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Dispersion of entropy waves advecting through combustion chambers

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UKCTRF Annual Meeting
15th September 2016, Durham University, Durham

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Outline

1. Motivation
    — Entropy wave and entropy noise

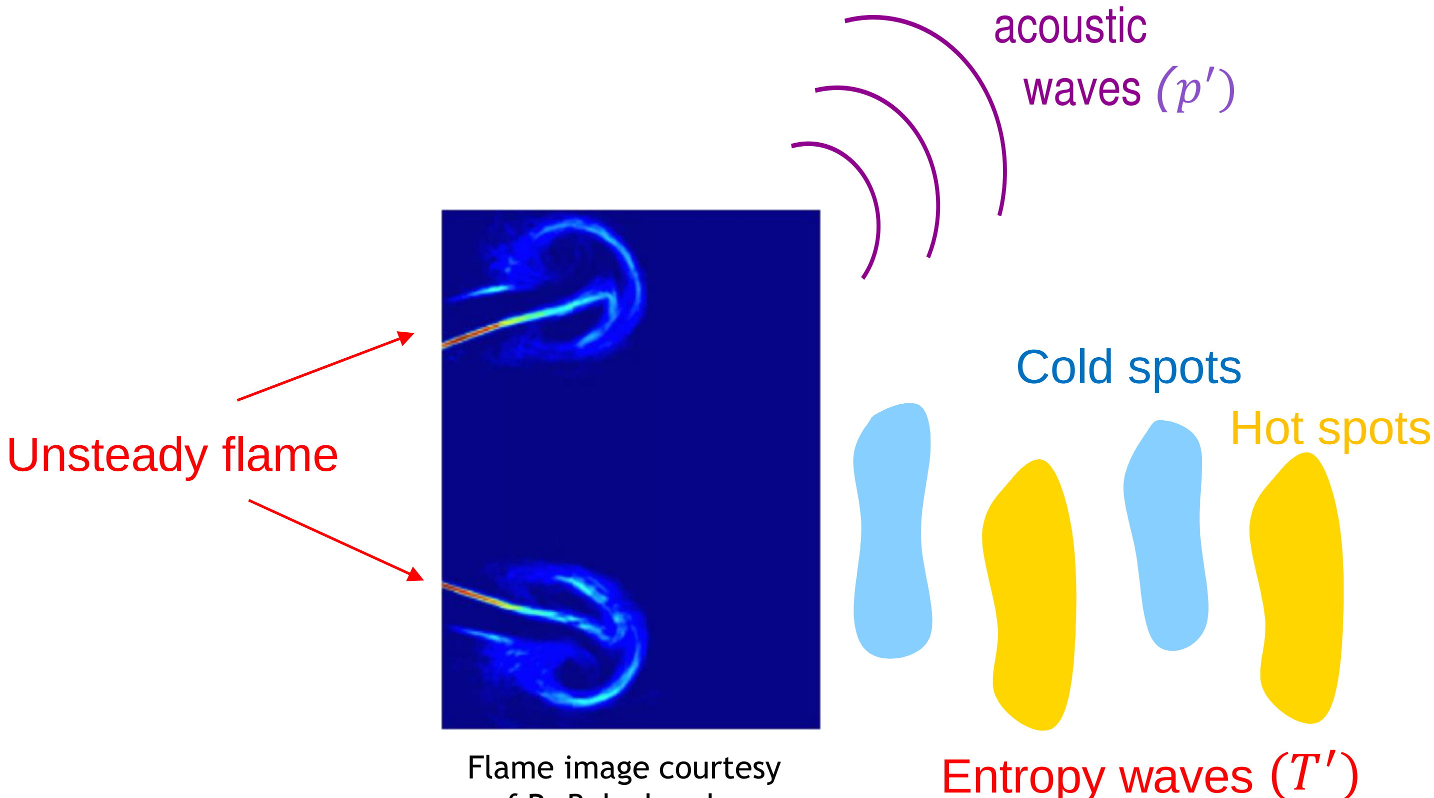
2. Methodology
    — Passive scalar entropy transport + flowfield LES

3. Result
    — Entropy wave advection in turbulent reacting flows

4. Conclusion & Future Work

1.1. Generation of entropy waves

Entropy waves are temperature fluctuations (T') generated by unsteady combustion in a gas turbine combustor, also known as "hot/cold spots".

