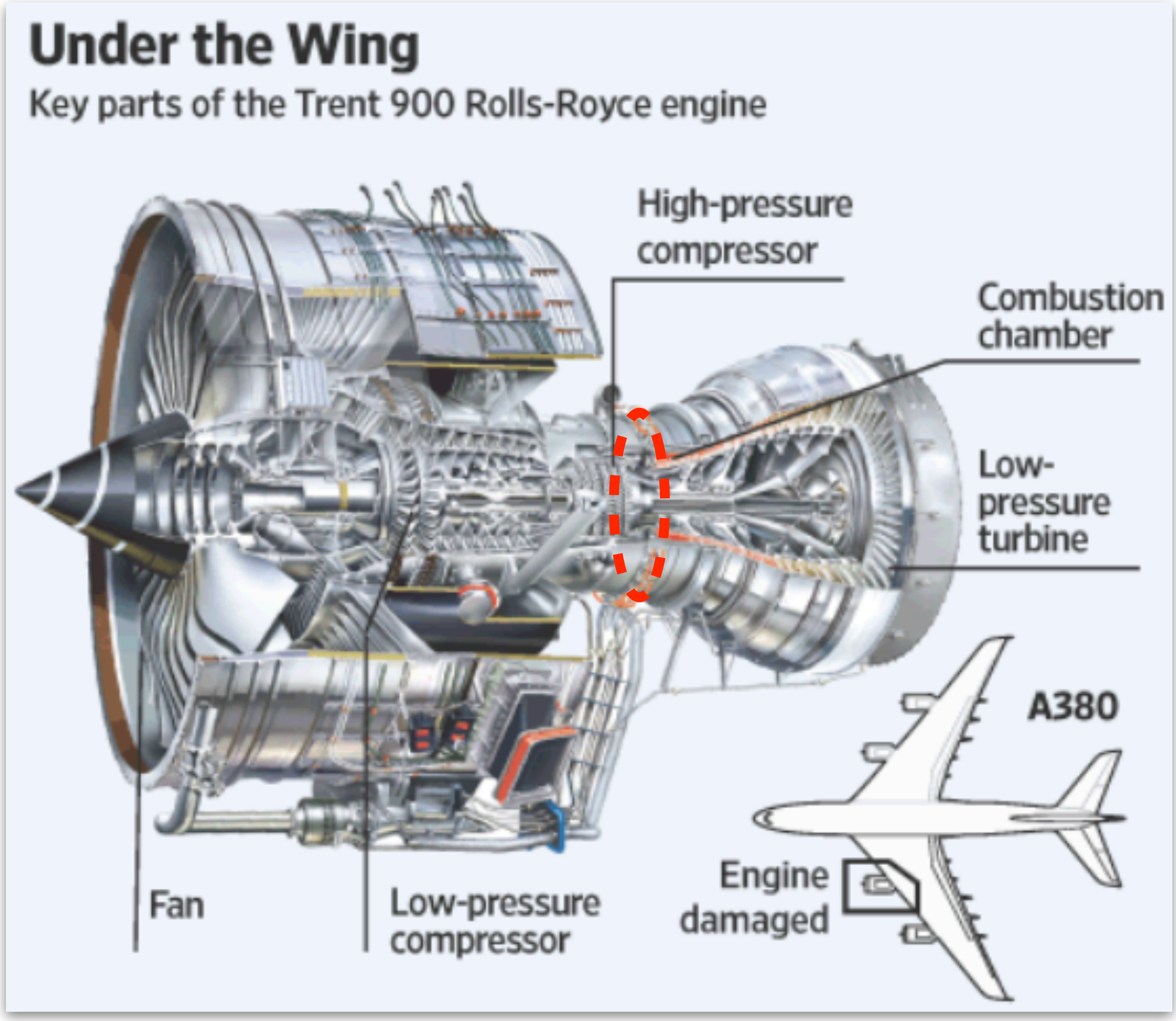

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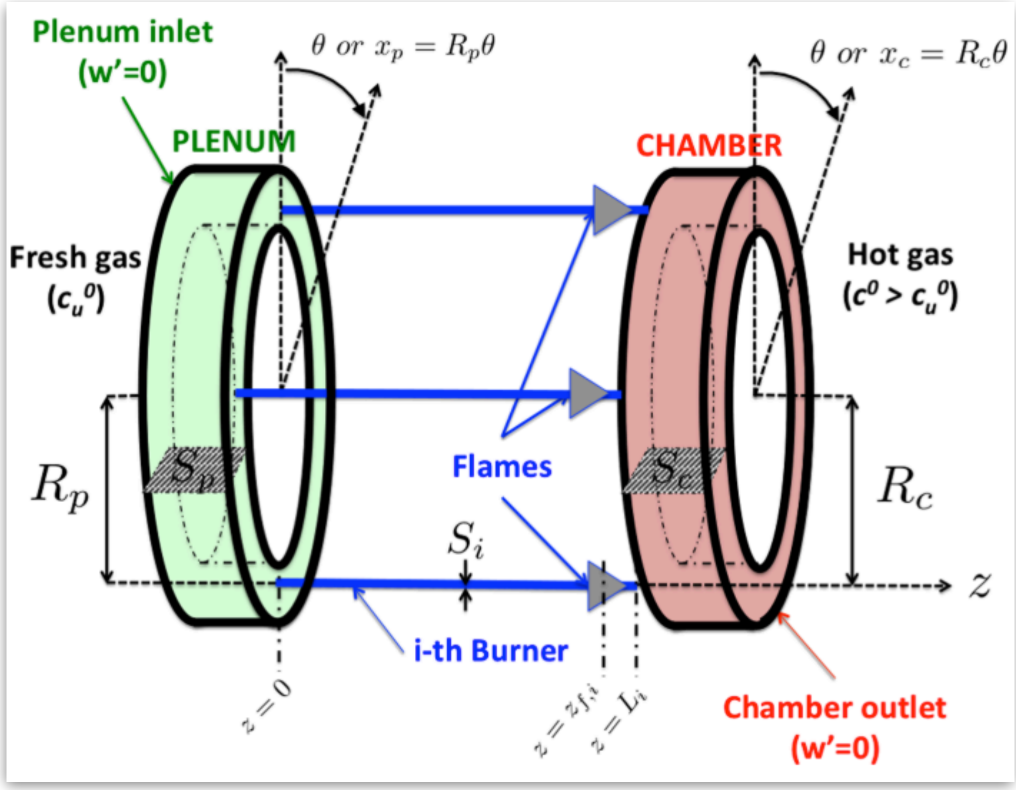
Smaller acoustic length compared to longitudinal modes

↓

Higher frequency and amplitude



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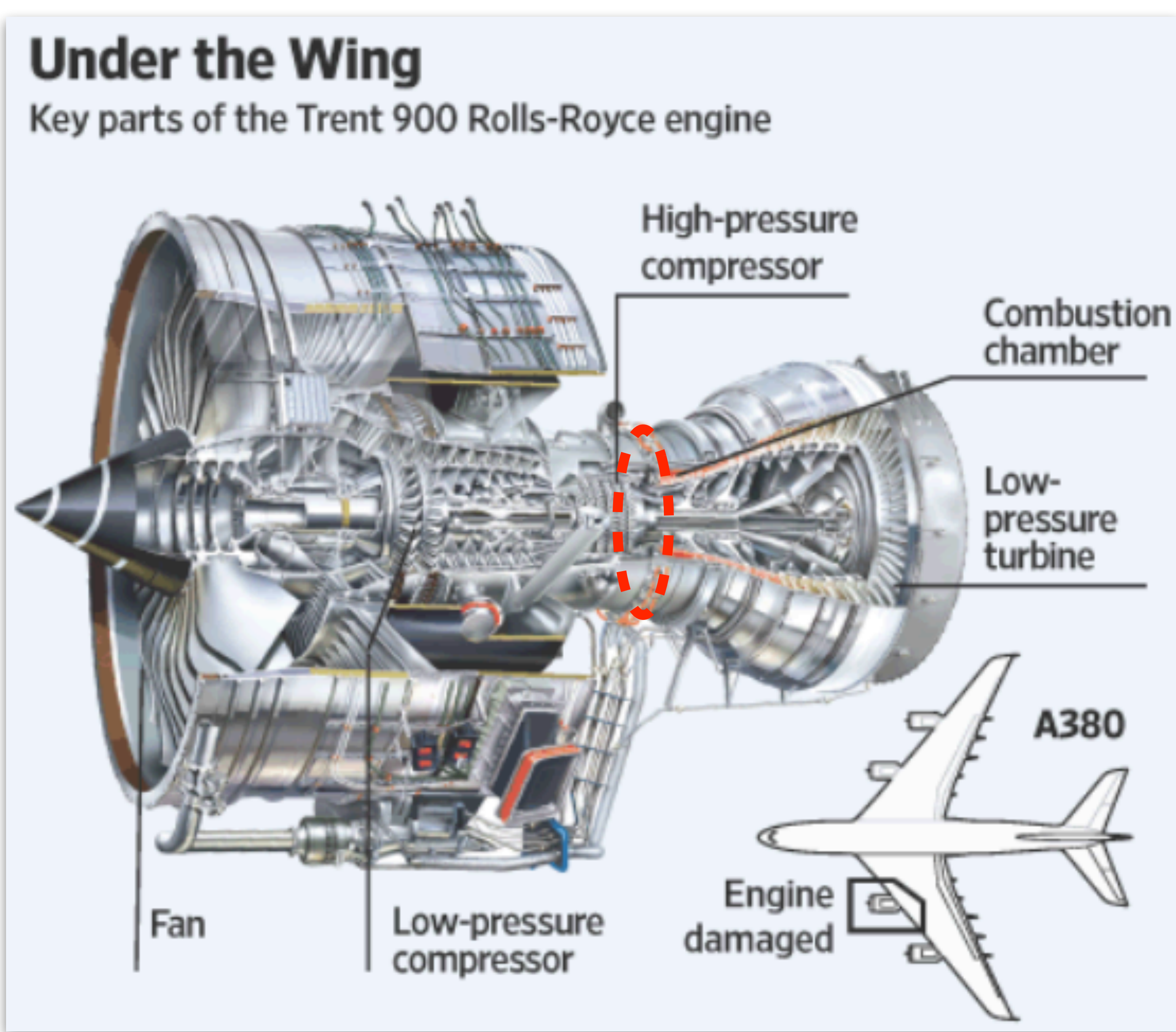

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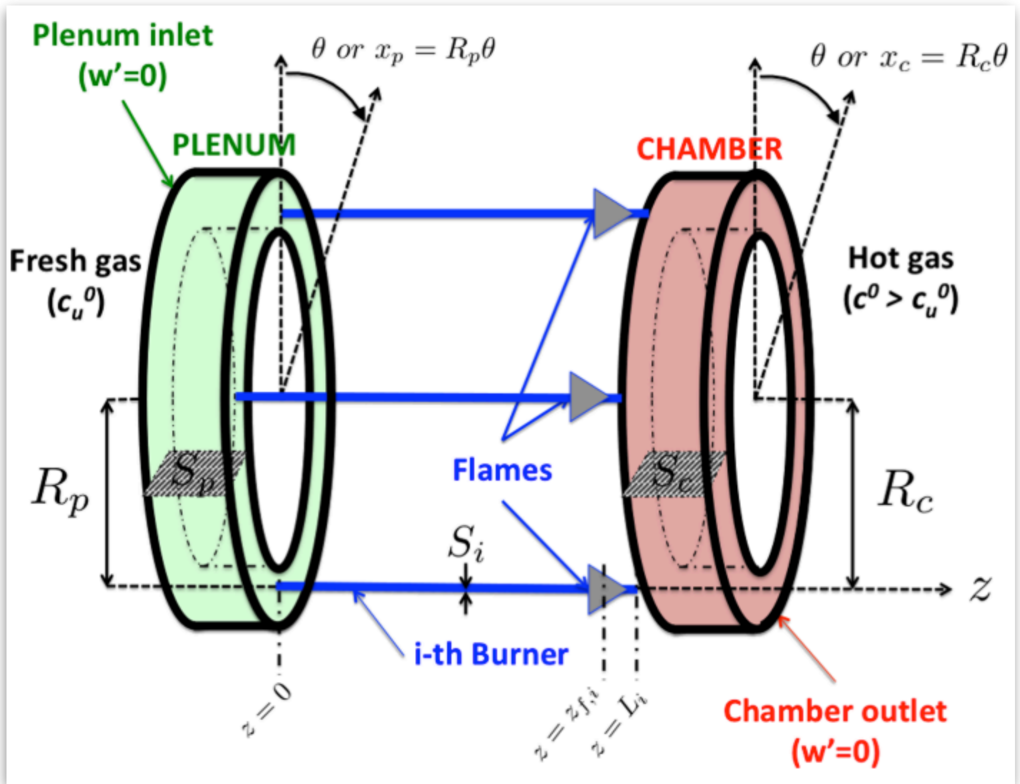

2

LES ⟶ Onset of azimuthal instabilities

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LES and combustion modelling

- 3D filtered N-S equations (mass, momentum and energy) are solved
- Compressibility effects are considered: pressure work heating, equation of state

A flamelet model for partially premixed combustion

Chemistry tabulation (GRI 3.0) using a collection of premixed flamelets

$$\varphi = \mathcal{F}(Z, c)$$

First two moments are transported along with enthalpy

$$\overline{\rho}\,\frac{D\widetilde{\varphi}}{Dt} = \nabla\cdot\left[\left(\overline{\mu}+\frac{\mu_t}{\mathrm{Sc}_t}\right)\nabla\widetilde{\varphi}\right] + \overline{S_\varphi^+} - \overline{S_\varphi^-}$$

$$\widetilde{\varphi} = \left\{\widetilde{Z},\, \widetilde{Z''^2},\, \widetilde{c},\, \widetilde{c''^2},\, \widetilde{h}\right\},$$

$$\overline{S_\varphi^+} = \left\{0,\, 2\frac{\mu_t}{\mathrm{Sc}_t}|\nabla\widetilde{Z}|^2,\, \overline{\dot{\omega}_c^*},\, 2\frac{\mu_t}{\mathrm{Sc}_t}|\nabla\widetilde{c}|^2 + 2\left(\overline{c\,\dot{\omega}_c^*} - \widetilde{c}\,\overline{\dot{\omega}_c^*}\right),\, \frac{D\overline{p}}{Dt}\right\},$$

$$\overline{S_\varphi^-} = \left\{0,\, 2\overline{\rho}\widetilde{\chi}_{Z,\mathrm{sgs}},\, 0,\, 2\overline{\rho}\widetilde{\chi}_{c,\mathrm{sgs}},\, 0\right\}.$$

=

Premixed

$$\boxed{\overline{\dot{\omega}}_c = \overline{\rho}\int_0^1\int_0^1 \frac{\dot{\omega}_c(\xi,\zeta)}{\rho(\xi,\zeta)}\,\widetilde{P}(\xi,\zeta)\; d\zeta\; d\xi}$$

+

$$\boxed{\overline{\dot{\omega}}_{\mathrm{np}} \simeq \widetilde{c}\left(\overline{\mu}|\nabla\widetilde{Z}|^2 + \overline{\rho}\widetilde{\chi}_{Z,\,\mathrm{sgs}}\right)\int_0^1 \frac{1}{\psi^{\mathrm{Eq}}}\frac{d^2\psi^{\mathrm{Eq}}}{d\xi^2}\widetilde{P}_\beta(\xi)\; d\xi}$$

Non-premixed

Refs: 1. Z.X. Chen et al., Combust. Flame 203 (2019) 279.
2. Z.X. Chen et al., Proc. Combust. Inst. 37 (2019) 2325.

