Large Eddy Simulation of a Swirl Stabilised Partially Premixed Flame Close to Blow-off

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Presentation Structure

1. Motivation
2. Numerical Modelling
3. Results
4. Summary

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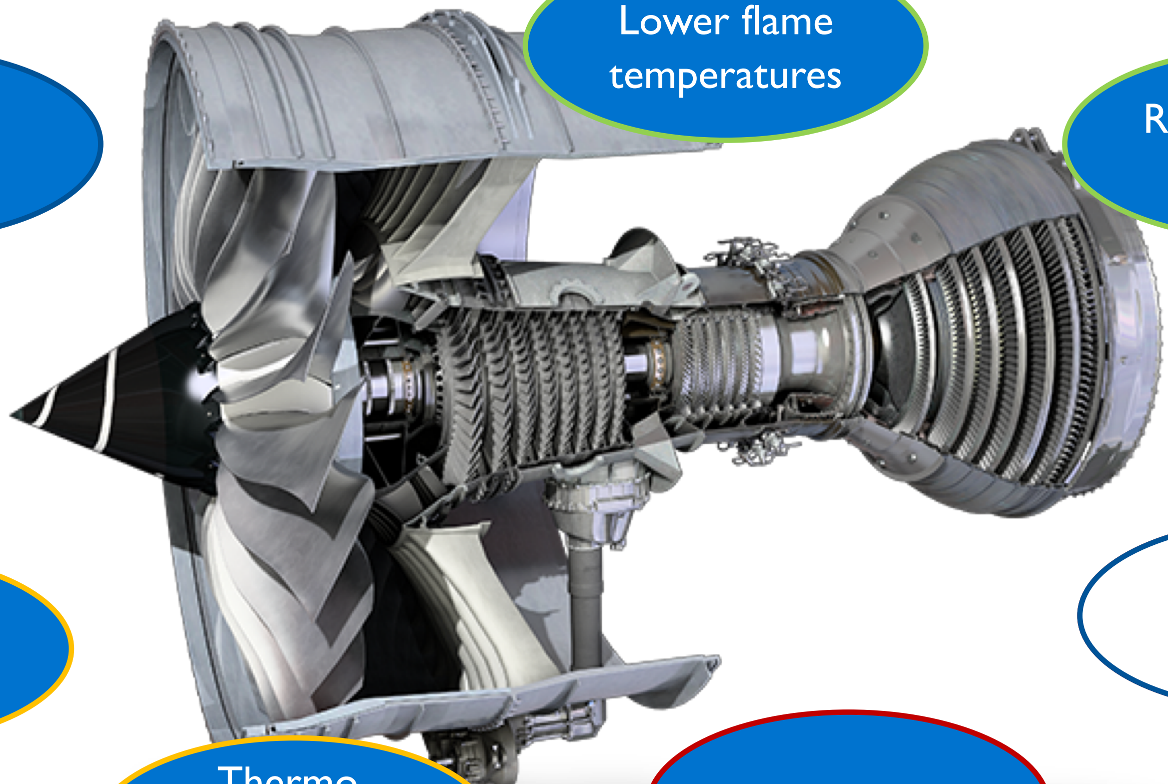
1. Motivation