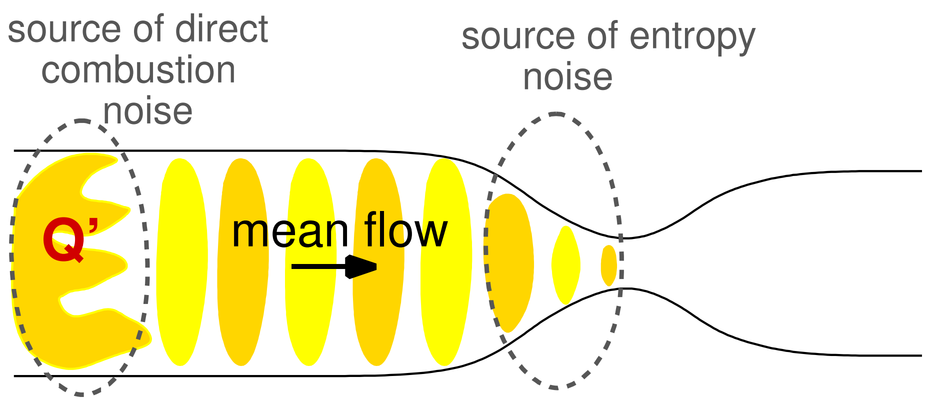


Flame image courtesy
of R. Balachandran

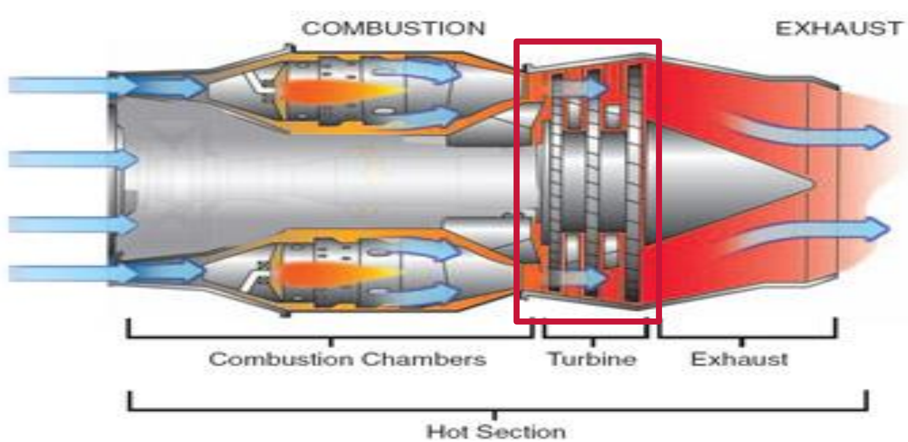
1.2. Entropy wave advection and release of entropy noise

The generated entropy waves are swept downstream by the mean flow, advecting towards the chamber exit, accelerating through the nozzle or turbine blades and releasing "entropy noise*" (also known as "indirect combustion noise").

Entropy wave acceleration in a supersonic nozzle



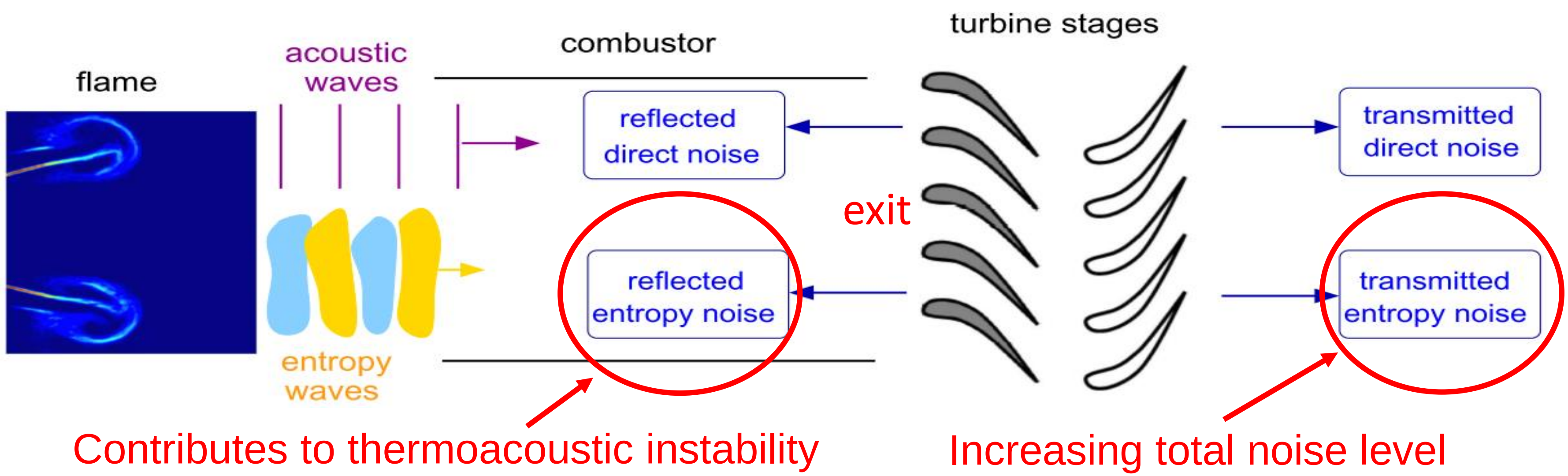
Entropy wave acceleration in turbine stages



* Marble & Candel. 1977

1.3. Impact of entropy noise on gas turbine performance

- The released entropy noise are transmitted further downstream, increasing the total noise level from gas turbine, and also reflected upstream and interact with the flame, contributing to the damaging thermoacoustic instabilities.
- The strength of entropy noise is proportional to the entropy wave amplitude at the combustor exit, which is an order of magnitude larger* than the direct acoustic noise generated by the flame.

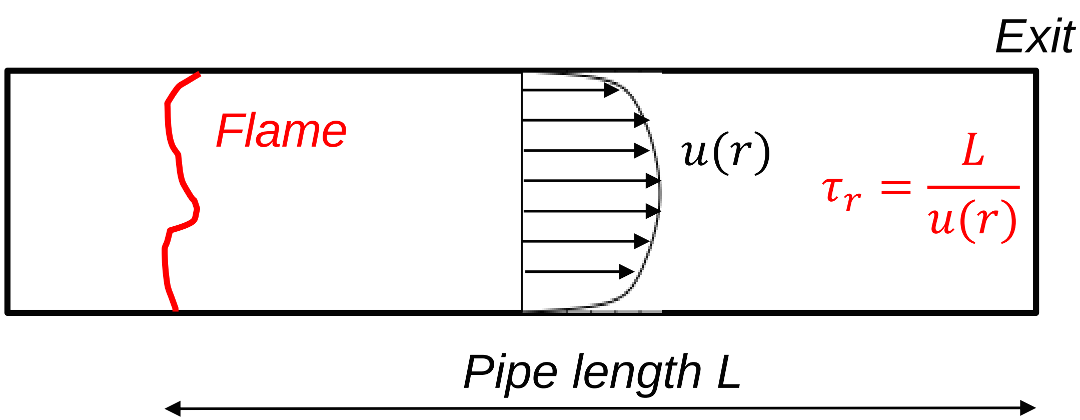


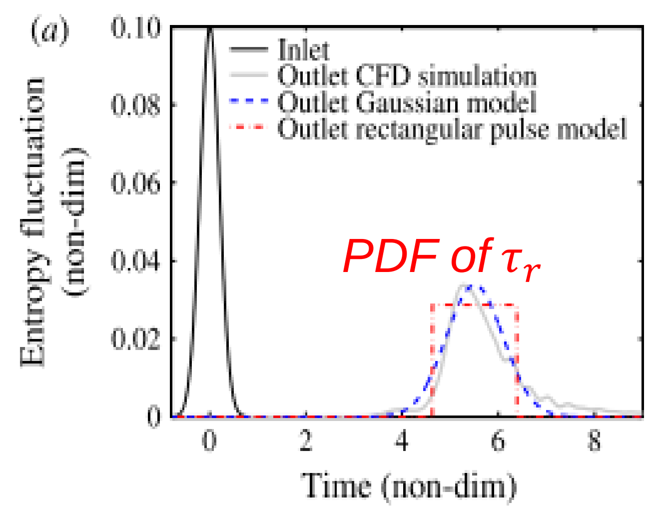
Schematics of flow perturbations in a gas turbine combustor