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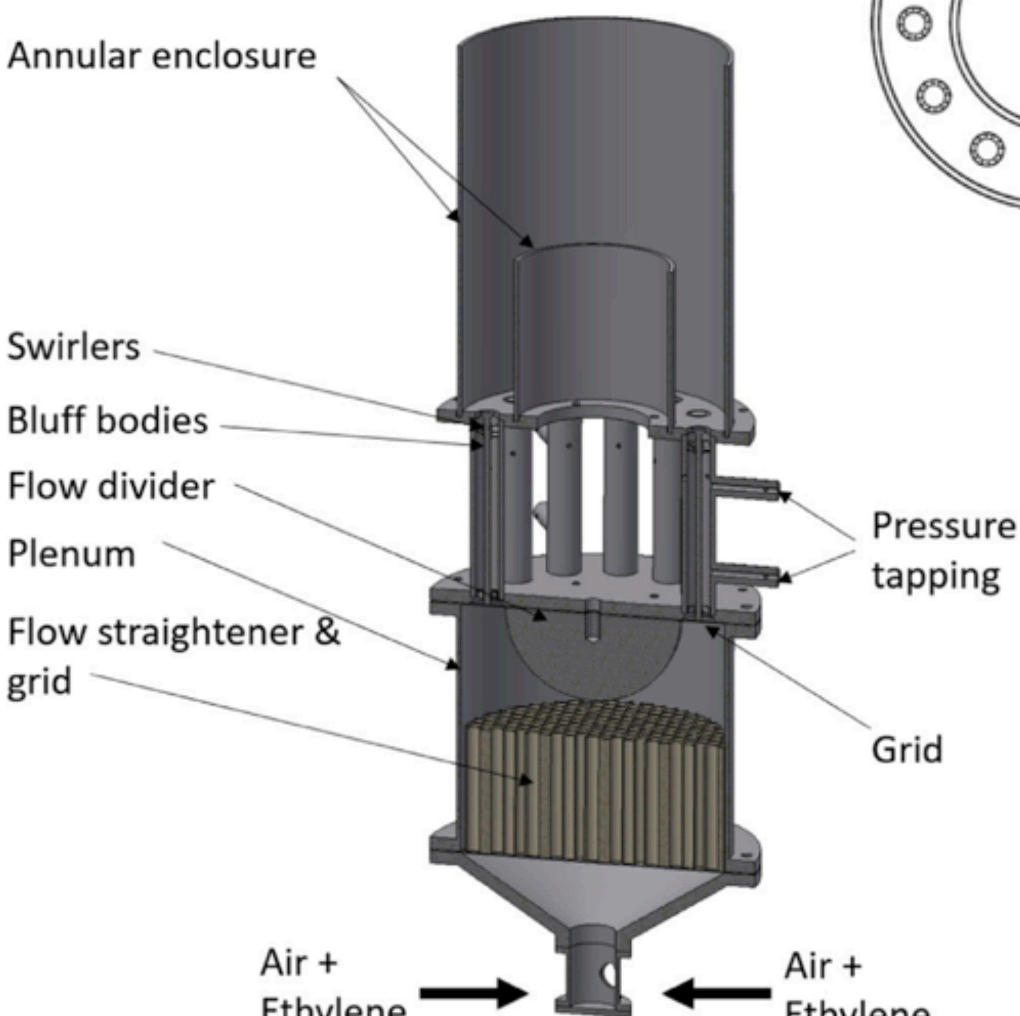
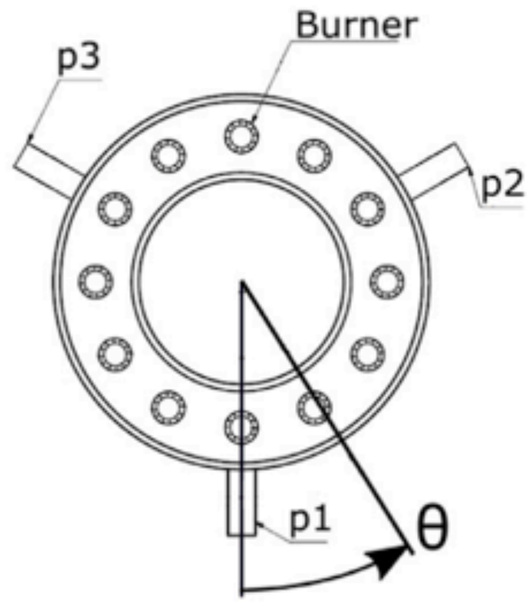
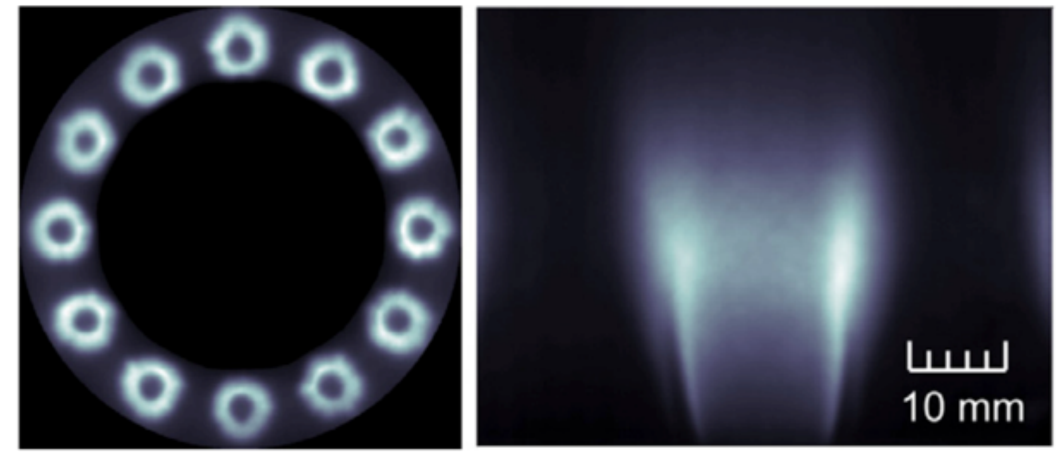
Cambridge/NTNU gas turbine model annular combustor







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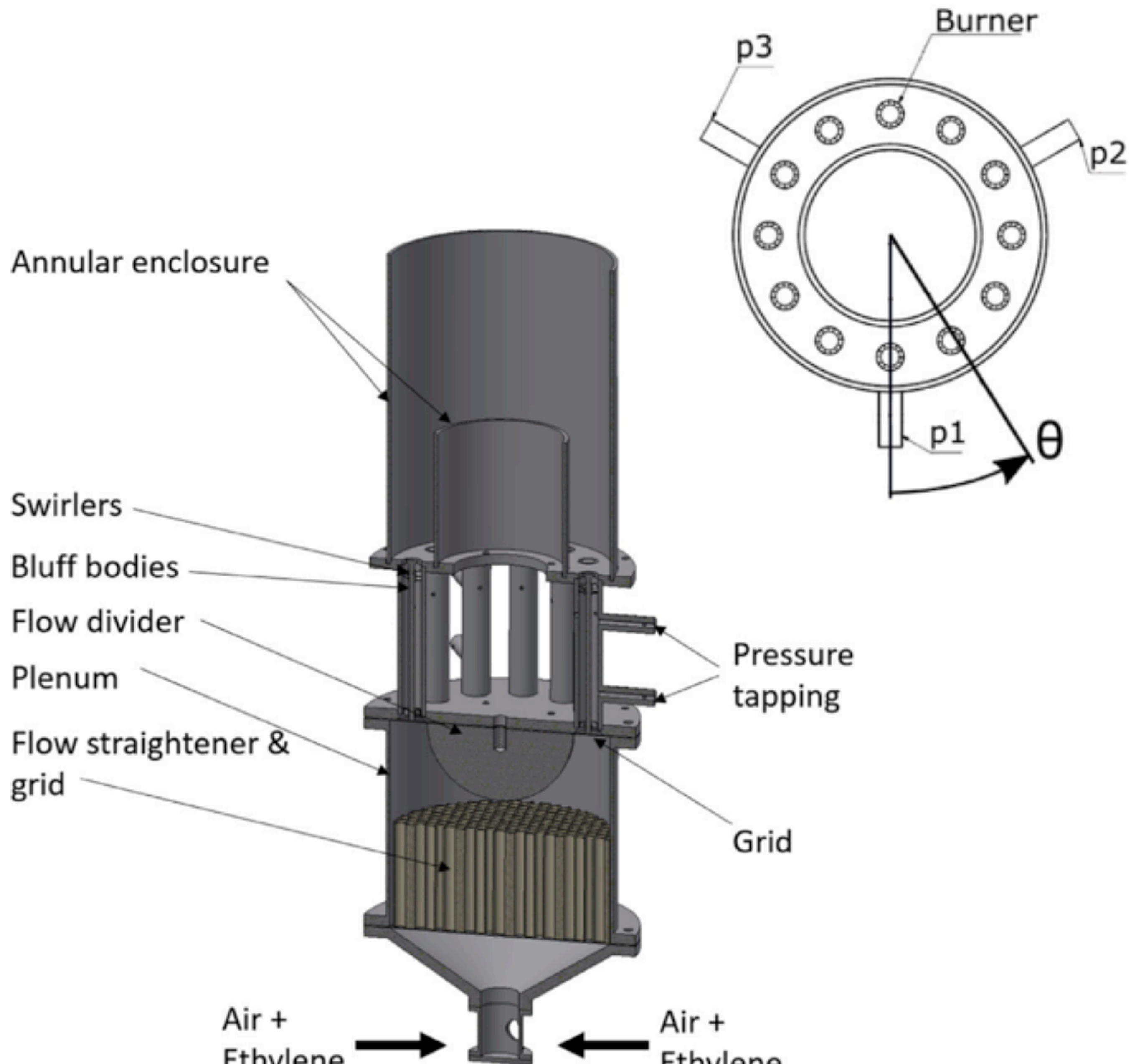

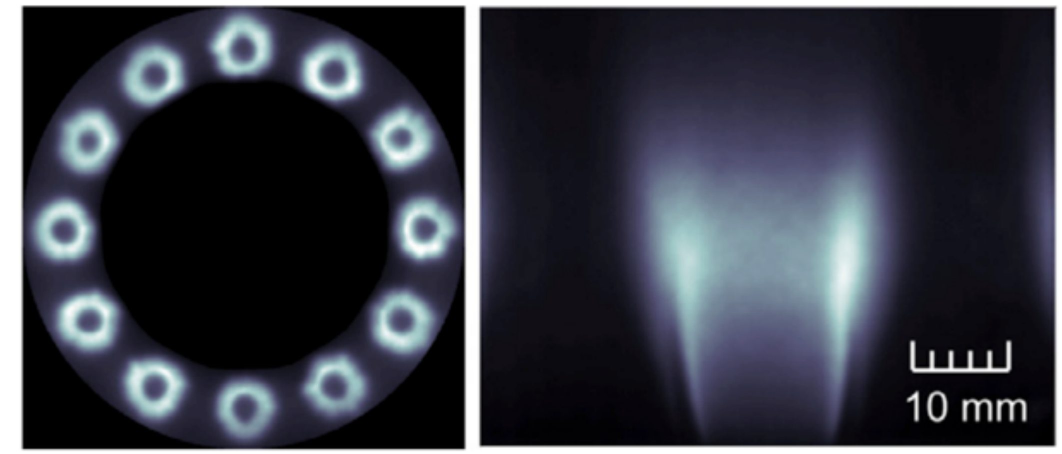

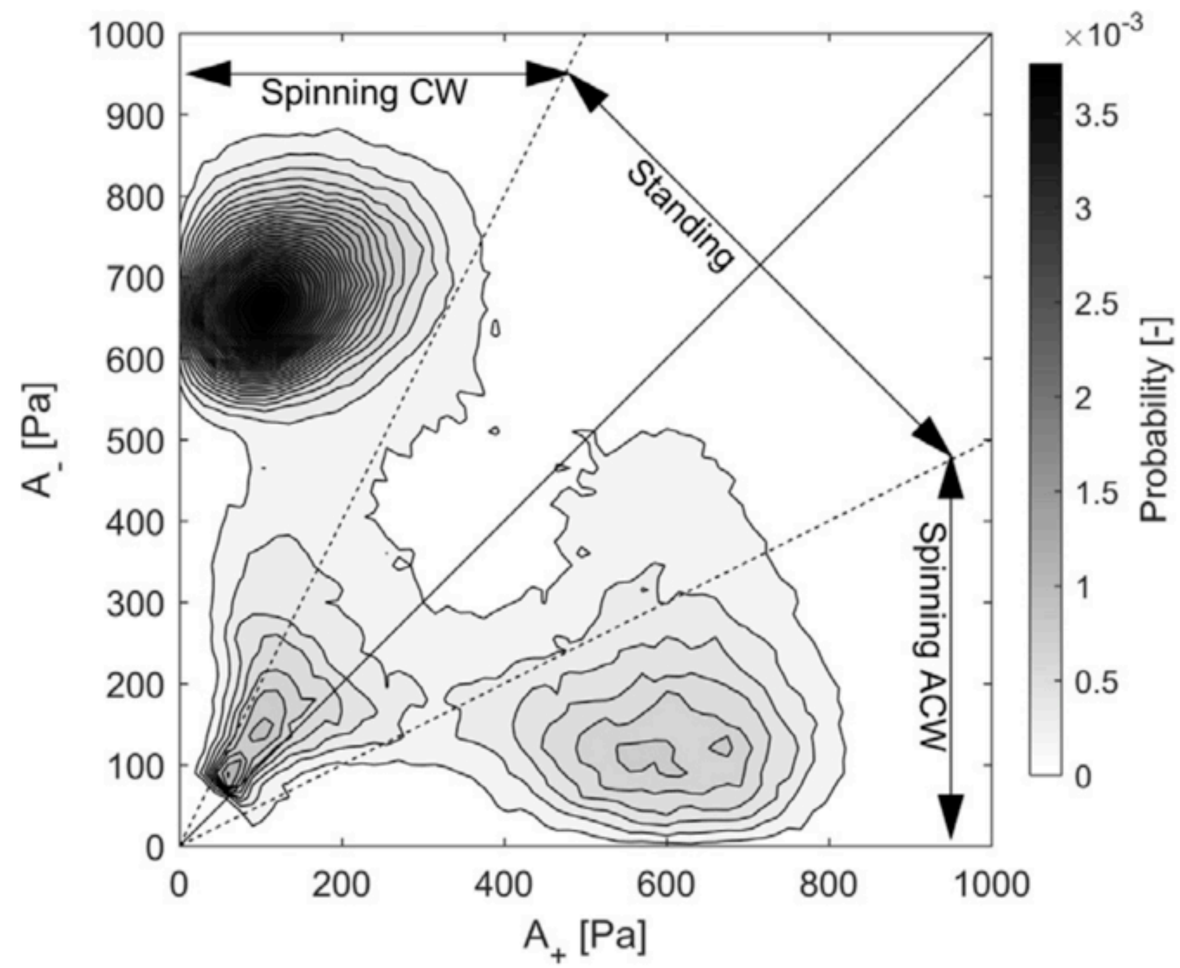

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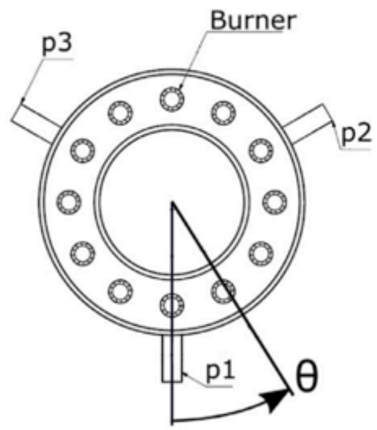
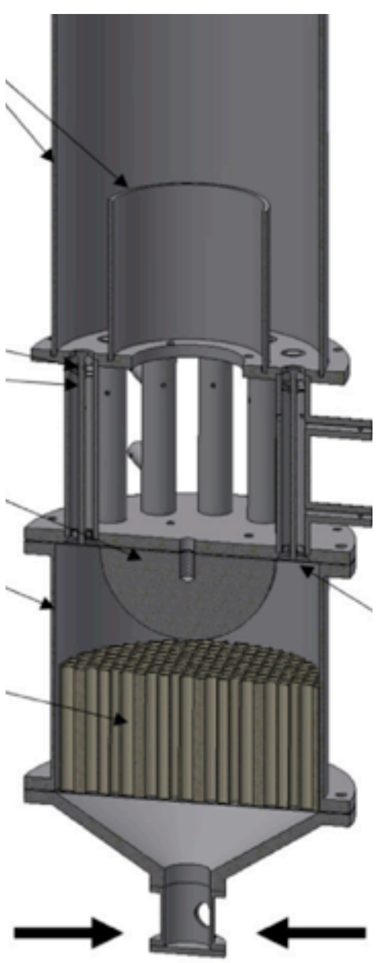
Single sector – grid sensitivity and flame transfer function





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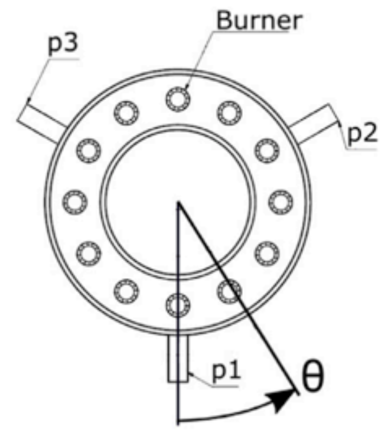