Lean combustion for future gas turbine design

Lean combustion

Lower flame temperatures

Reduced NO_x emissions



Flame stabilisation issues

Thermo-acoustic instabilities

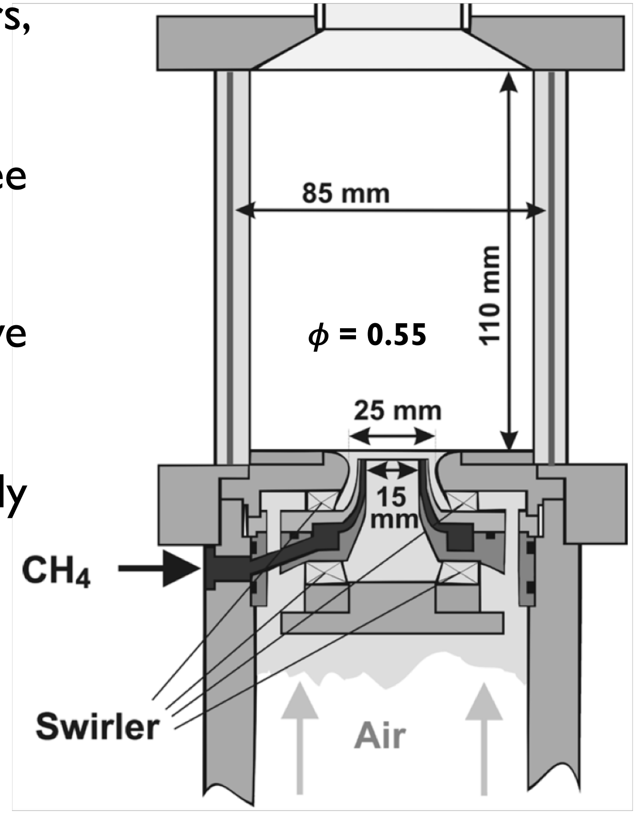
Failed ignition

Flame blow-off

1. Motivation

Test case

- Gas turbine model combustor with dual swirlers, developed at DLR Stuggart, Germany [1,2].
- LDV, PIV and Raman measurements taken for three operating conditions.
- The thermo-acoustically stable and unstable flames have been analysed using CFD [3].
- Unstable flame close to blow-off has been experimentally observed in [4].
    - Different flame shapes seen.
    - Random lift-off occurred 1-2 times every second [3].
    - Loss and re-stabilisation of a flame root.



Gas turbine model combustor [1,2].

1. P. Weigand, W. Meier, X. R. Duan, W. Stricker and M. Aigner. *Combust. Flame*, **144** (1-2), p. 205-224 (2006).
2. W. Meier, X. R. Duan and P. Weigand. *Combust. Flame*, **144** (1-2), p. 225-236 (2006).
3. Z. X. Chen, N. Swaminathan, M. Stöhr and W. Meier. *Proc. Combust. Inst.* (2018).
4. M. Stöhr, I. Boxx, C. Carter and W. Meier. *Proc. Combust. Inst.*, **33** (2), p. 2953-2960 (2011).

1. Motivation

LES modelling

- Crucial for the development of combustion models for CFD to capture these instabilities.

- LES can predict such phenomena through the chosen sub-grid scale closure for combustion.

- Flamelet models are beneficial in terms of the lower computational cost.

- An unstrained flamelet model has proved to be successful for modelling this gas turbine combustor under thermo-acoustically stable and unstable conditions using LES.

1. Motivation

Objectives of this study

- Blow-off is not well understood, along with the precursors that lead to blow-off.
- Numerical studies investigating blow-off are very limited for premixed and partially premixed cases.

- Hence, the prime objective is to investigate the various physical processes involved in the stabilisation leading to flame blow-off:

  1. To use the unstrained flamelet model as SGS combustion closure to simulate the flame close to blow-off in the DLR model gas turbine combustor.
  2. Validate the simulations by using the time-averaged statistics from the experiment.
  3. Provide insights on the random lift-off event.

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1. Motivation
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4. Summary

2. Numerical Modelling
Governing equations

- Favre-filtered equations for mass and momentum are solved.
- SGS viscosity modelled using constant Smagorinsky model.
- First two moments of the mixture fraction and the progress variable, along with the thermo-chemical enthalpy are transported using:

$$\overline{\rho}\frac{\mathrm{D}\widetilde{\boldsymbol{\varphi}}}{\mathrm{D}t} = \nabla\cdot\left[\left(\overline{\mu}+\frac{\mu_T}{\mathrm{Sc}_T}\right)\nabla\boldsymbol{\varphi}\right] + \overline{\boldsymbol{S}_{\varphi}^{+}} - \overline{\boldsymbol{S}_{\varphi}^{-}}$$

where: $\widetilde{\boldsymbol{\varphi}} = \left\{\widetilde{\xi}\,,\ \sigma^2_{\xi,\mathrm{sgs}}\,,\ \widetilde{c}\,,\ \sigma^2_{c,\mathrm{sgs}}\,,\ \widetilde{h}\right\}$

$$\overline{\boldsymbol{S}_{\varphi}^{+}} = \left\{0\,,\ 2\frac{\mu_T}{\mathrm{Sc}_T}\left|\nabla\widetilde{\xi}\right|^2,\ \overline{\dot{\omega}^*}\,,\ 2\frac{\mu_T}{\mathrm{Sc}_T}\left|\nabla\widetilde{c}\right|^2 + 2\left(\overline{c\,\dot{\omega}^*} - \widetilde{c}\,\overline{\dot{\omega}^*}\right)\,,\ 0\right\}$$