* *Leyko et al. 2009*

1.4. Entropy wave dispersion in fully-developed pipe flow

- Traditional low-order models* for entropy noise neglect entropy wave advection and assume uniform amplitude at exit plane, but entropy wave advection can be dispersive and attenuate the exiting entropy amplitude and affect the generated entropy noise.
- E.g. in a fully-developed pipe flow**, the PDF of the residence time τ_r from flame to pipe exit follows a Gaussian distribution, with highly-decreased entropy wave amplitude at pipe exit. This is due to the dispersion effect of the non-uniform velocity profile $u(r)$.





* Marble & Candel. 1977

** Morgans et al, JFM, 2013

1.5. Aim of this work

- Different from a fully-developed pipe flow, the turbulent reacting flow in a gas turbine combustor is much more complex (e.g. vortex shedding, flow swirling), which is expected to have higher dispersion effects on entropy wave advection.
- In this work, the entropy wave advection in a full-scale industrial combustor is studied, operated under lean premixed condition at 3 bar pressure, with cold gaseous methane (CH_4) premixed with hot preheated air.

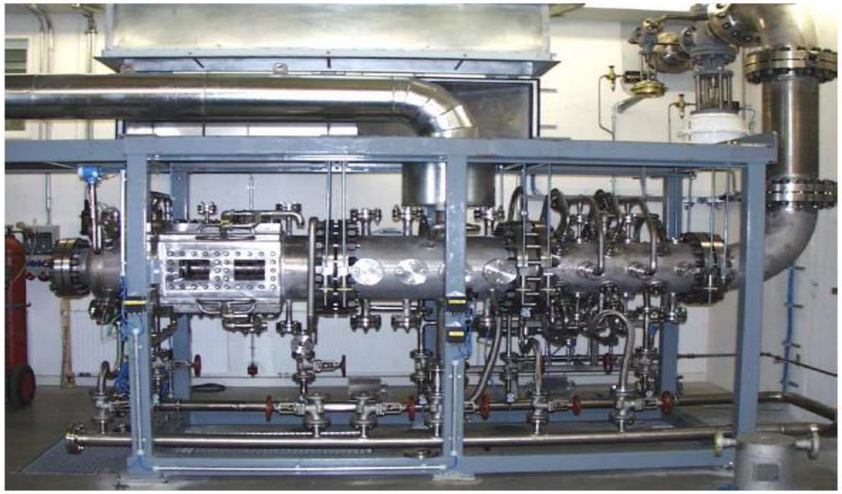
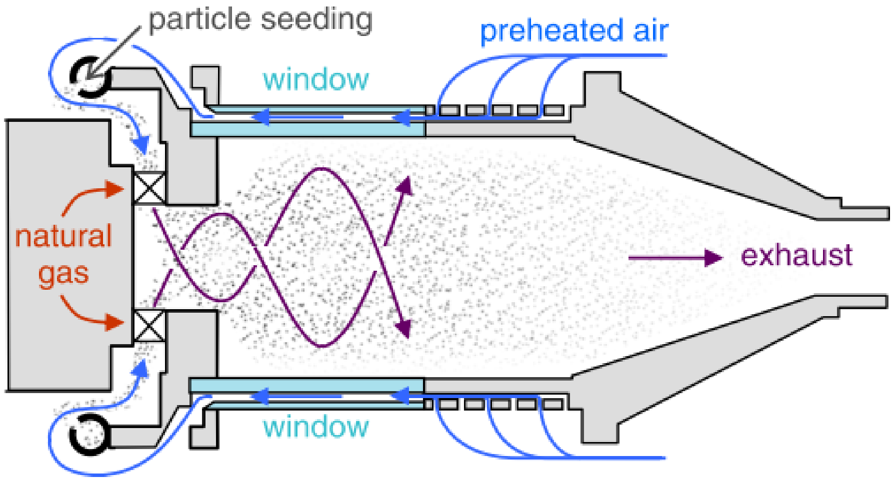


Photo of the test combustor, taken from a Siemens SGT-100 gas turbine (Stopper 2013)



Sketch of the combustion chamber, Indicating flow swirling and CH_4/air premixing

2.1. Entropy wave equation

The governing equation for entropy wave within a fluid flow is:

$$\underbrace{\boxed{\rho T \frac{Ds}{Dt}}}_{\text{Entropy advection}} = \underbrace{\boxed{q}}_{\text{Heat addition}} + \underbrace{\boxed{\nabla \cdot (k \nabla T)}}_{\text{Thermal gradients}} + \underbrace{\boxed{\tau_{ij} \frac{\partial u_i}{\partial x_j}}}_{\text{Frictional heating}}$$

The non-dimensional version of above equation is then obtained:

$$\breve{T}\left(\frac{\partial \breve{s}}{\partial \breve{t}} + \breve{u}_i \frac{\partial \breve{s}}{\partial \breve{x}_i}\right) = \frac{1}{Re\, Pr} \frac{\partial^2 \breve{T}}{\partial \breve{x}_i \partial \breve{x}_i} + \frac{(\gamma - 1) M_{bulk}^2}{Re} \breve{\tau}_{ij} \frac{\partial \breve{u}_i}{\partial \breve{x}_j}$$