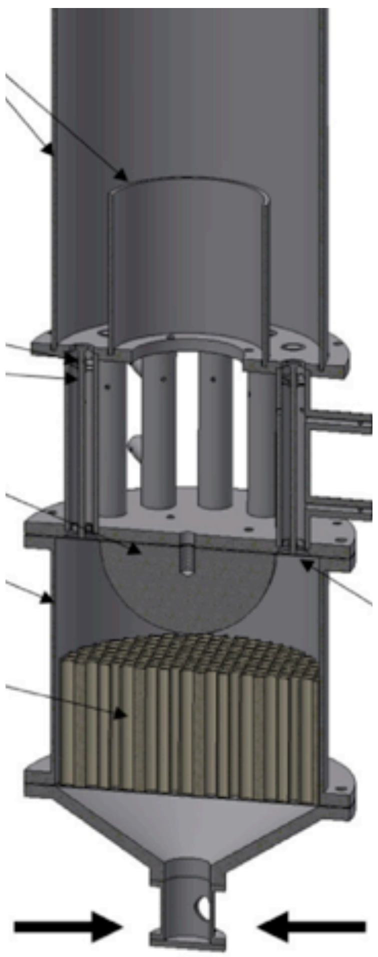

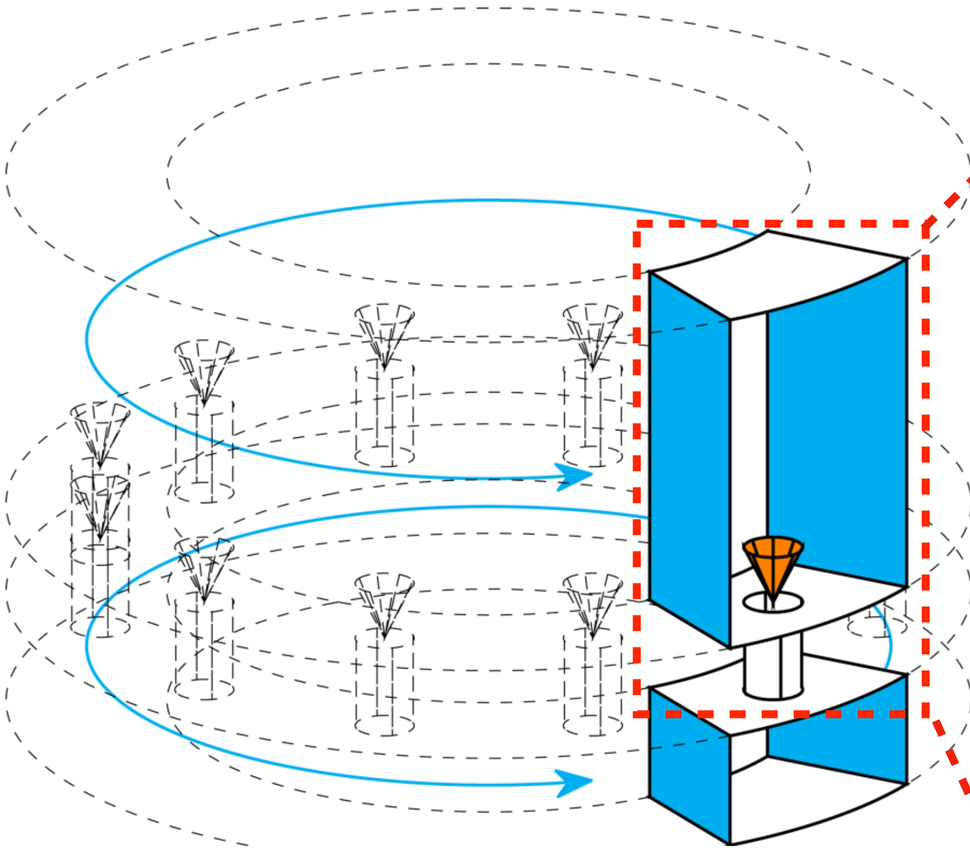

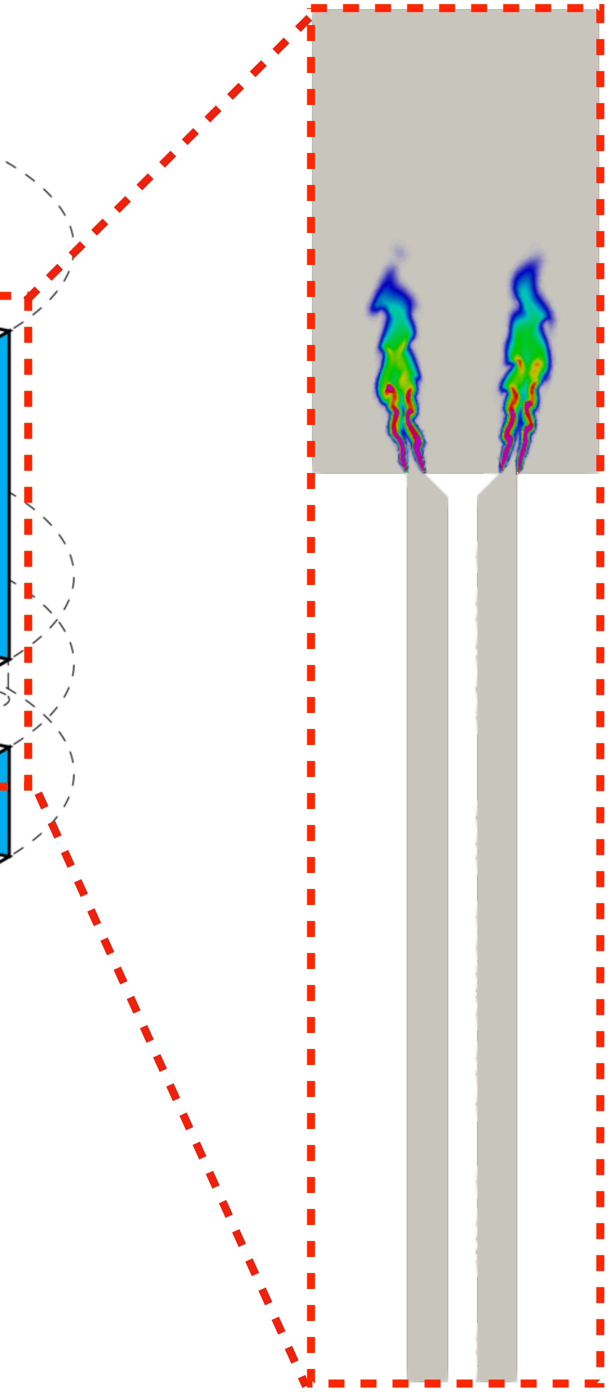

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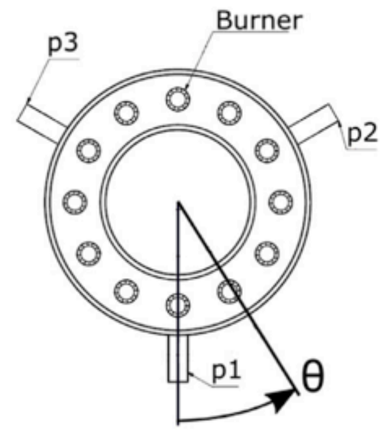

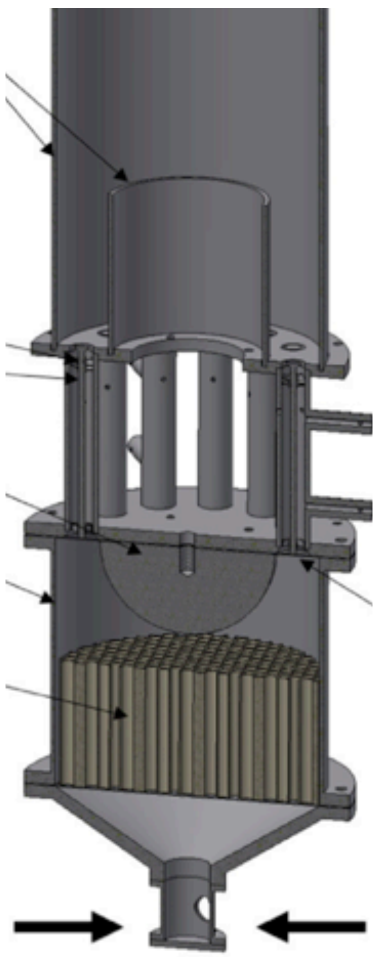

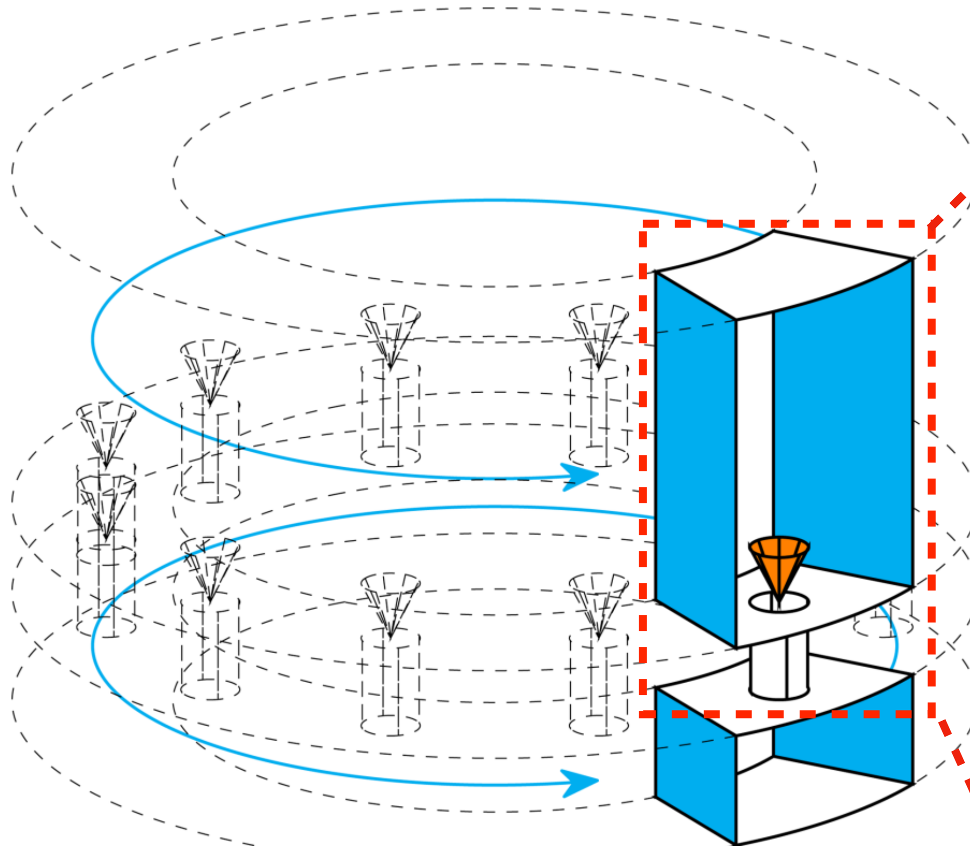

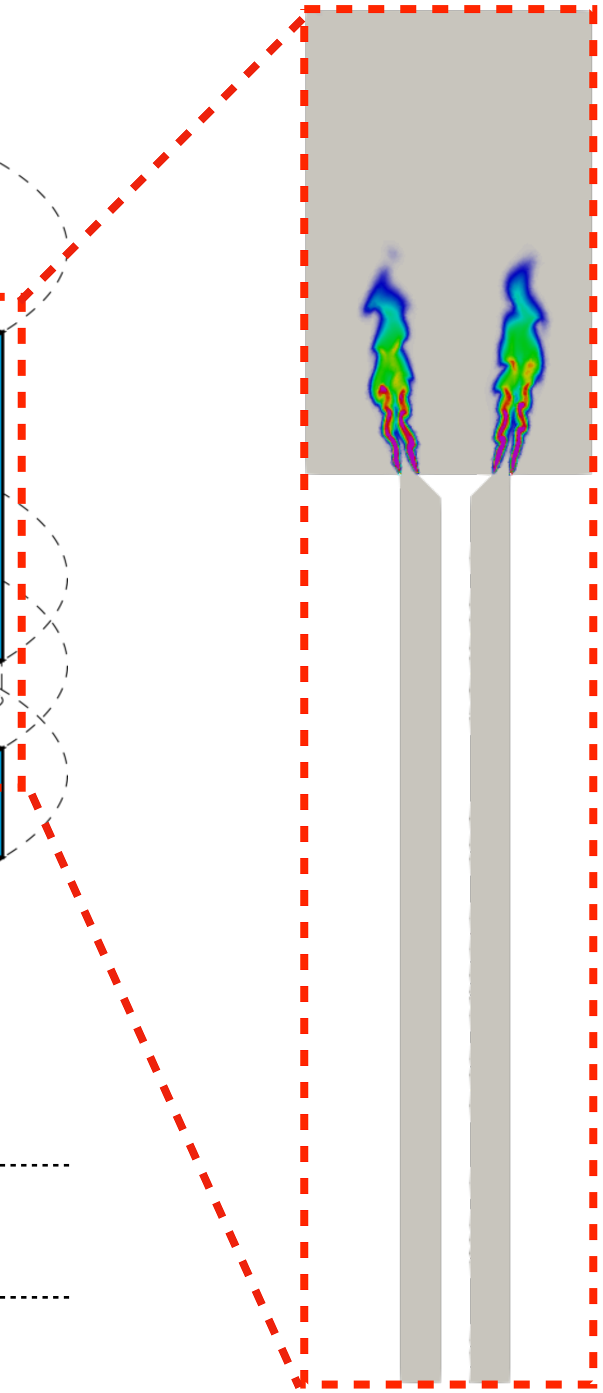

Grid	G1	G2
$\Delta x/\delta_{th}^{0}$	2	1.2
No. Cells	1.4M	2.1M

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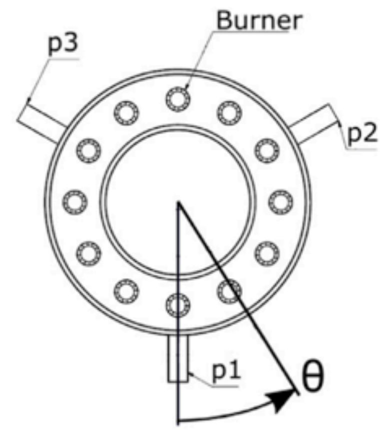

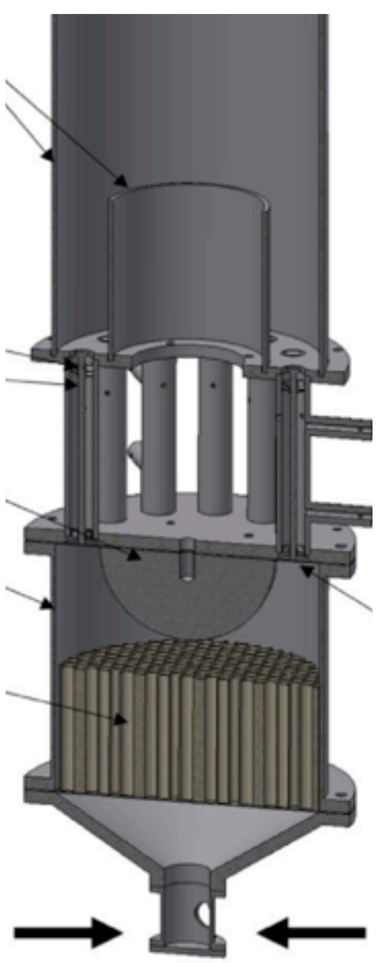

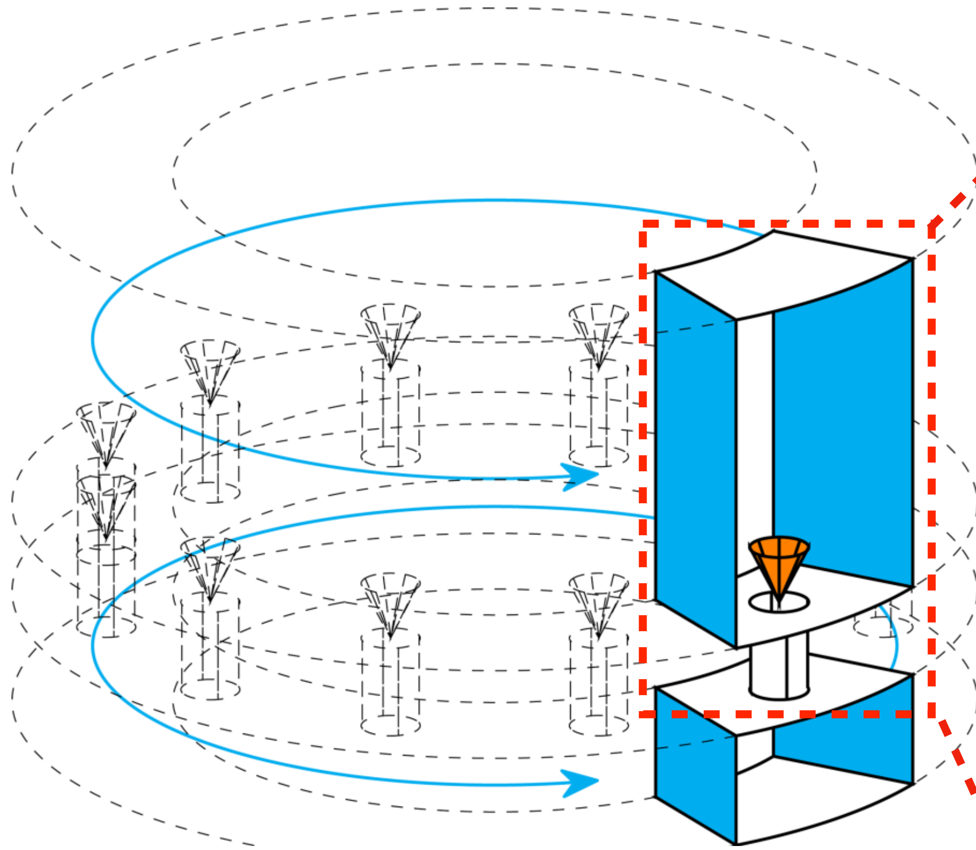

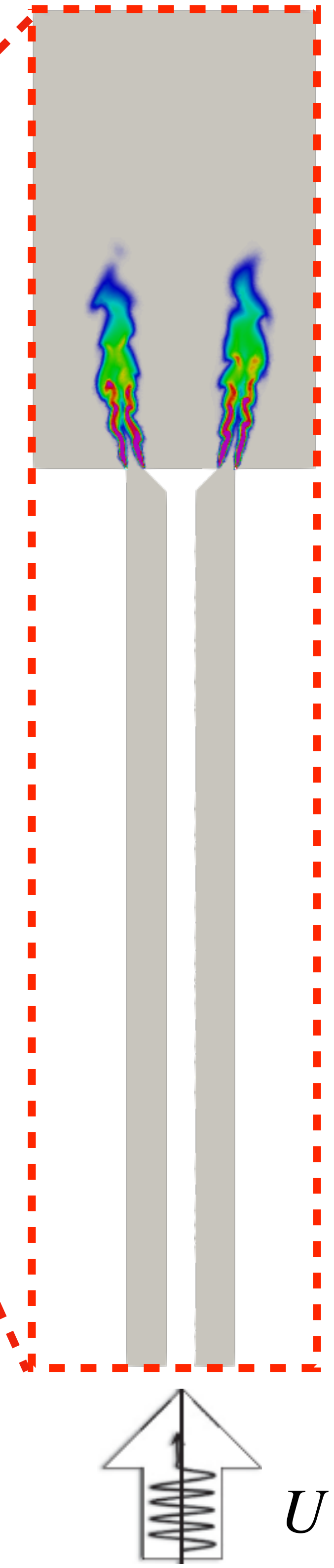

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$f = 1800$ Hz
(1st azim. mode)