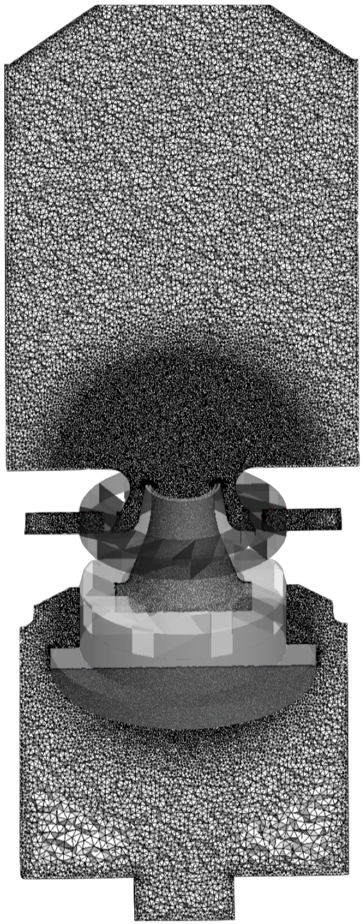
$$\overline{\boldsymbol{S}_{\varphi}^{-}} = \left\{0\,,\ 2\overline{\rho}\widetilde{\chi}_{\xi,\mathrm{sgs}}\,,\ 0\,,\ 2\overline{\rho}\widetilde{\chi}_{c,\mathrm{sgs}}\,,\ 0\right\}$$

5. Z. Chen, S. Ruan and N. Swaminathan. *Proc. Combust. Inst.*, **36** (2), p. 1645-1652 (2017).

2. Numerical Modelling

Solver and computational grid details

- Pressured based solver in OpenFOAM is used and the PIMPLE algorithm is used for the pressure-velocity coupling.
- Unstructured grid with 21M tetrahedral cells is used – validated for isothermal and thermo-acoustically stable and acoustically unstable conditions [3].
- Second-order schemes are used for spatial derivatives and an implicit Euler scheme for time derivatives.
- A time-step of 0.15 μs is used, to ensure the CFL number does not exceed 0.4.



Computational grid of the gas turbine model combustor.