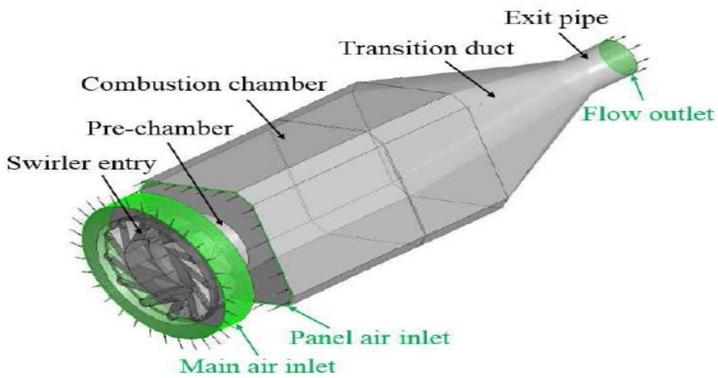
For a turbulent reacting flow with low bulk *Ma* number and large bulk *Re* number ,

the entropy wave equation simplifies into a purely entropy advection equation:

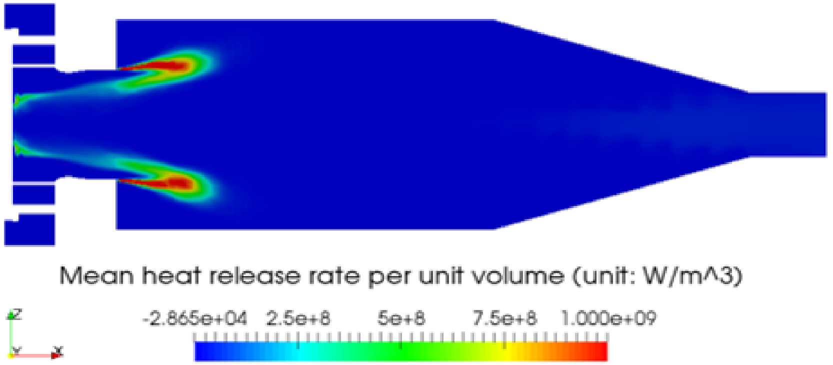
$$\left(\frac{\partial \breve{s}}{\partial \breve{t}} + \breve{u}_i \frac{\partial \breve{s}}{\partial \breve{x}_i}\right) = 0$$

2.2. Large eddy simulation (LES) of turbulent reacting flow

The open-source low-Mach LES code OpenFOAM is used to simulate turbulent reacting flows in this combustor.



The computational domain* contains 8.5m structured mesh cells with flame refined.



Contour of mean heat release rate per unit volume on symmetry plane Y=0

Numerical settings

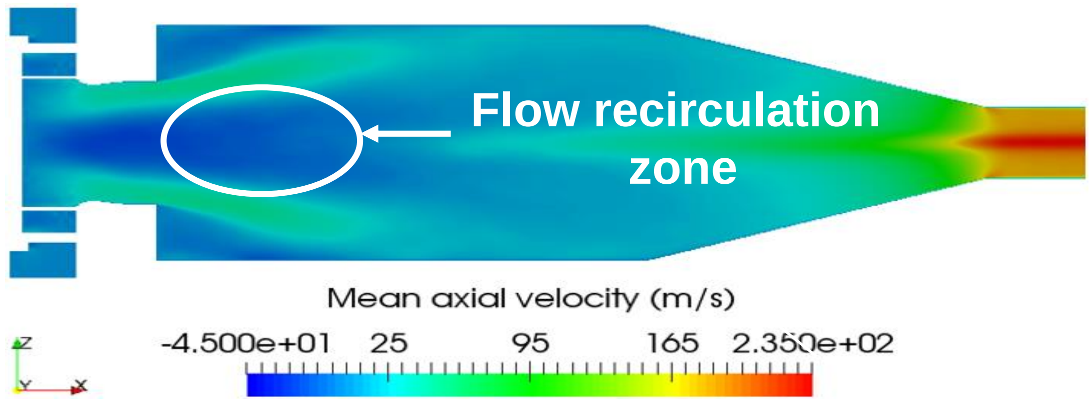
- 1st-order (Euler) time discretisation + 2nd-order (Gaussian) spatial discretisation;
- Smagorinsky model for sub-grid scale turbulent modelling, and Partially-Stirred Reactor (PaSR) model for turbulence-chemistry interaction;
- 4-step reduced mechanism for methane/air reaction, involving 7 intermediate species (incl. CH_4, CO, CO_2, H_2, H_2O, O_2, N_2).

* G. Bulat. 2012

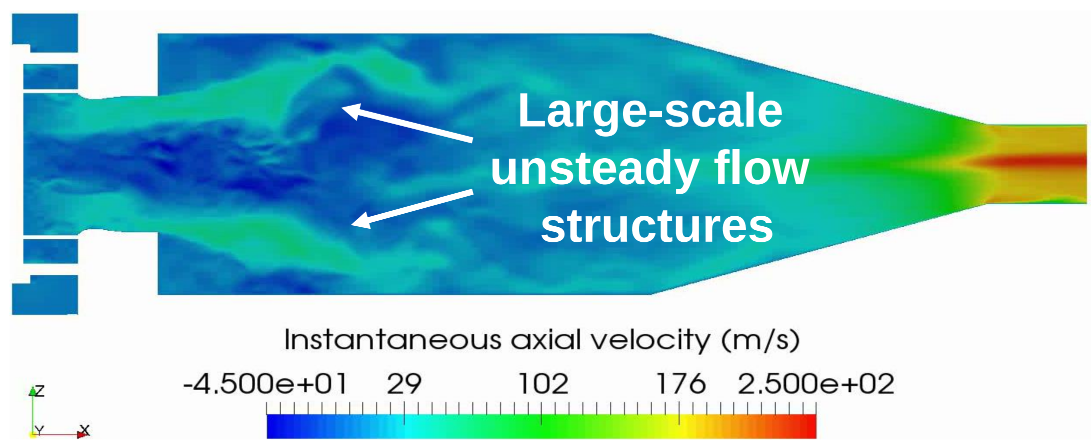
2.2. Large eddy simulation (LES) of turbulent reacting flow

The mean and an instantaneous flowfield are both simulated. A flow recirculation zone exists in both flowfields, but the instantaneous flowfield also exhibits large-scale unsteady flow structures (e.g. swirl), which are not captured in the mean flowfield.