$U_b = 15\ m/s$

$U = A\ U_b\, sin(2\pi f t)$

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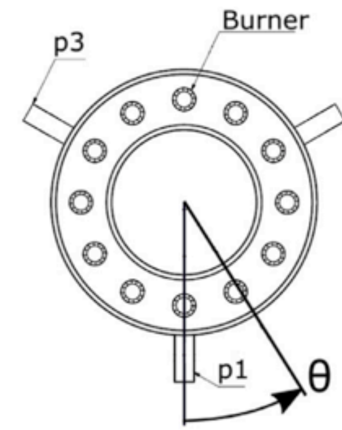

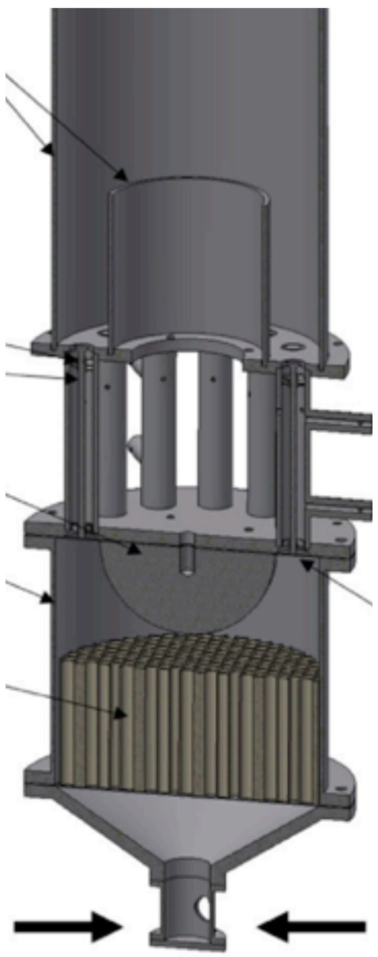

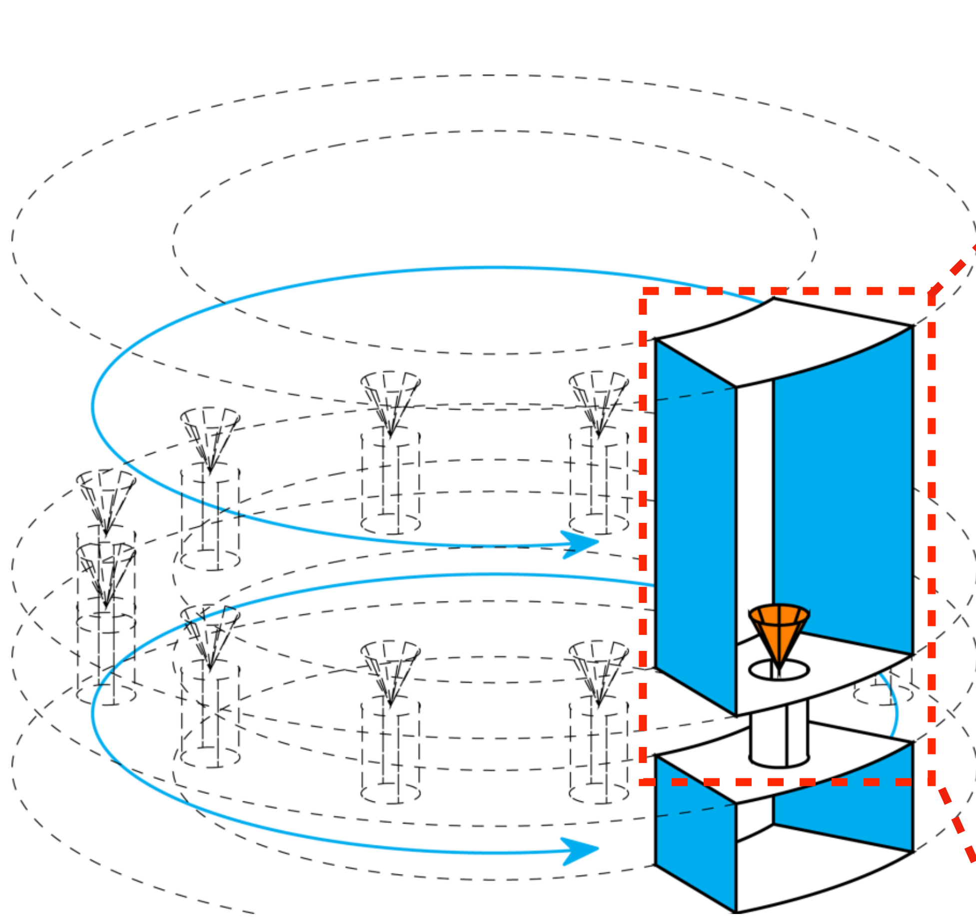

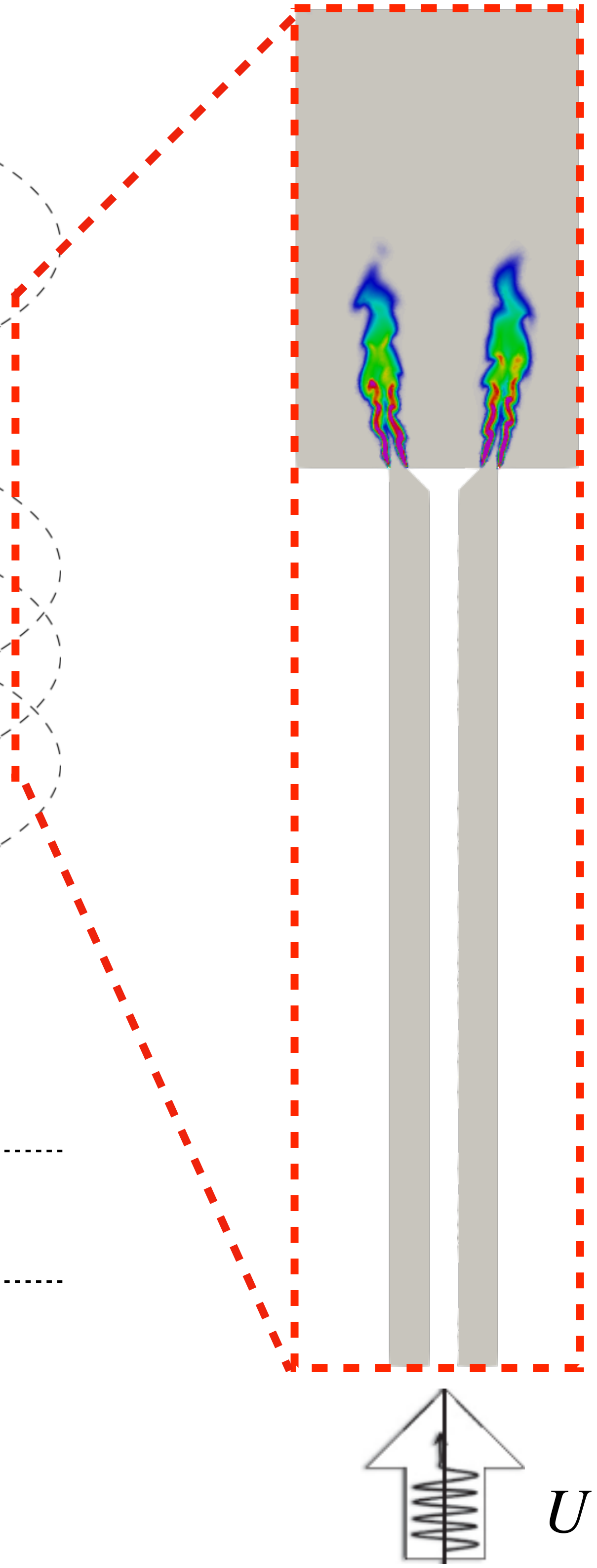

$$\text{FTF} = \frac{\dot{q}'/\overline{\dot{q}}}{U_0'/\overline{U_0}}$$

$$= G(\omega)\, e^{i\Phi\omega}$$

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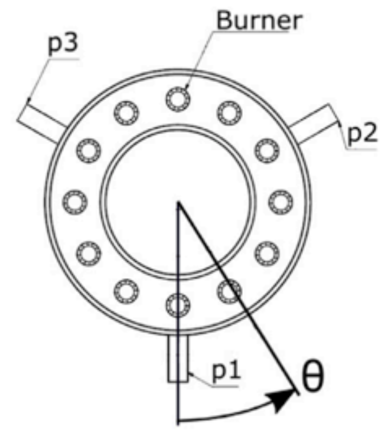

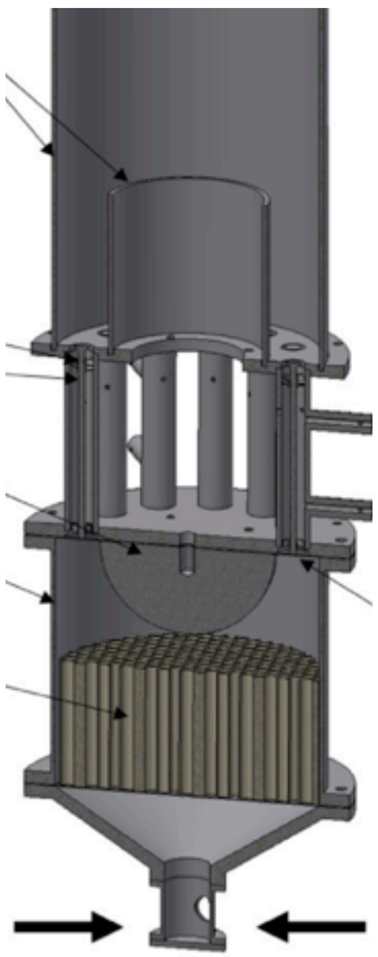

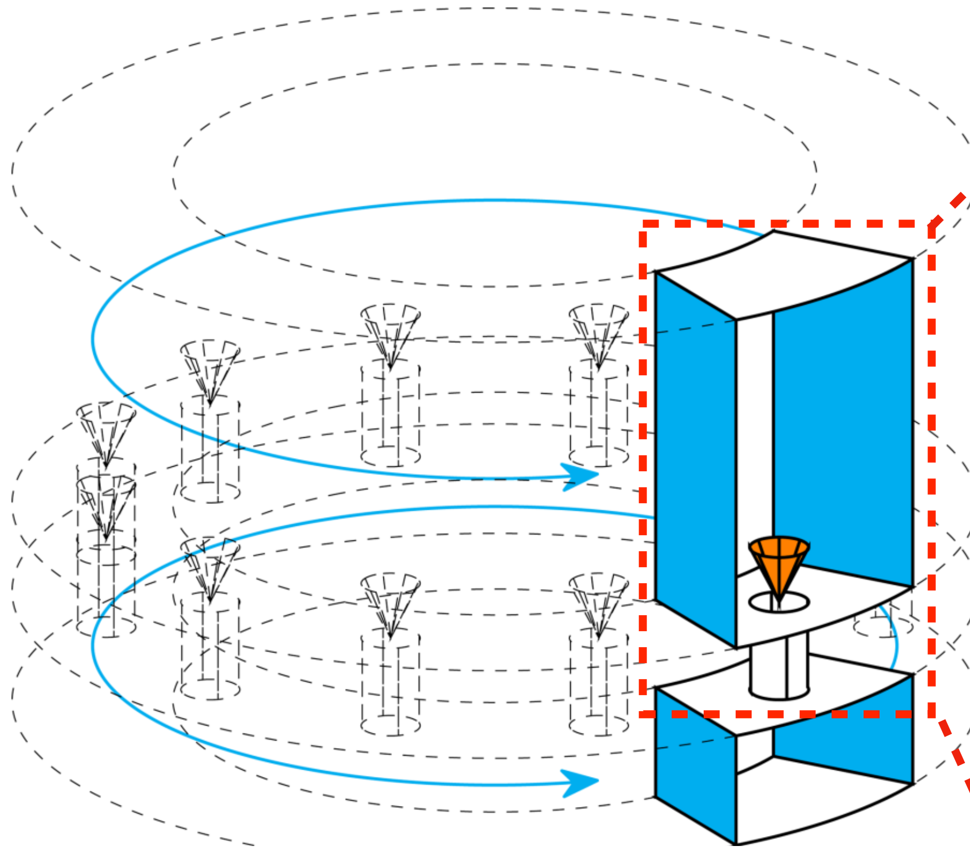

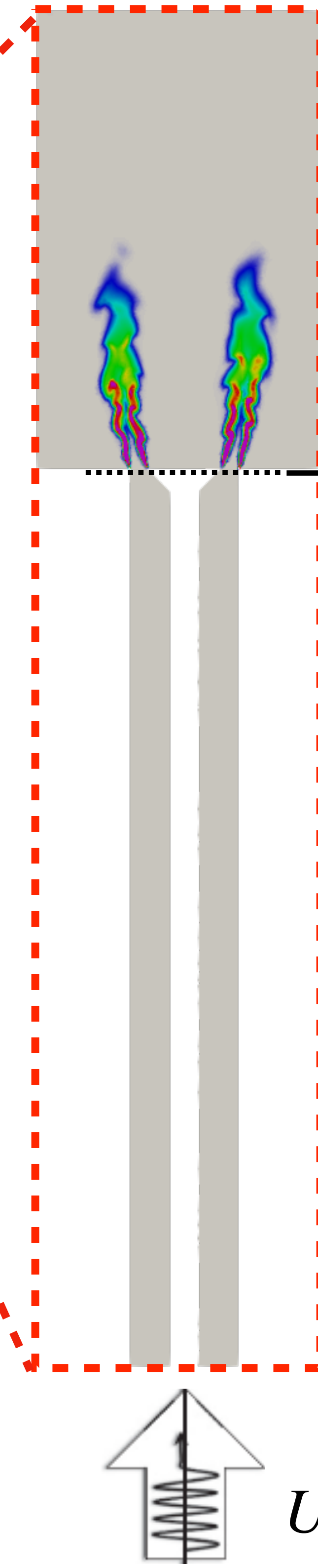

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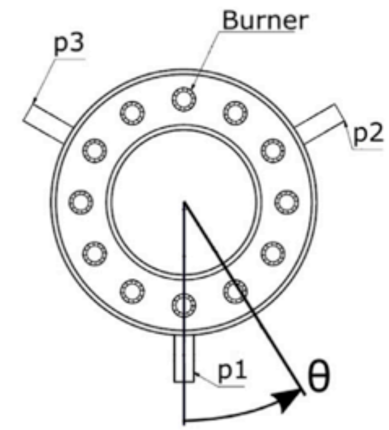