3. Z. X. Chen, N. Swaminathan, M. Stöhr and W. Meier. *Proc. Combust. Inst.* (2018).

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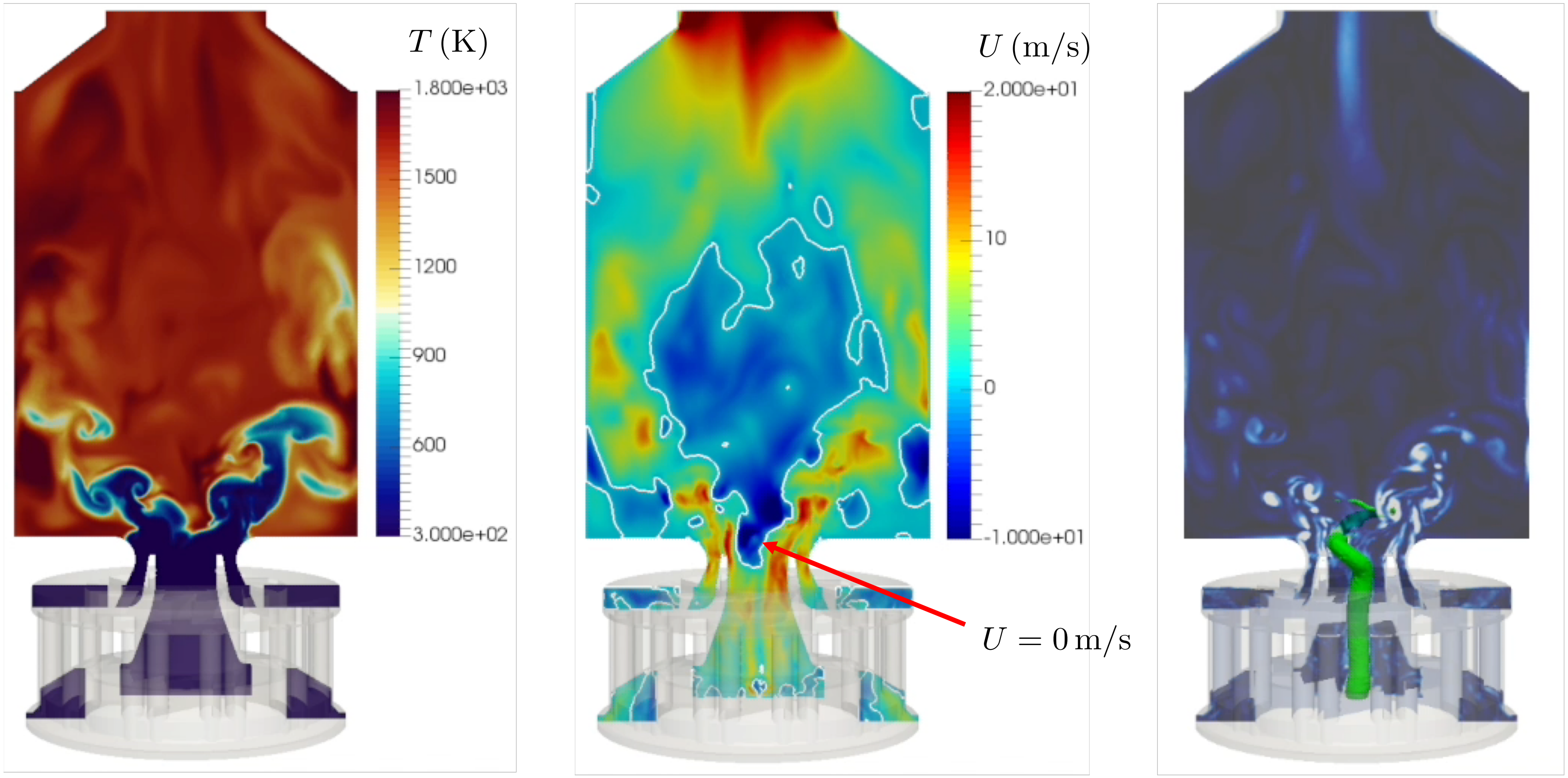
3. **Results**
4. Summary

3. Results

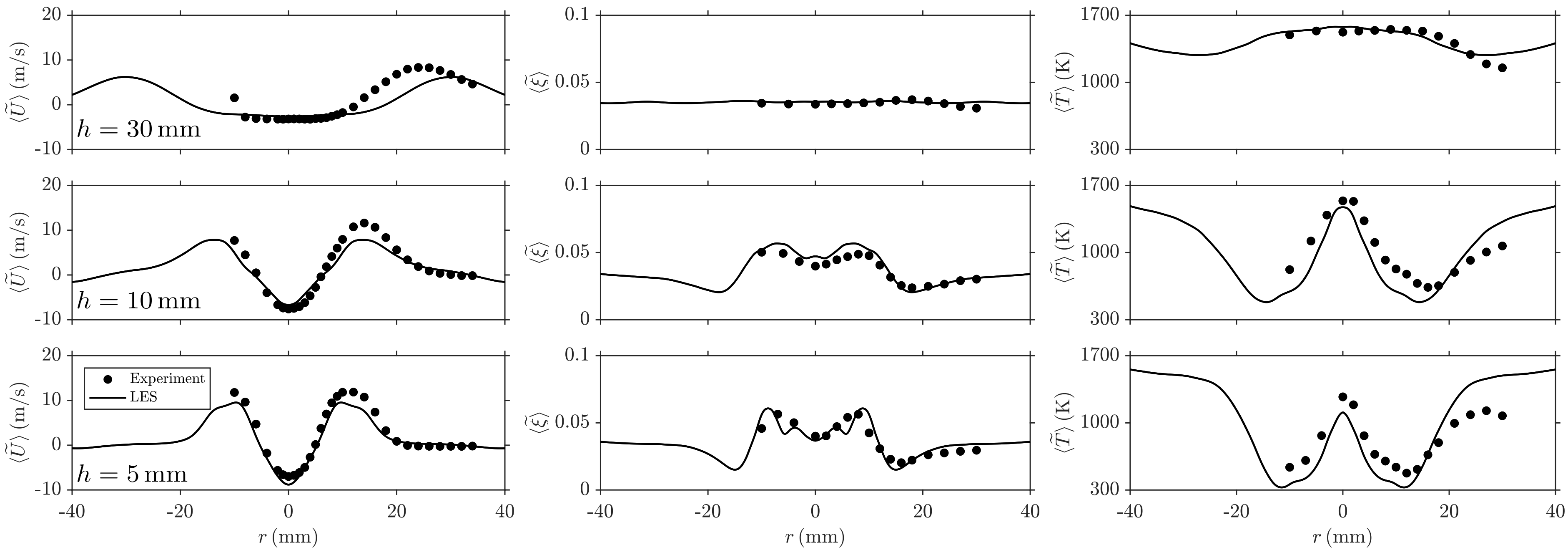
Temperature, axial velocity and vorticity fields