"Time-frozen" mean flowfield

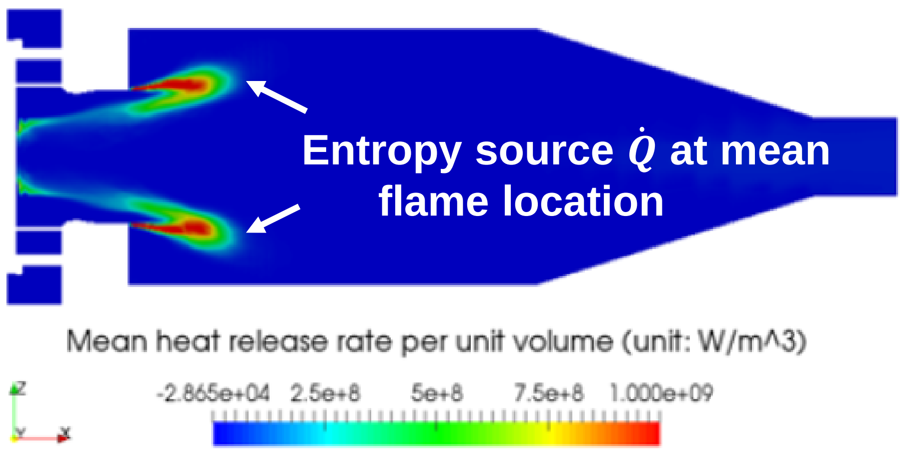


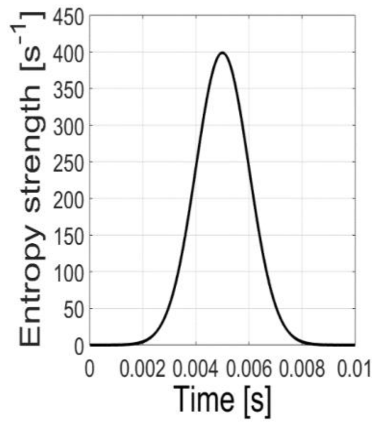
"Time-varying" instantaneous flowfield



2.3. Passive scalar entropy transport method

A Gaussian-type impulsive entropy source $\dot{Q}$ is defined at the mean flame location based on the mean heat release field q_{mean}, introducing passive scalar entropy into the combustor.





Time-variation of entropy source $\dot{Q}$

Now the pure entropy advection equation has a source term $\dot{Q}$ on its right-hand side:

$$\frac{\partial \breve{s}}{\partial t} + \boldsymbol{u}_{mean} \cdot \nabla \breve{s} = \boxed{\dot{Q}} \quad \text{where} \quad \dot{Q} = \boxed{G_{in}(t - t_1, \sigma_1)} \cdot \frac{q_{mean}}{\int_\Omega q_{mean}\, d\Omega}$$

||

Gaussian shape function:
$(t_1 = 0.005\ s\,, \sigma_1 = 0.001\ s)$

$$\boxed{G_{in}(t - t_1, \sigma_1) = \frac{1}{\sigma_1\sqrt{2\pi}} \exp\left[\frac{-(t - t_1)^2}{2\sigma_1^2}\right]}$$

2.3. Passive scalar entropy transport method

With the impulsive entropy source $\dot{Q}$, the entropy advection equation becomes a passive scalar transport equation:

$$\boxed{\frac{\partial \breve{s}}{\partial t} + \boldsymbol{u}_{mean} \cdot \nabla \breve{s} = \dot{Q}}$$

The entropy $\breve{s}$ is a passive scalar

which advects within the mean velocity field

from flame location to combustor chamber exit

For an instantaneous flowfield, u_{mean} is replaced by instantaneous vector u_{ins}:

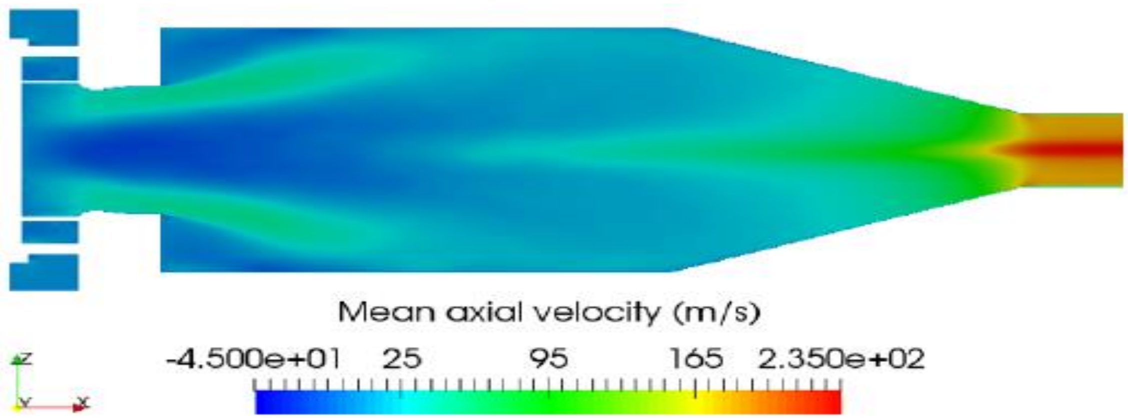
$$\boxed{\frac{\partial \breve{s}}{\partial t} + u_{ins} \cdot \nabla \breve{s} = \dot{Q}}$$

Above two key equations are then simulated for entropy wave advection in a turbulent premixed combustor.