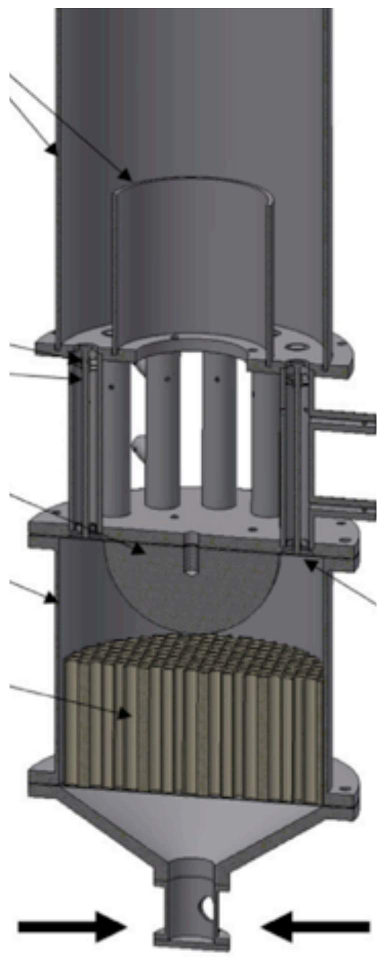

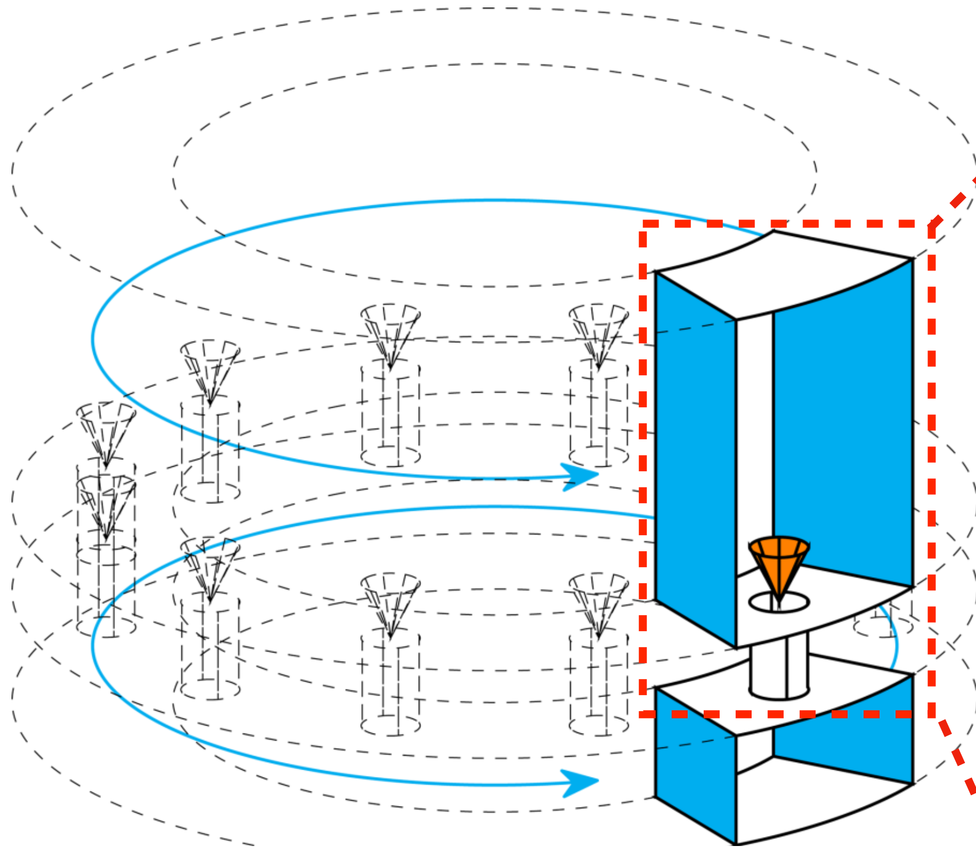

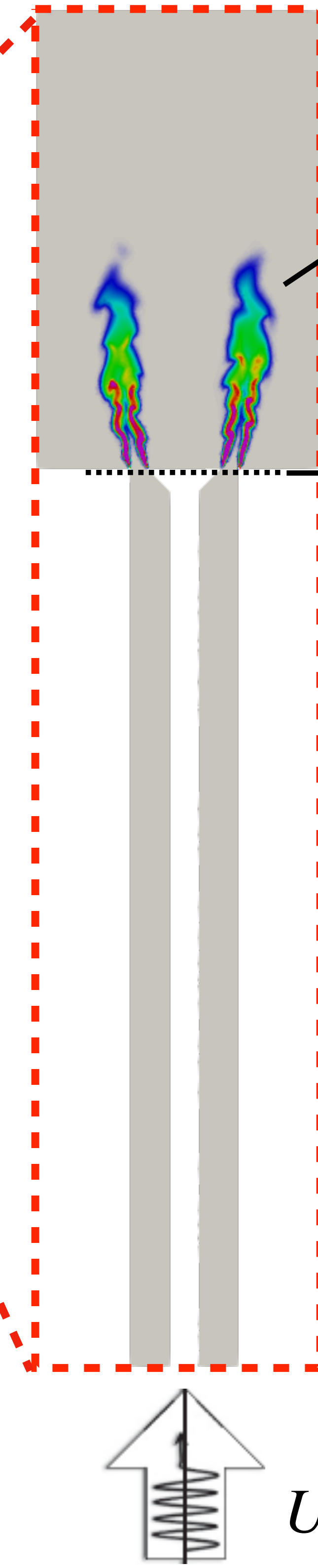

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Single sector – grid sensitivity for temperature and velocity fields

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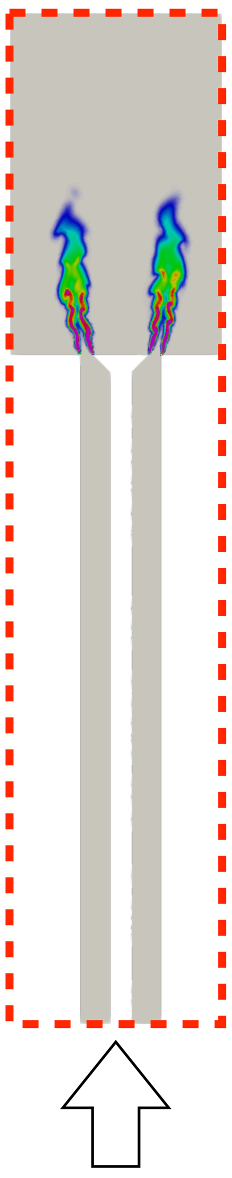

Single sector – grid sensitivity for temperature and velocity fields

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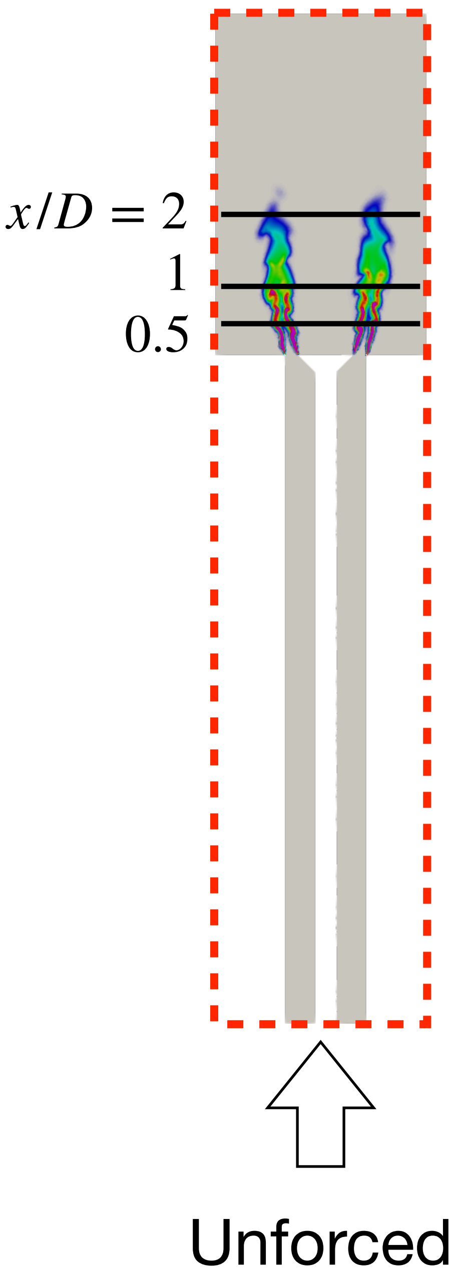

Grid	G1	G2
$\Delta x/\delta_{th}^{0}$	2	1.2
No. Cells	1.4M	2.1M

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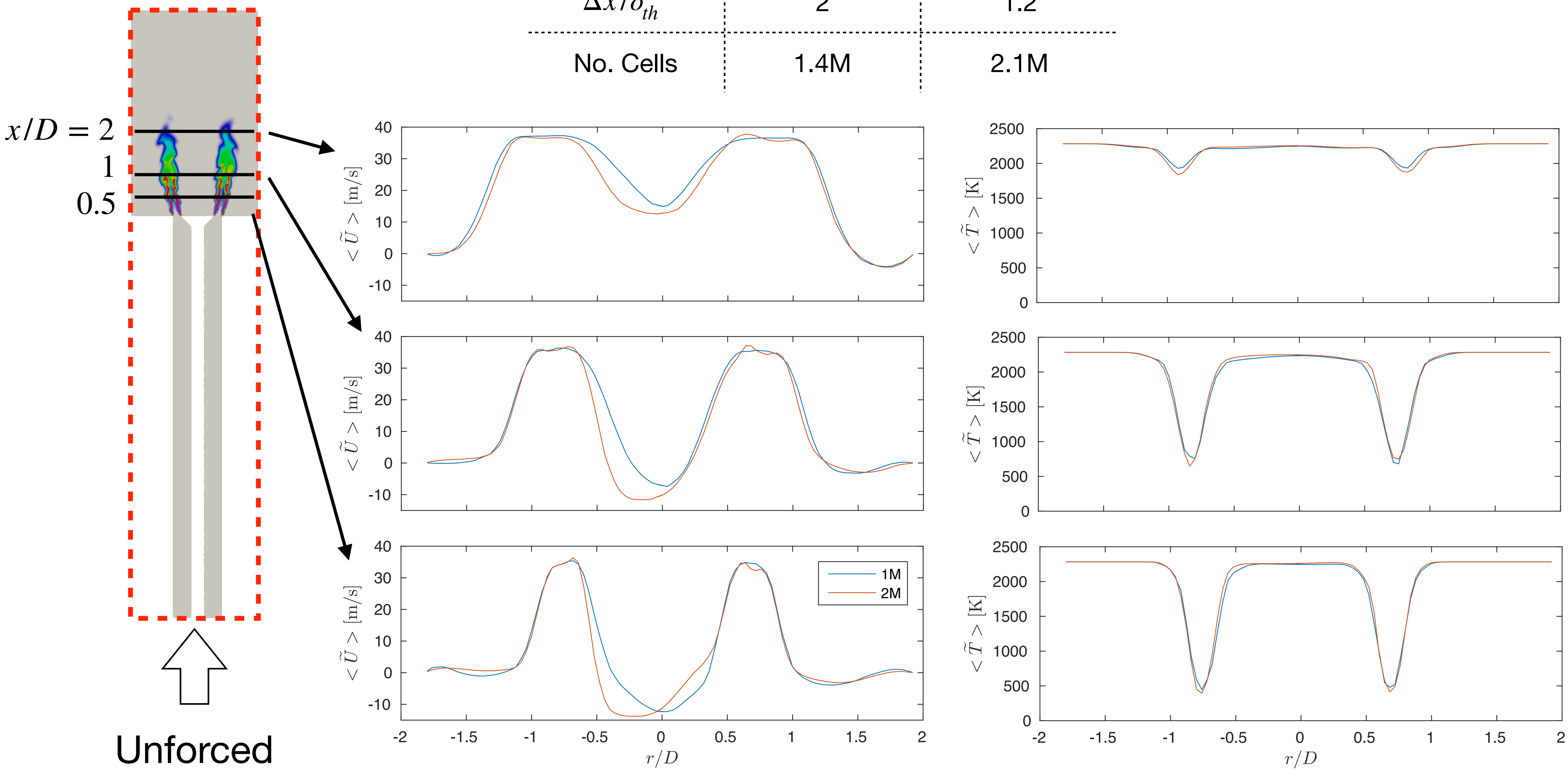
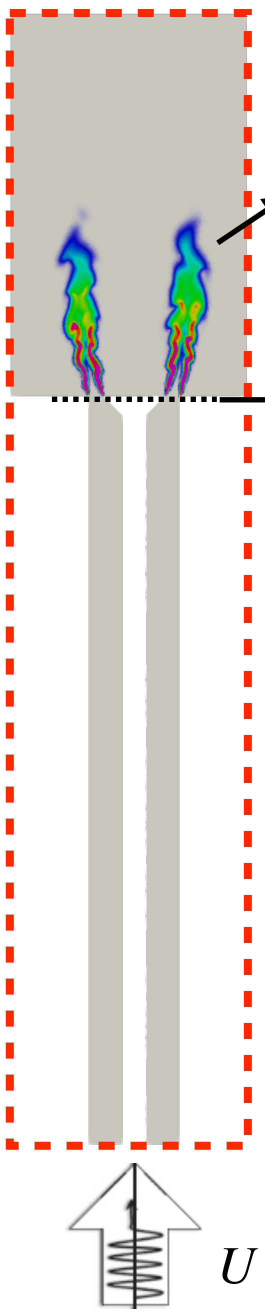


Mean axial velocity

Mean temperature

Single sector – grid sensitivity for flame transfer function



$$\dot{q} = \int_V HRR(\underline{x}, t)\, dV$$

$$\mathrm{FTF} = \frac{\dot{q}'/\overline{\dot{q}}}{U_0'/\overline{U_0}} = G(\omega)\, e^{i\Phi\omega}$$

$$U = A\, U_b\, sin(2\pi f t)$$

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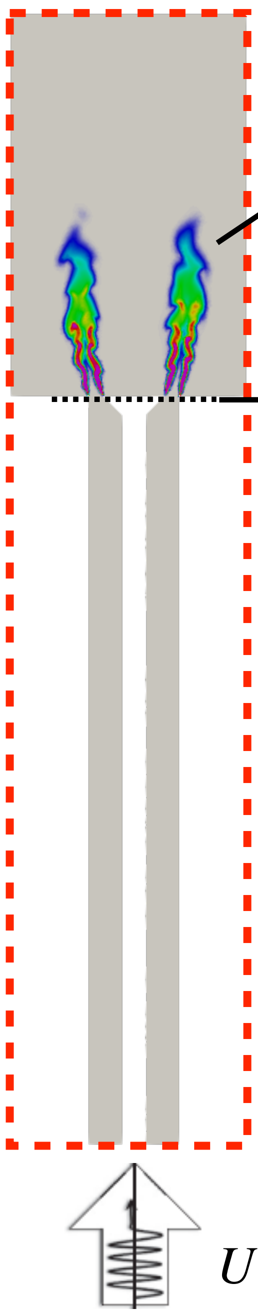

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$$p'/\overline{p} < 1\,\%$$

Two excitation amplitudes are tested: 5% & 10%

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Single sector – grid sensitivity for flame transfer function

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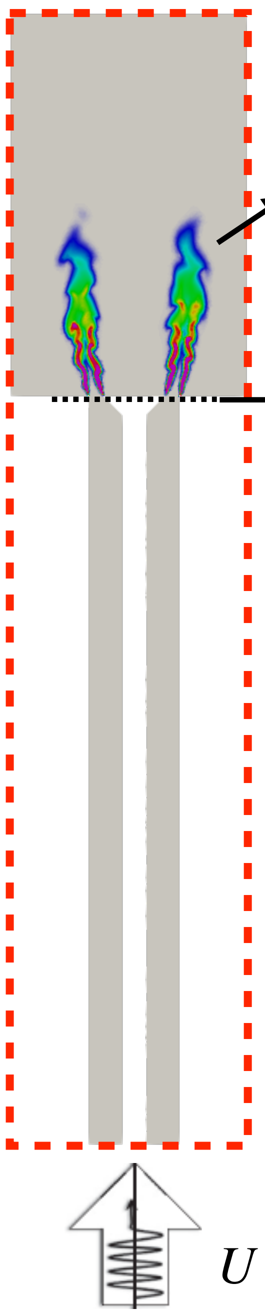

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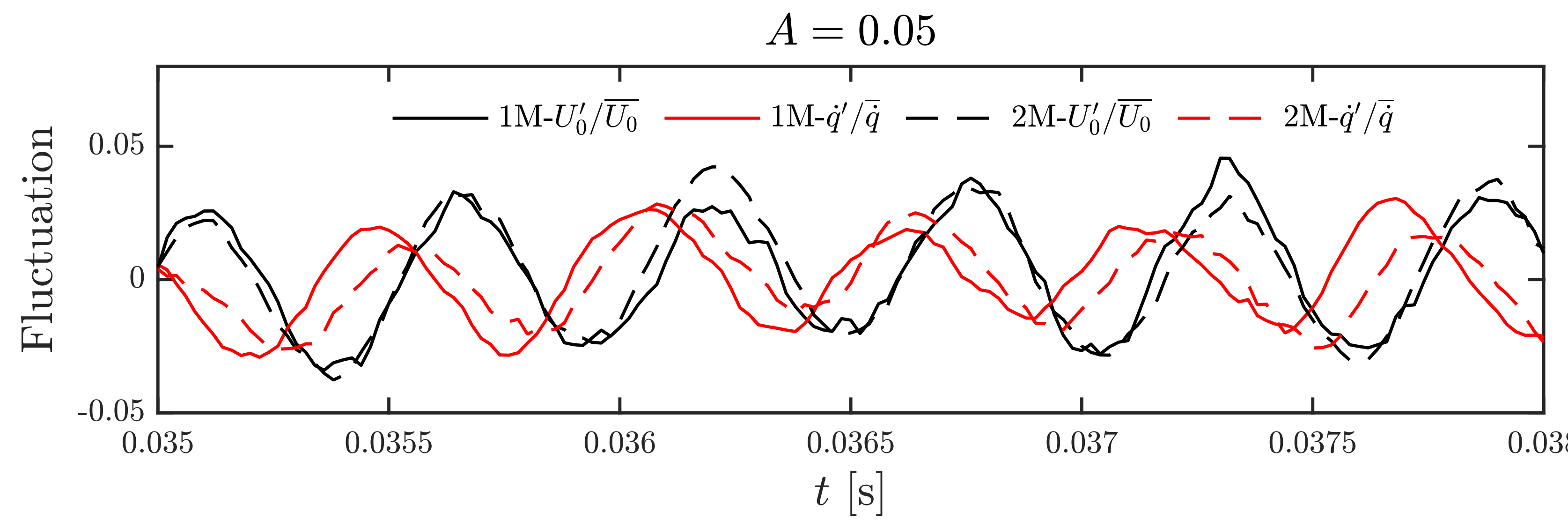