Total length = 15 ms at 10 fps (animation length = 20 s).

3. Results

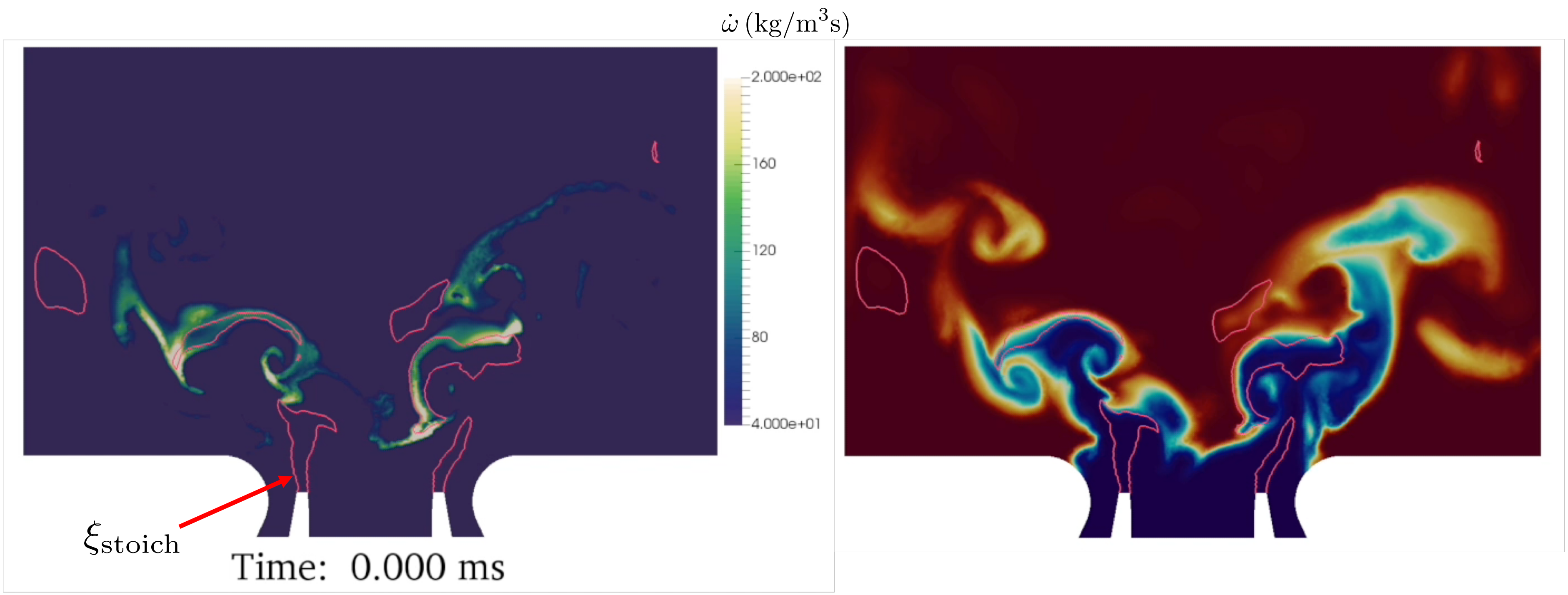
Time-averaged profiles for validation



Radial profiles for axial velocity (left), mixture fraction (middle) and temperature (right).