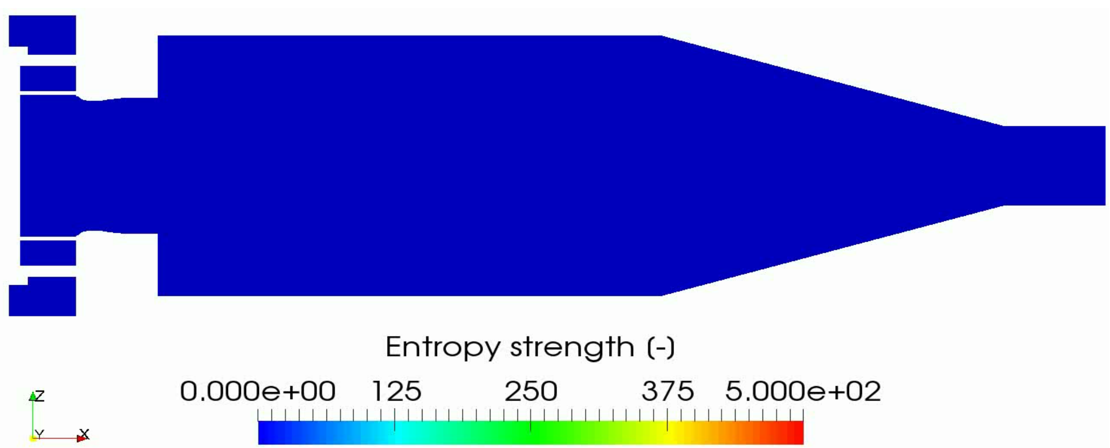
3.1. Entropy advection within "time-frozen" mean flowfield

In the "time-frozen" mean flowfield, entropy waves close to the side-walls reach the chamber exit earlier, but near the centreline the waves are drawn upstream by flow recirculation zone and trapped inside it for a long time.

"Time-frozen" mean flowfield
on plane Y=0



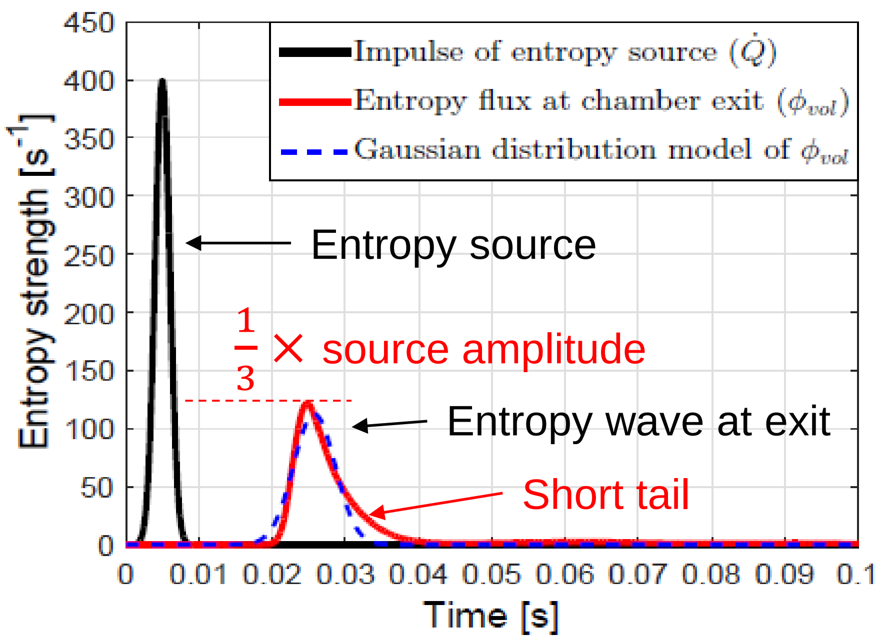
Entropy wave advection
on plane Y=0



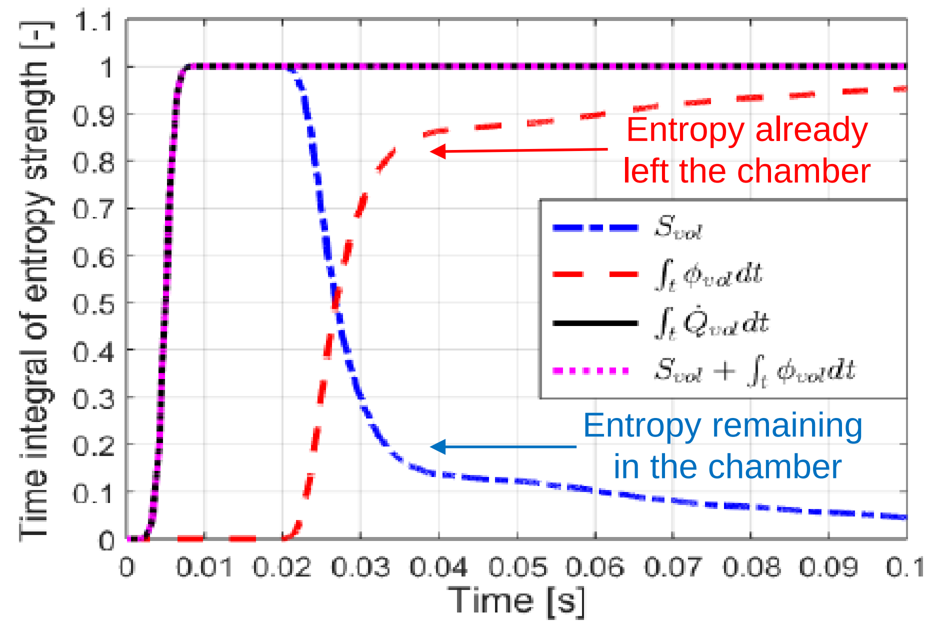
3.1. Entropy advection within “time-frozen” mean flowfield

The entropy wave amplitude at chamber exit follows the Gaussian shape, and remains 1/3 of the source amplitude due to the non-uniform mean velocity profile.

It takes a long time (~0.2s) for all the entropy waves to exit the chamber, due to the “dragging & trapping” effects of the flow recirculation zone near centreline.