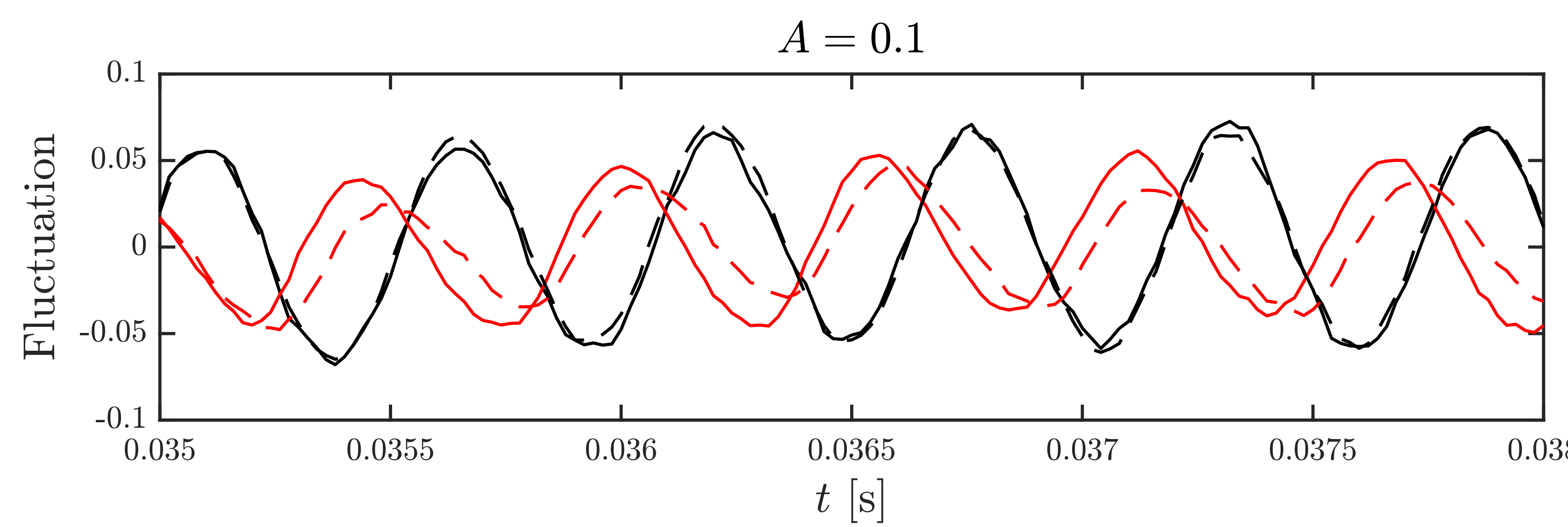

Single sector – grid sensitivity for flame transfer function

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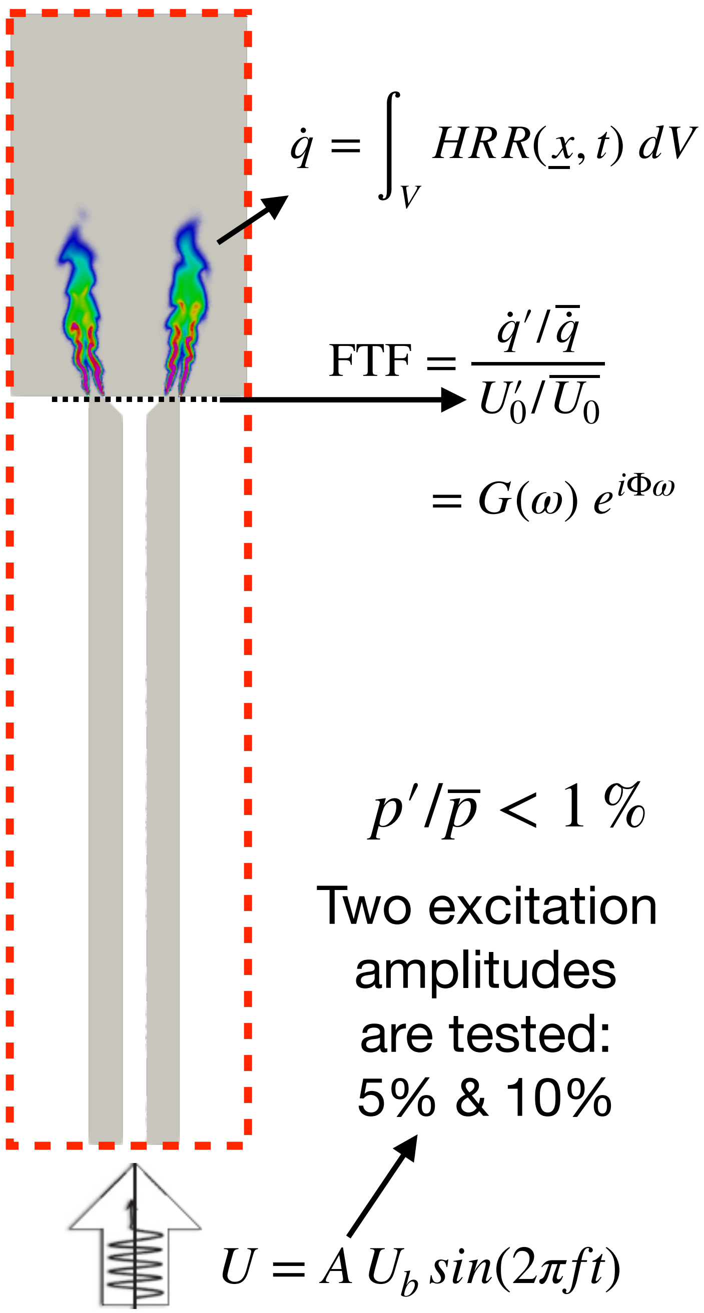

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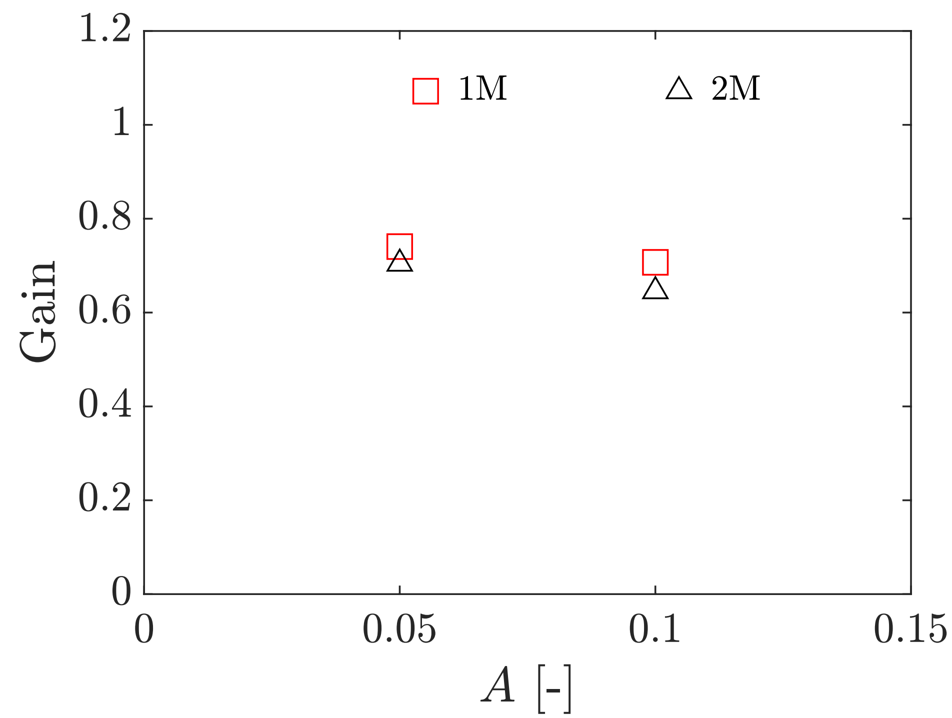

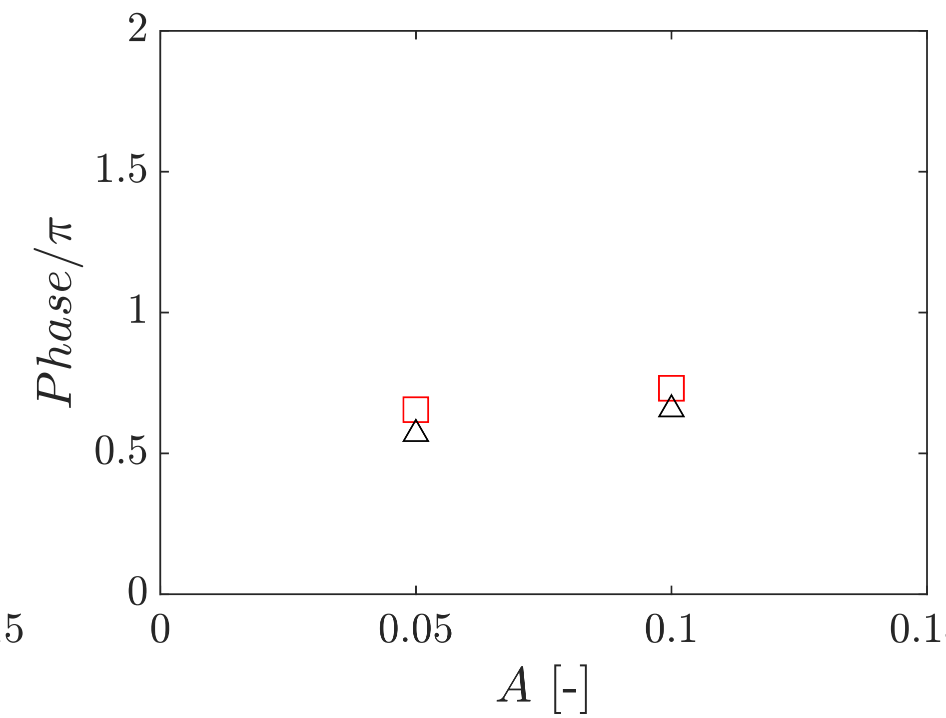

Outline

- Background – thermoacoustic instabilities & azimuthal mode
- LES formulation and combustion modelling
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Computed pressure signals in the plenum tubes

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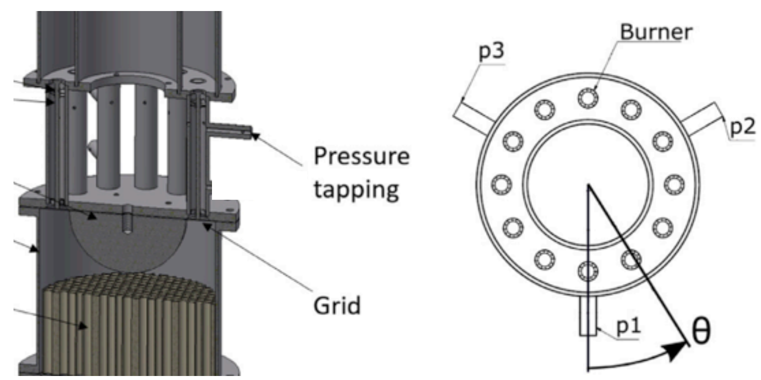

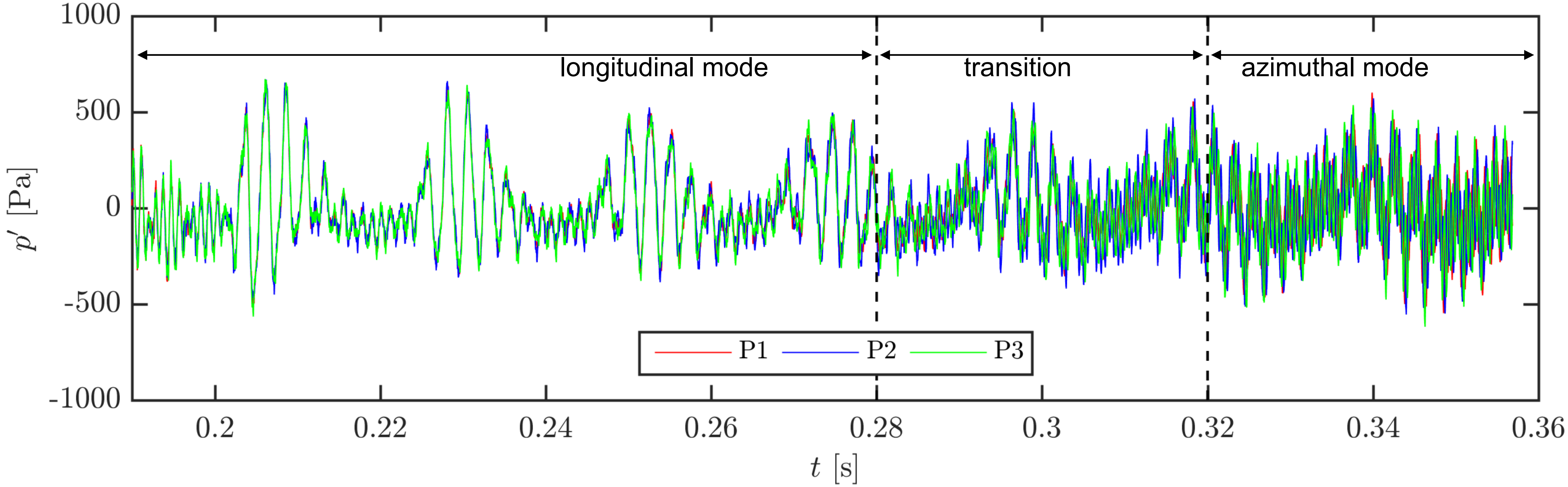

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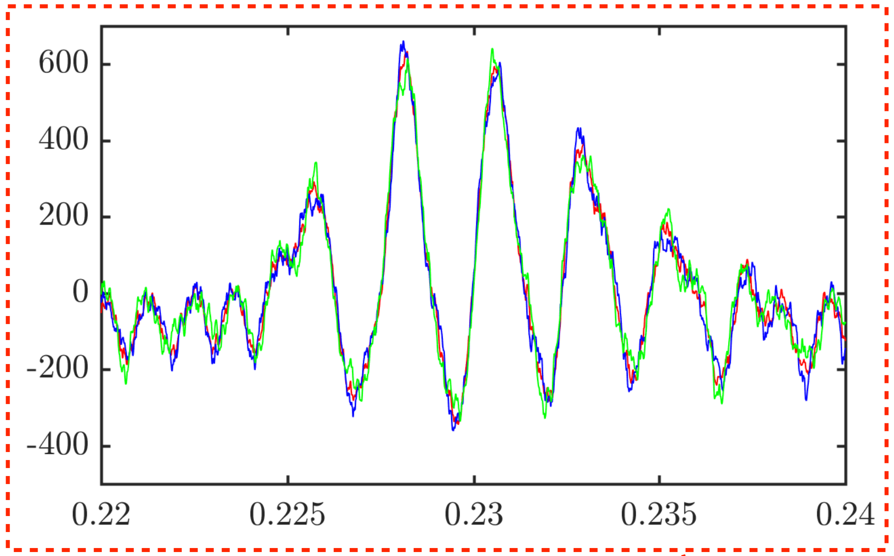