(a) Time variation of entropy strengths



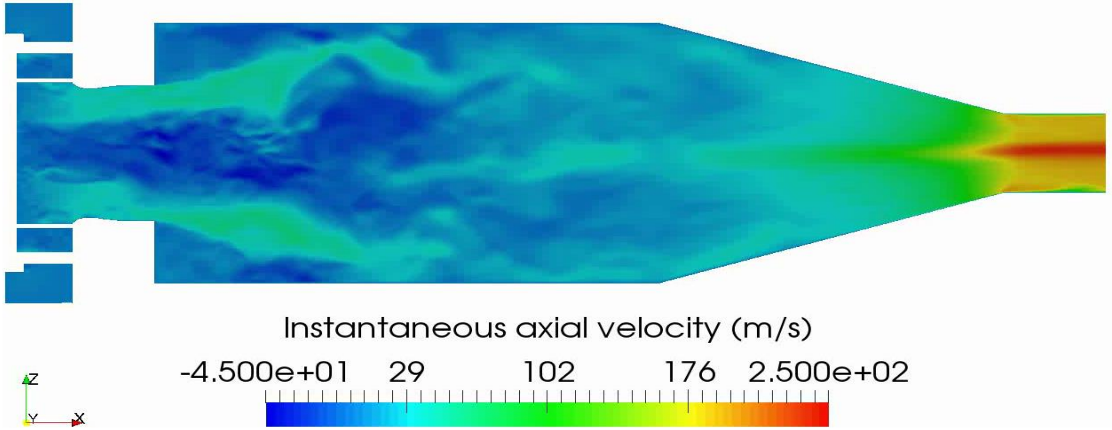
(b) Time integral of entropy strengths

Entropy wave advection within the “time-frozen” mean flowfield

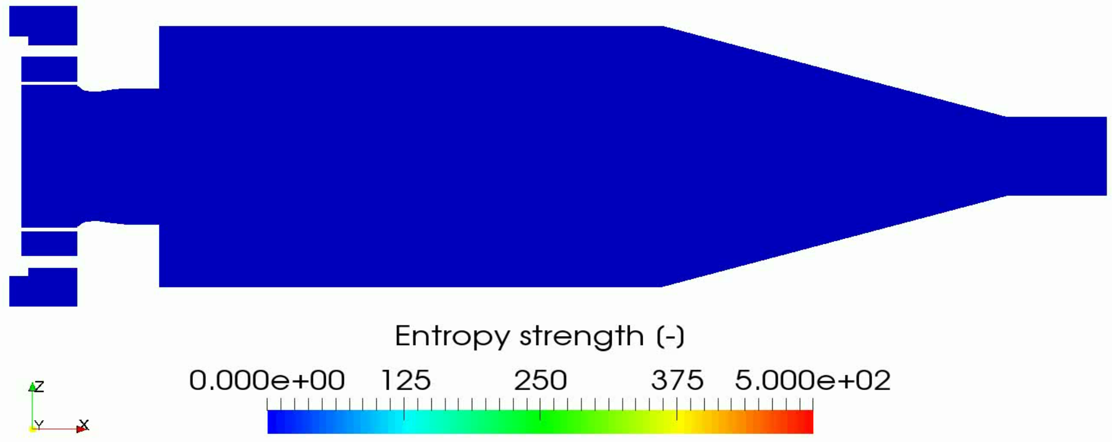
3.2. Entropy advection within "time-varying" instantaneous flowfield

In a "time-varying" instantaneous flowfield, entropy wave advection is irregular and faster due to large-scale unsteady flow features increasing the downstream speed. The effect of the centreline flow recirculation zone is much weaker and negligible.

"Time-varying" instantaneous flow field on plane Y=0



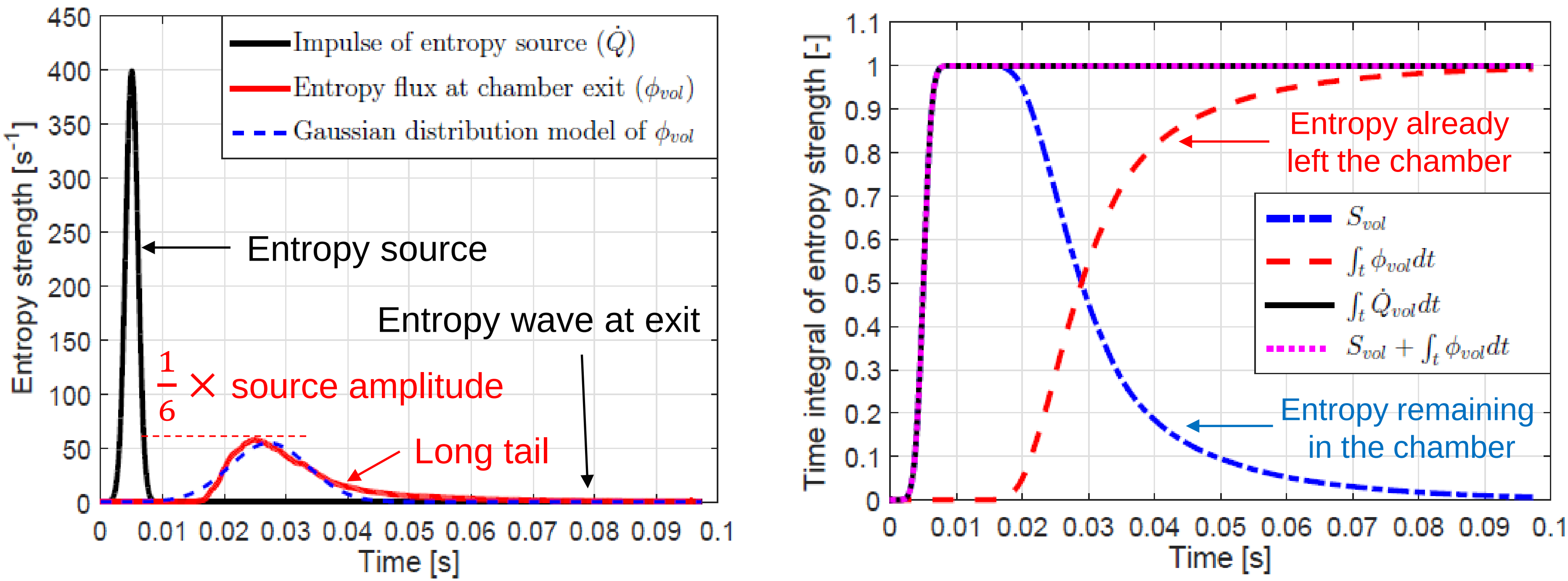
Entropy wave advection on plane Y=0



3.2. Entropy advection within "time-varying" instantaneous flowfield

The entropy wave amplitude at combustor exit follows a much flatter Gaussian distribution, due to the stronger dispersion effects of the large-scale unsteady flow structures.