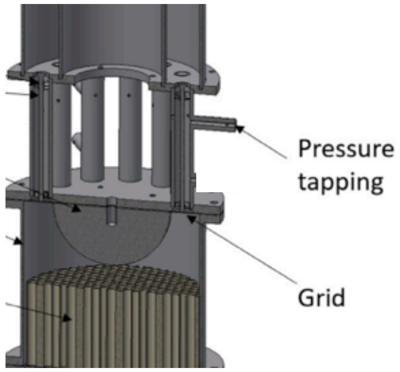

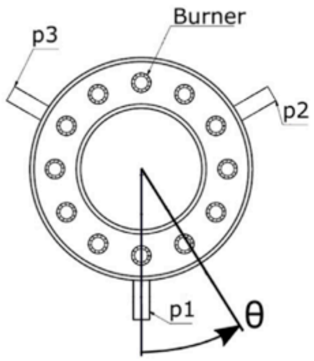

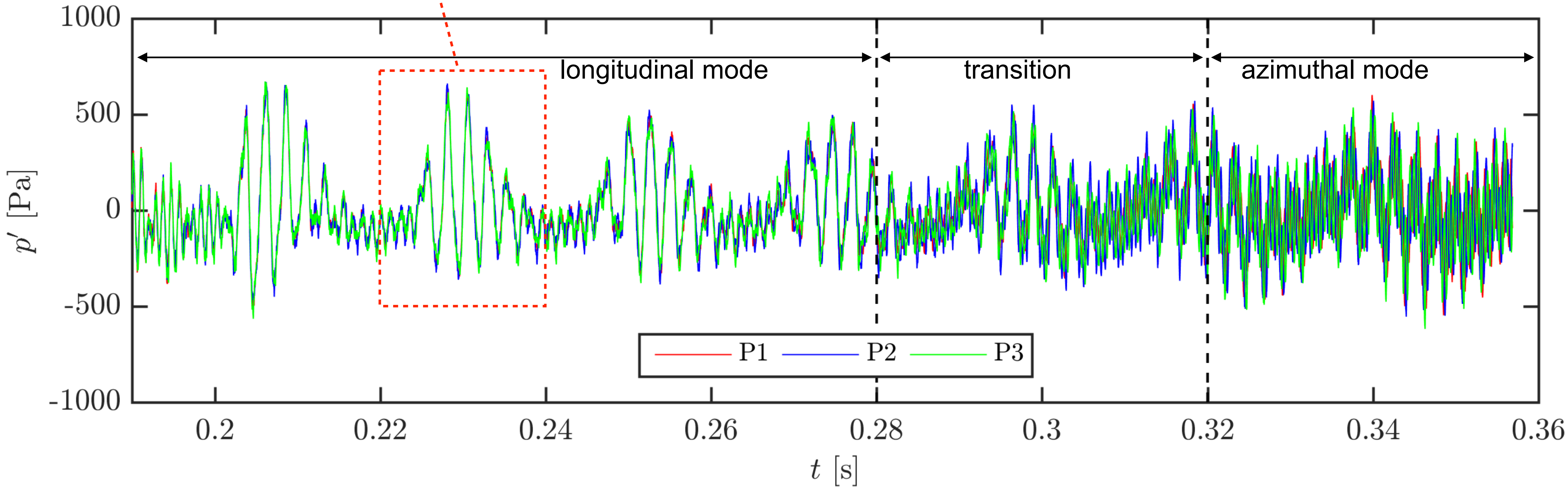

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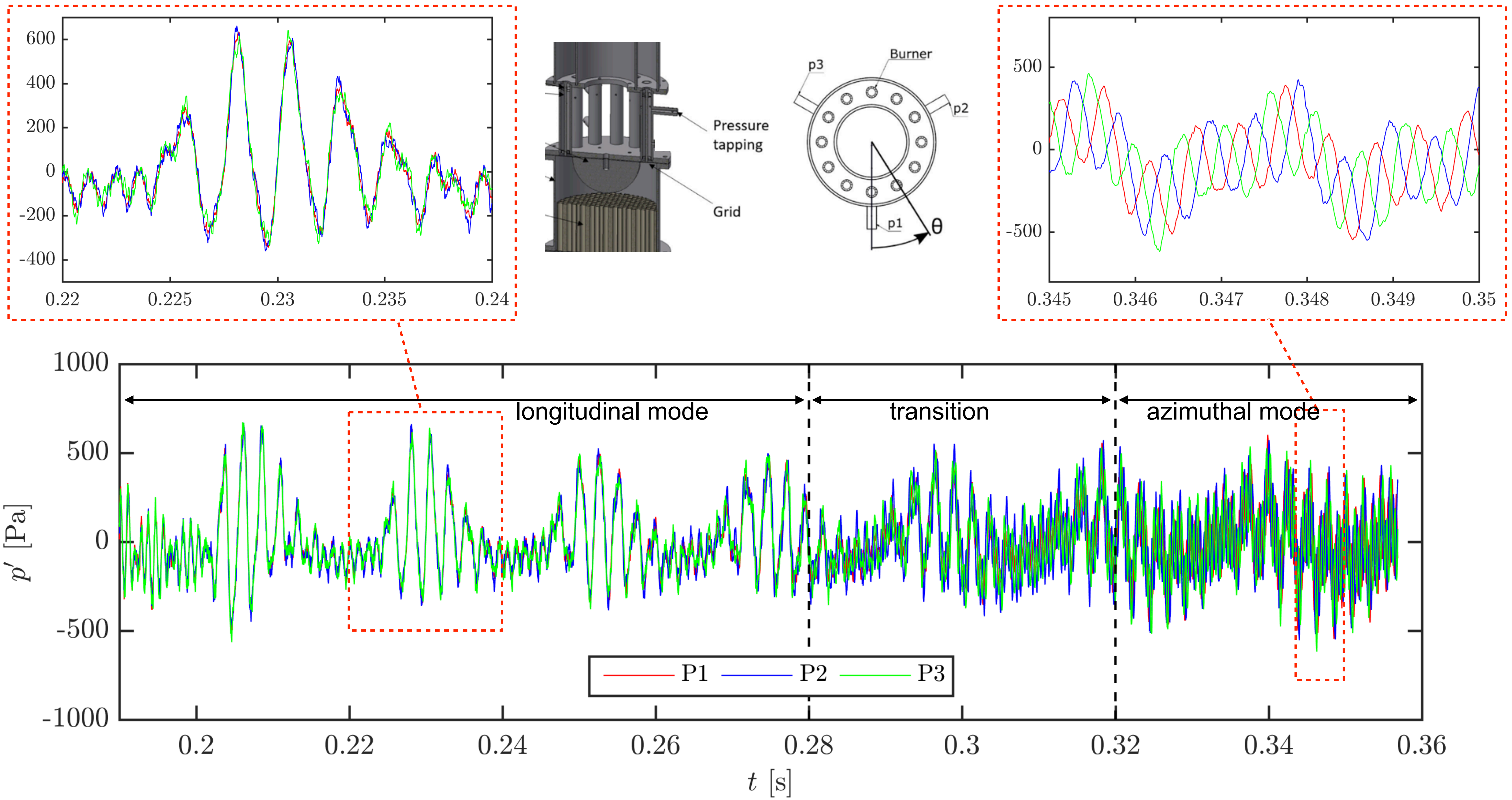

Computed pressure signals in the plenum tubes

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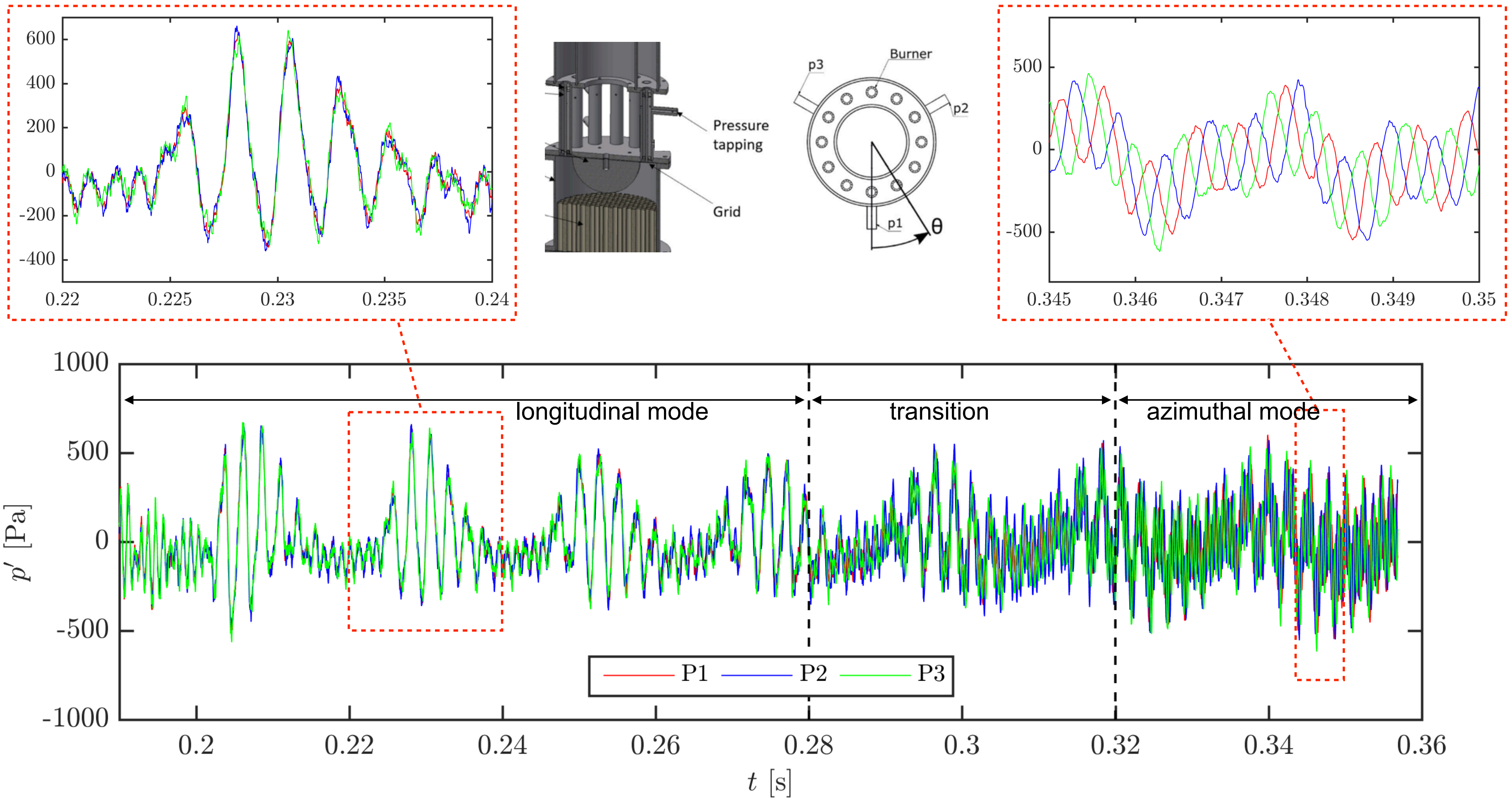

Computational cost: 48 hrs on wall-clock for 0.1s using 1248 cores, 20M cells —> 900 kAUs

Longitudinal mode

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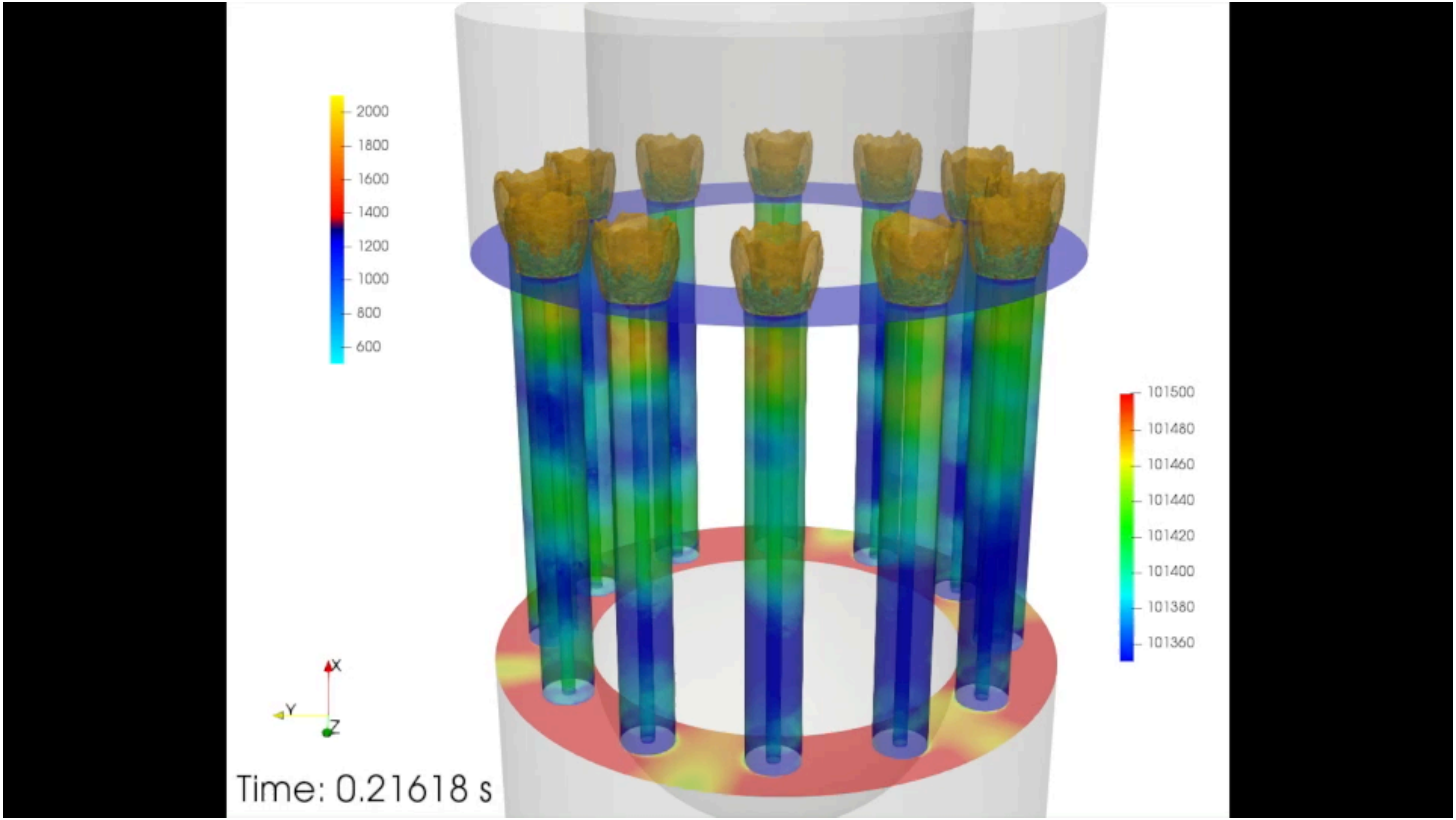
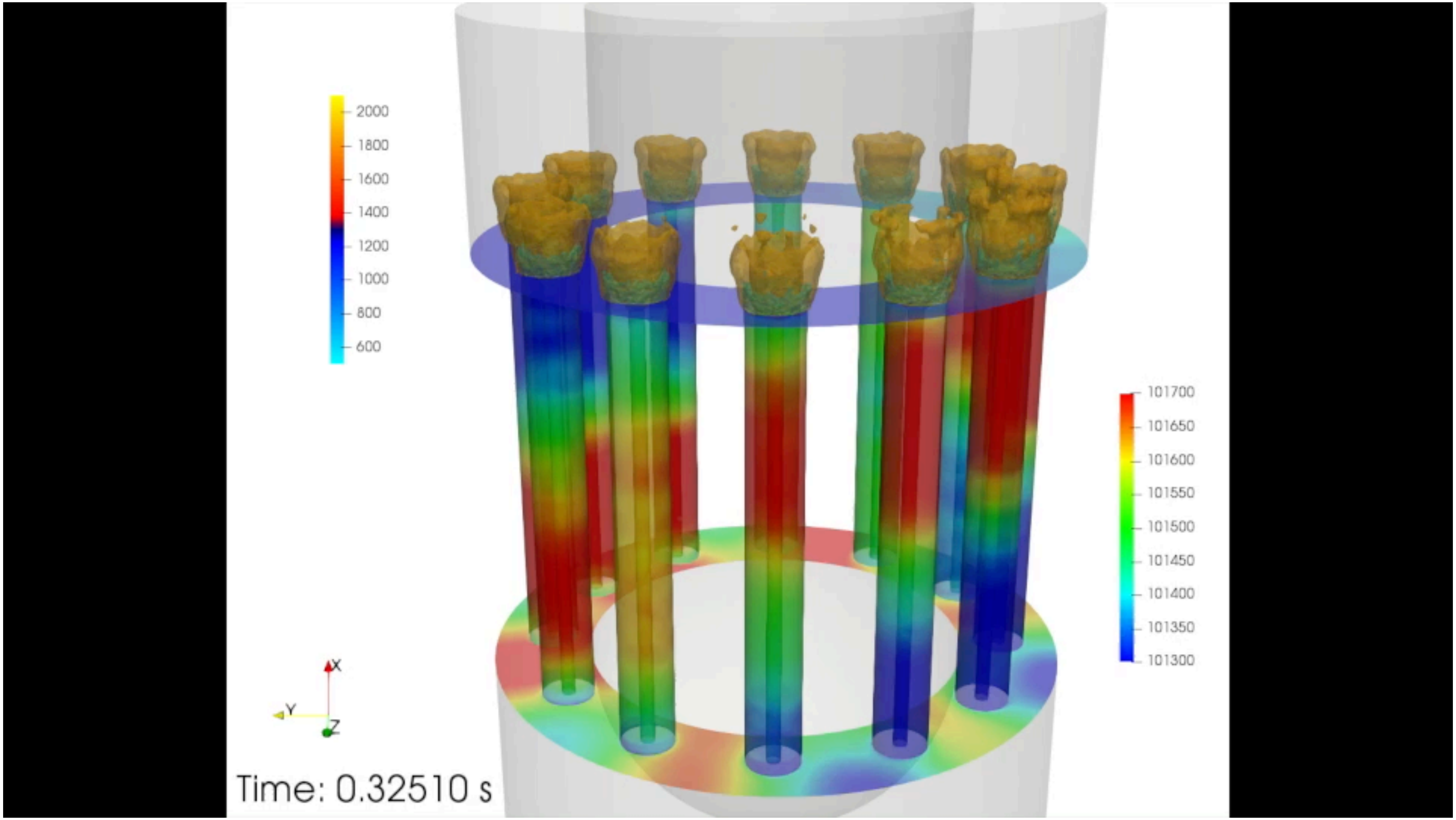
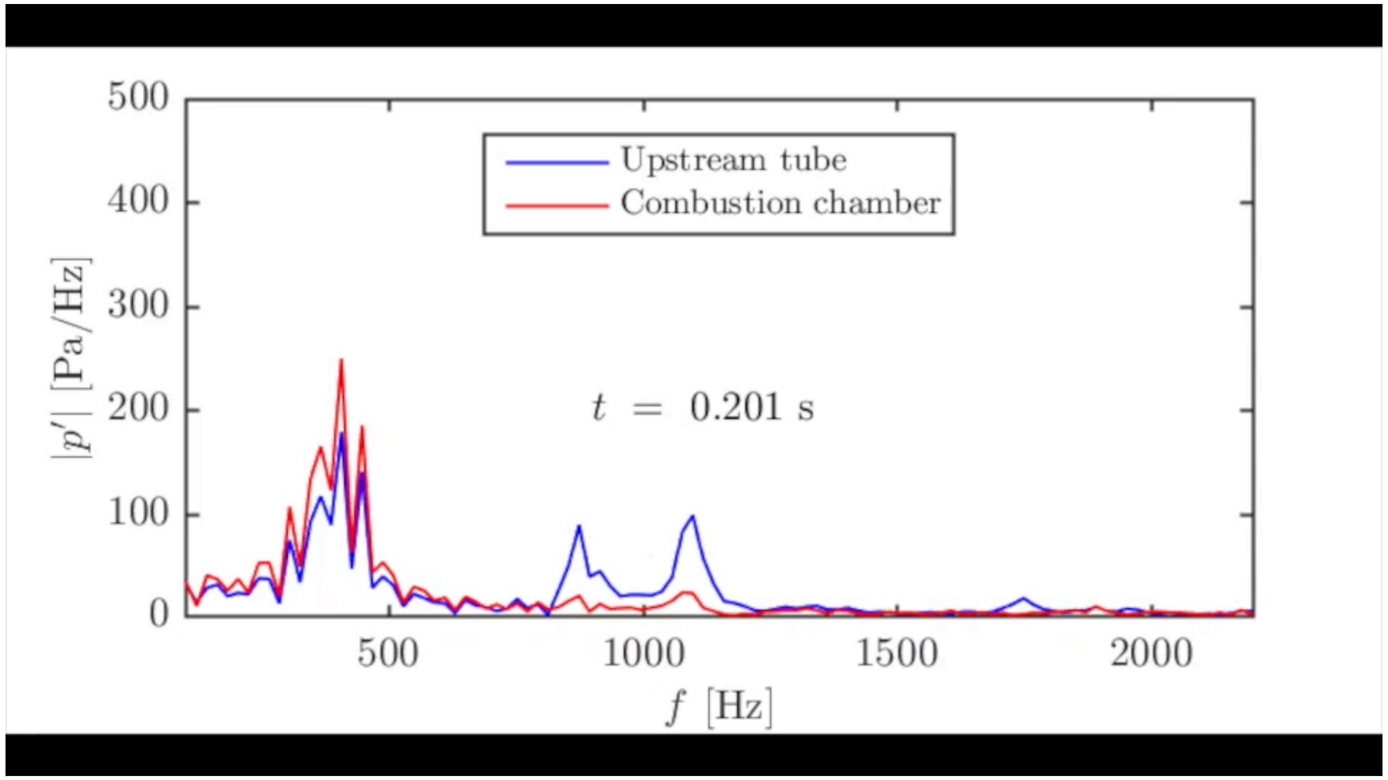
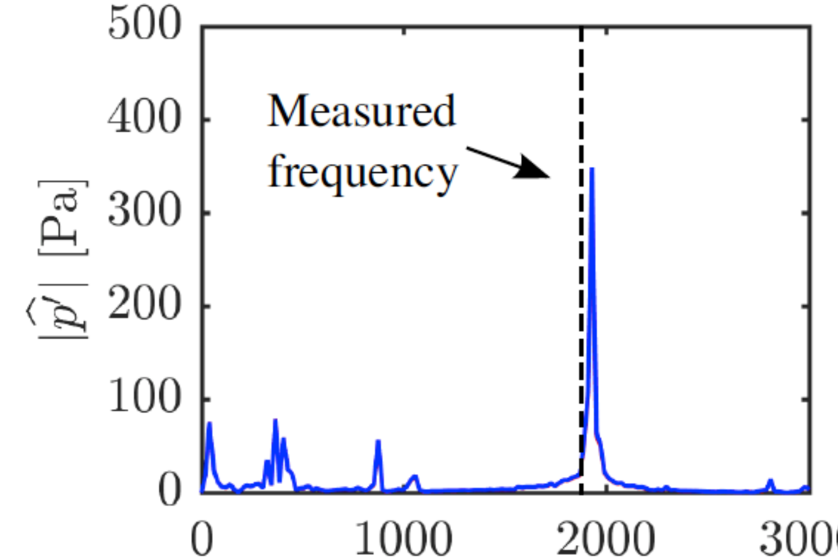