The unsteady flow structures modify the advection speed and overcome the delay from flow recirculation zone, leading to a much shorter total exit time of 0.1s.



(a) Time variation of entropy strengths

(b) Time integral of entropy strengths

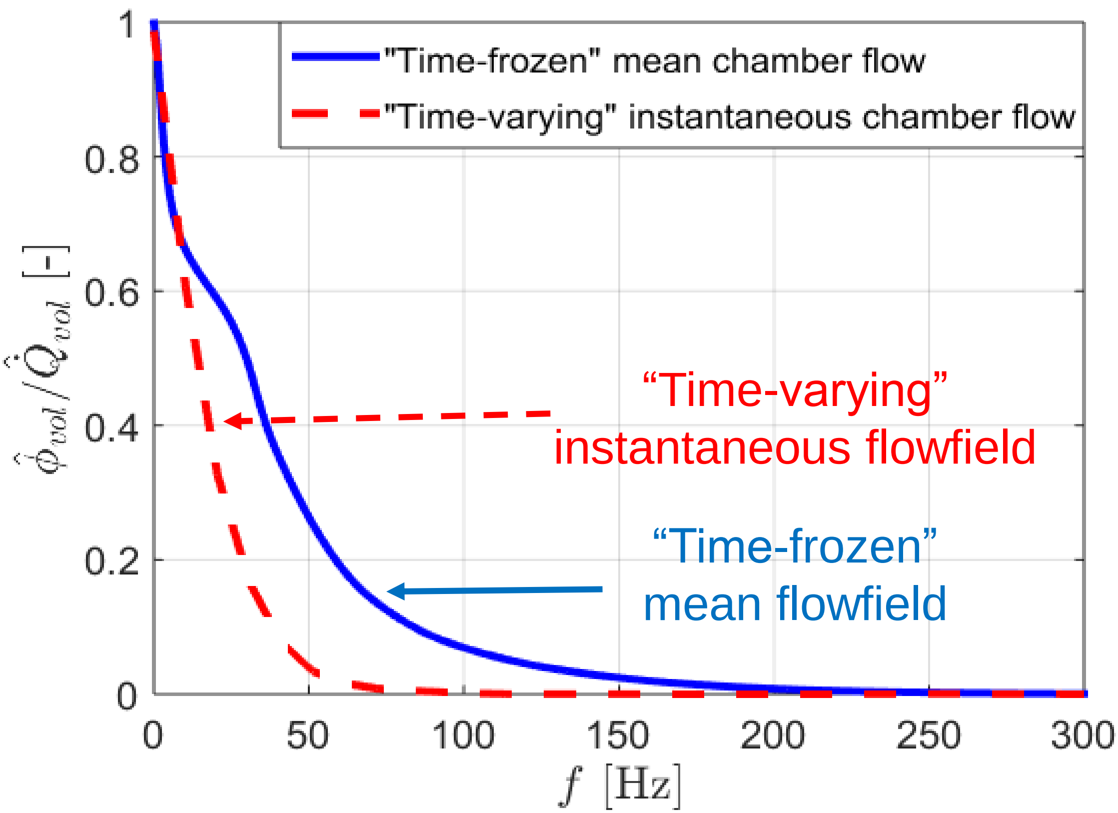
Entropy wave advection within the "time-varying" instantaneous flow field

3.3. Fourier transfer functions for entropy wave advection

Based on integrated entropy source $\dot{Q}_{vol}$ and entropy wave flux ϕ_{vol} at exit, transfer functions of entropy advection are defined by Fourier transform ratio of $\phi_{vol}/\dot{Q}_{vol}$:

Transfer function for mean flowfield has broader bandwidth, meaning the large-scale unsteady flow structures act to reduce the bandwidth of entropy wave signal at combustor exit.

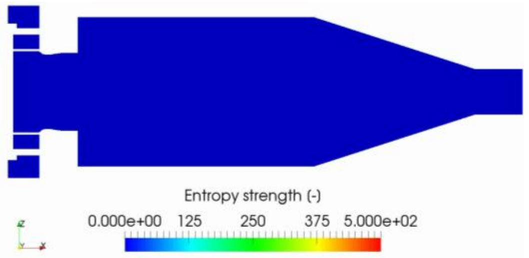
Entropy noise in mean flowflied has higher potential to affect thermoacoustic instabilities.



Fourier transfer functions for entropy wave advection on two flowfields.

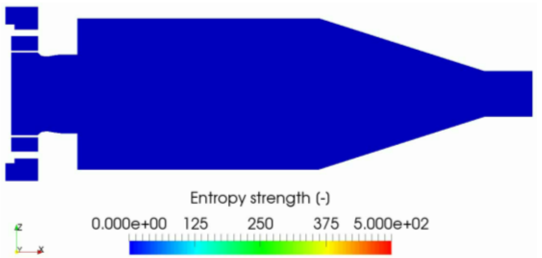
4. Conclusion & Future work

1. The entropy wave advection in a full-scale gas turbine combustor is studied:
   - Using turbulent reacting flow LES;
   - Superimposed with passive scalar entropy transport.



2. Entropy wave advection in the "time-frozen" mean flowfield:
   - Dispersed by a non-uniform mean velocity profile;
   - Entropy waves near centreline are trapped & delayed by flow recirculation zone;
   - Exiting amplitude follows Gaussian distribution and remains 1/3 of the source amplitude.

3. Entropy wave advection in a "time-varying" instantaneous flowfield:
   - Irregular & dominated by large-scale unsteady flow structures;
   - A shorter total exit time of 0.1s (>0.2s for mean flowfield);
   - Exiting amplitude follows a much flatter Gaussian response with only 1/6 of the source amplitude.



4. Future work will focus on entropy noise effect on thermoacoustic instabilities.

References

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