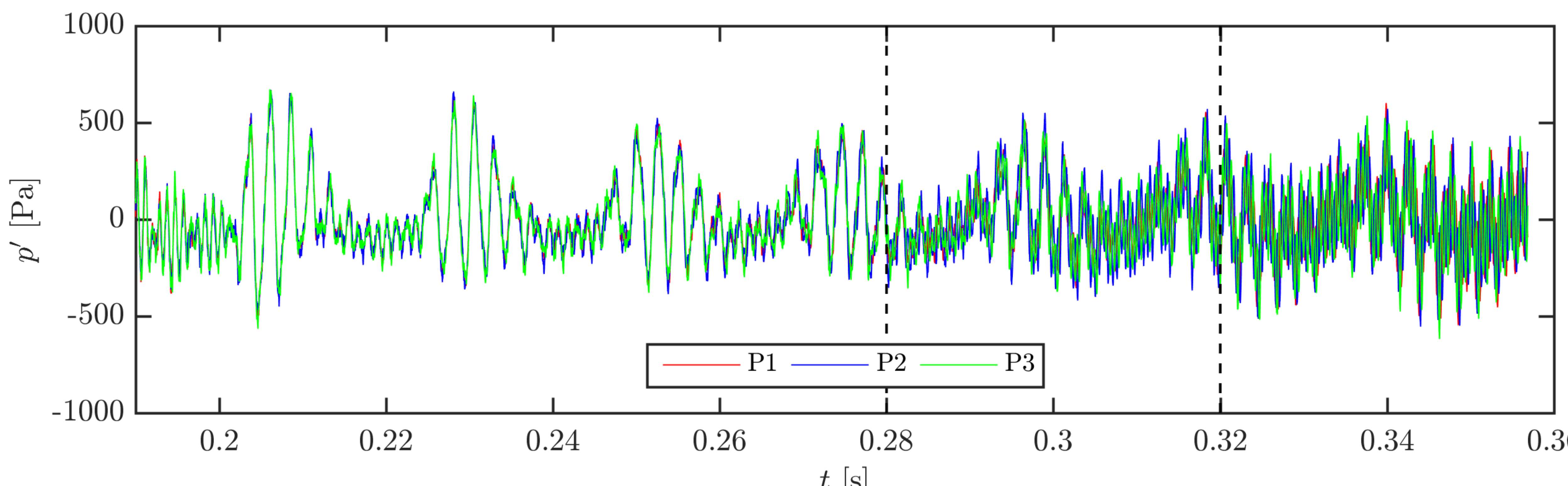
Azimuthal mode



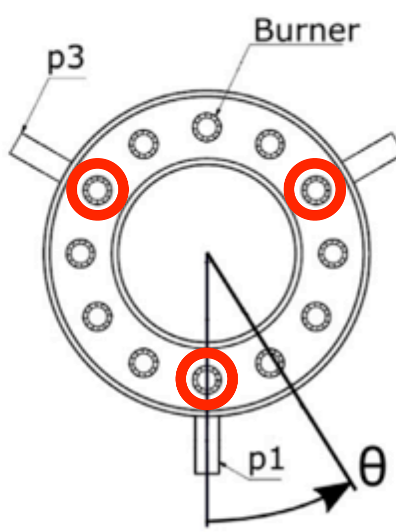
Longitudinal -> Azimuthal mode transition in frequency domain

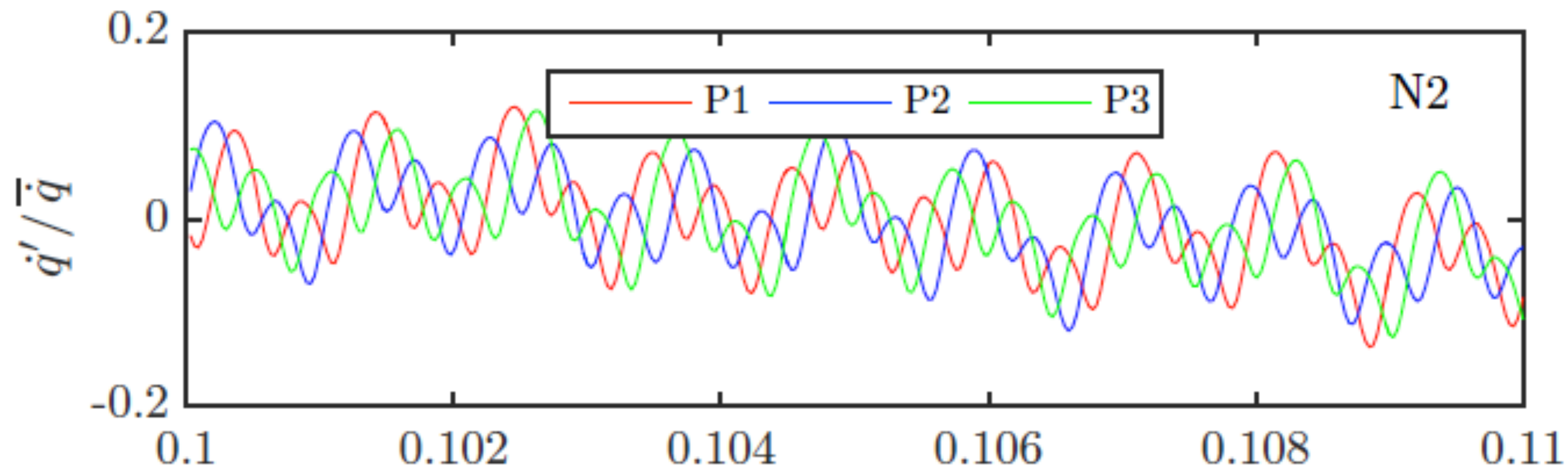


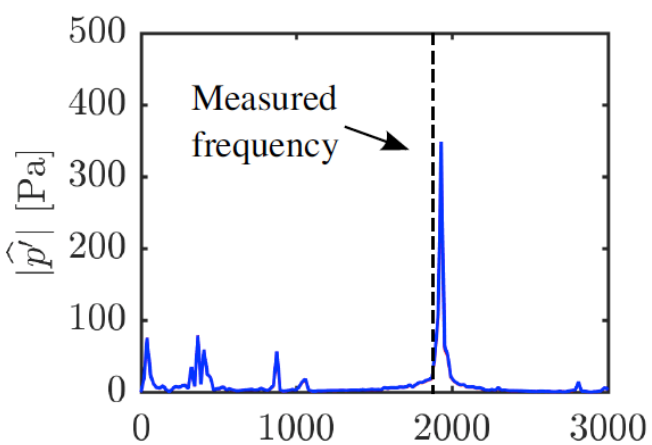


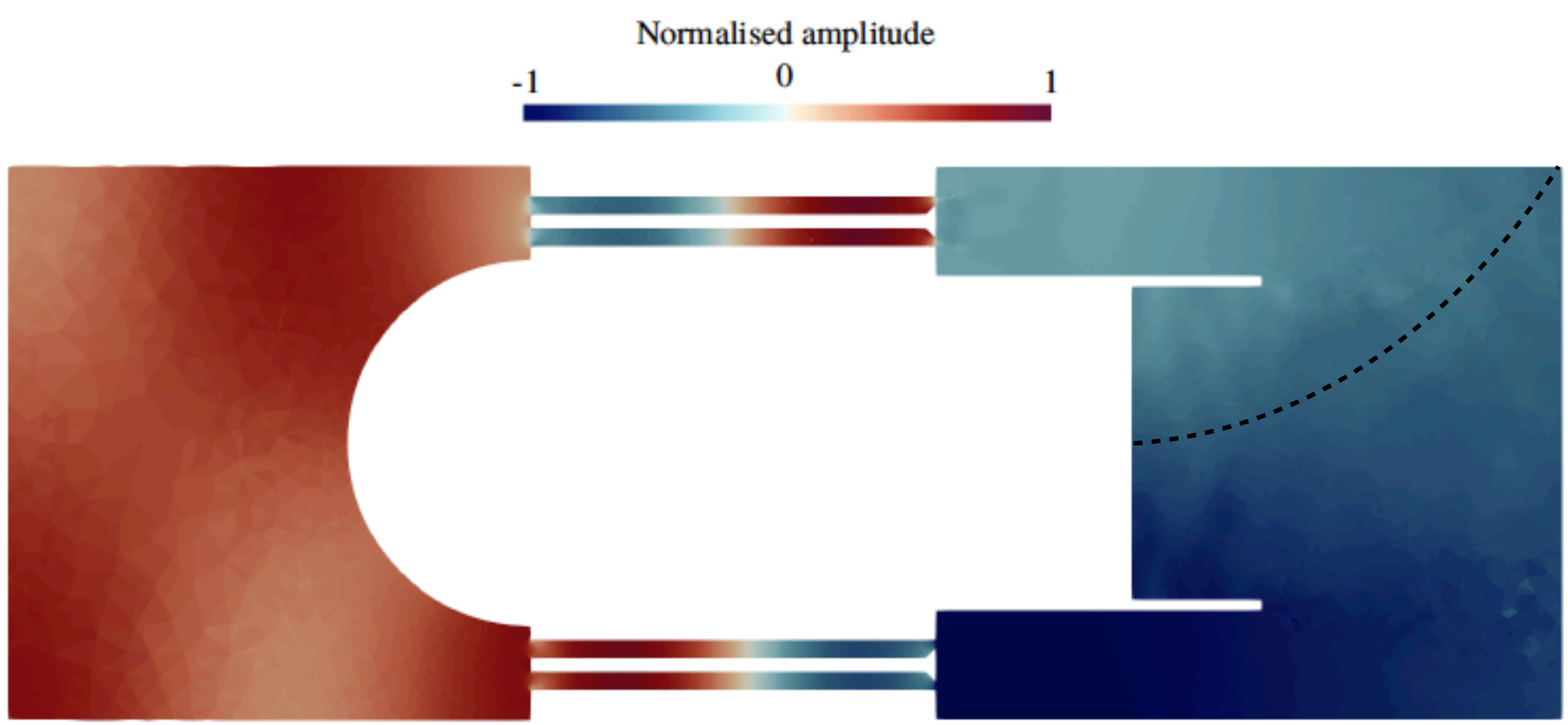


Heat release rate fluctuations and acoustic mode structure









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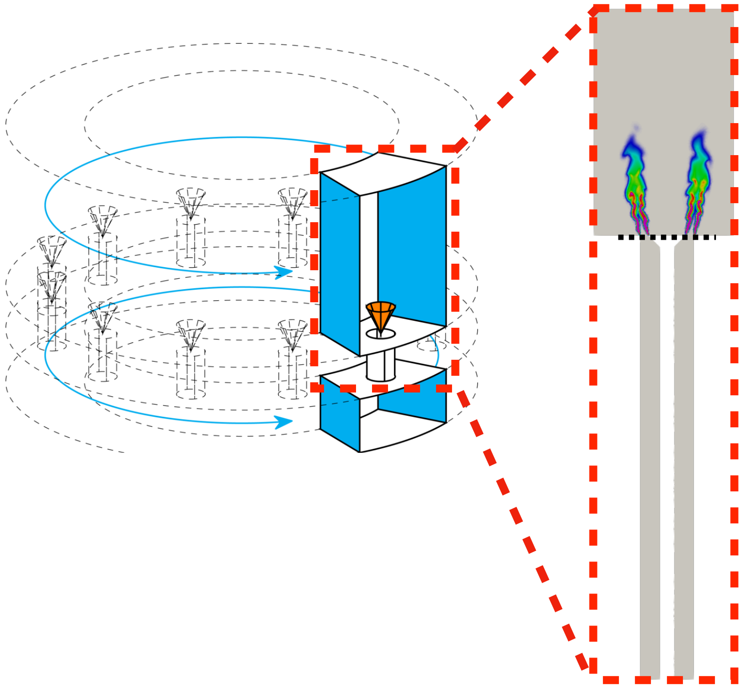
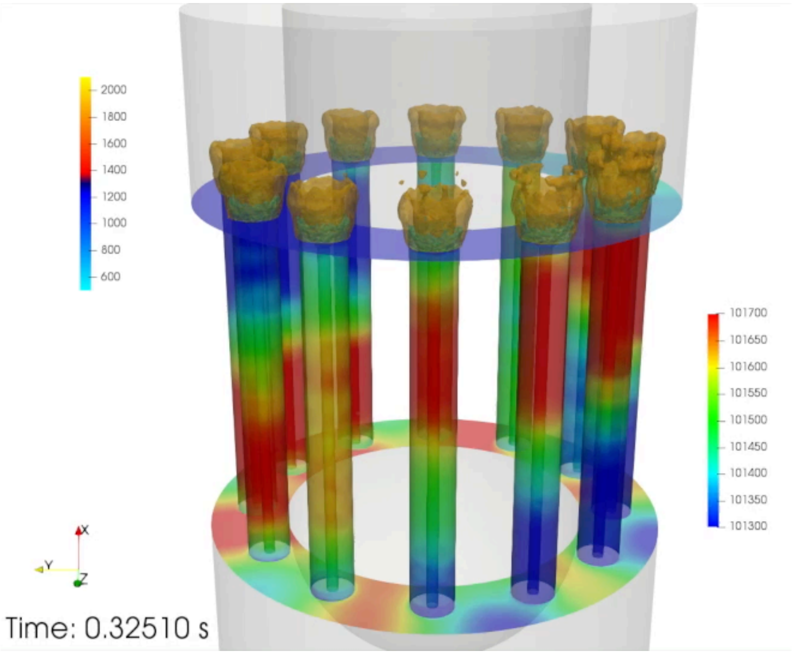
Summary and future work

- Azimuthal instability in a model annular combustor is studied using LES



- LES are performed in two steps:
    - Single sector – grid sensitivity and flame transfer function (external forcing)
    - 12 burner full annular – self-excited oscillations: transition from longitudinal to azimuthal mode



- Projected future works:
    - Analyse the LES data to study mode switching
    - Non-adiabatic simulations

Acknowledgements

UNIVERSITY OF CAMBRIDGE

MITSUBISHI HEAVY INDUSTRIES

UK CTRF UK CONSORTIUM ON TURBULENT REACTING FLOWS 2014 - 2023

UNIVERSITY OF CAMBRIDGE Research Computing Services

EPSRC Engineering and Physical Sciences Research Council

archer

Thank you for listening!

Questions?