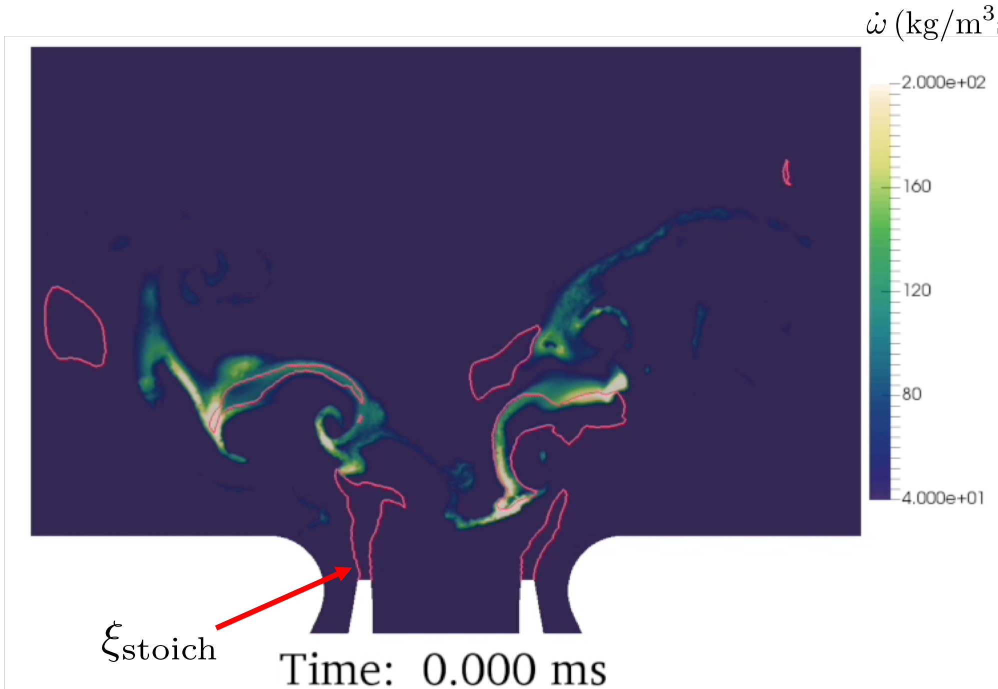
3. Results

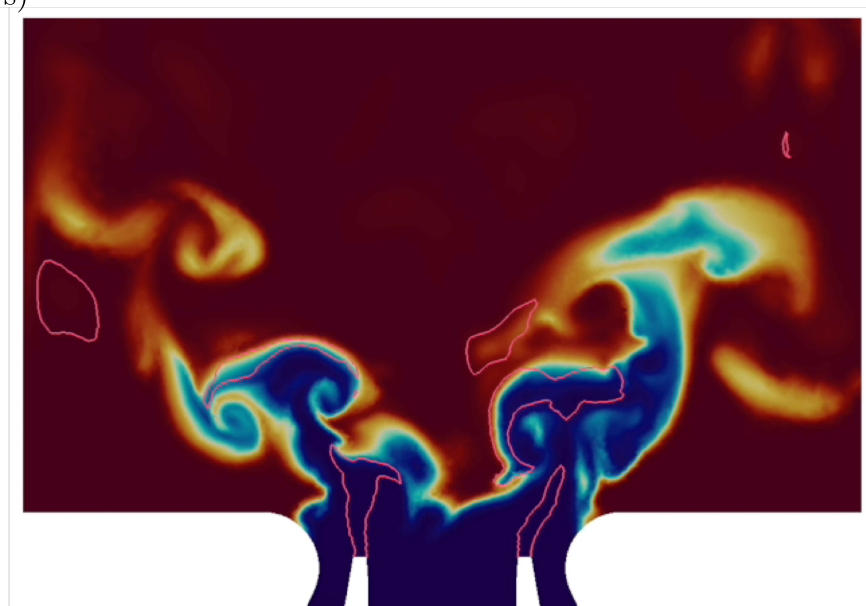
Progress variable and reaction rate



3. Results

Progress variable and reaction rate

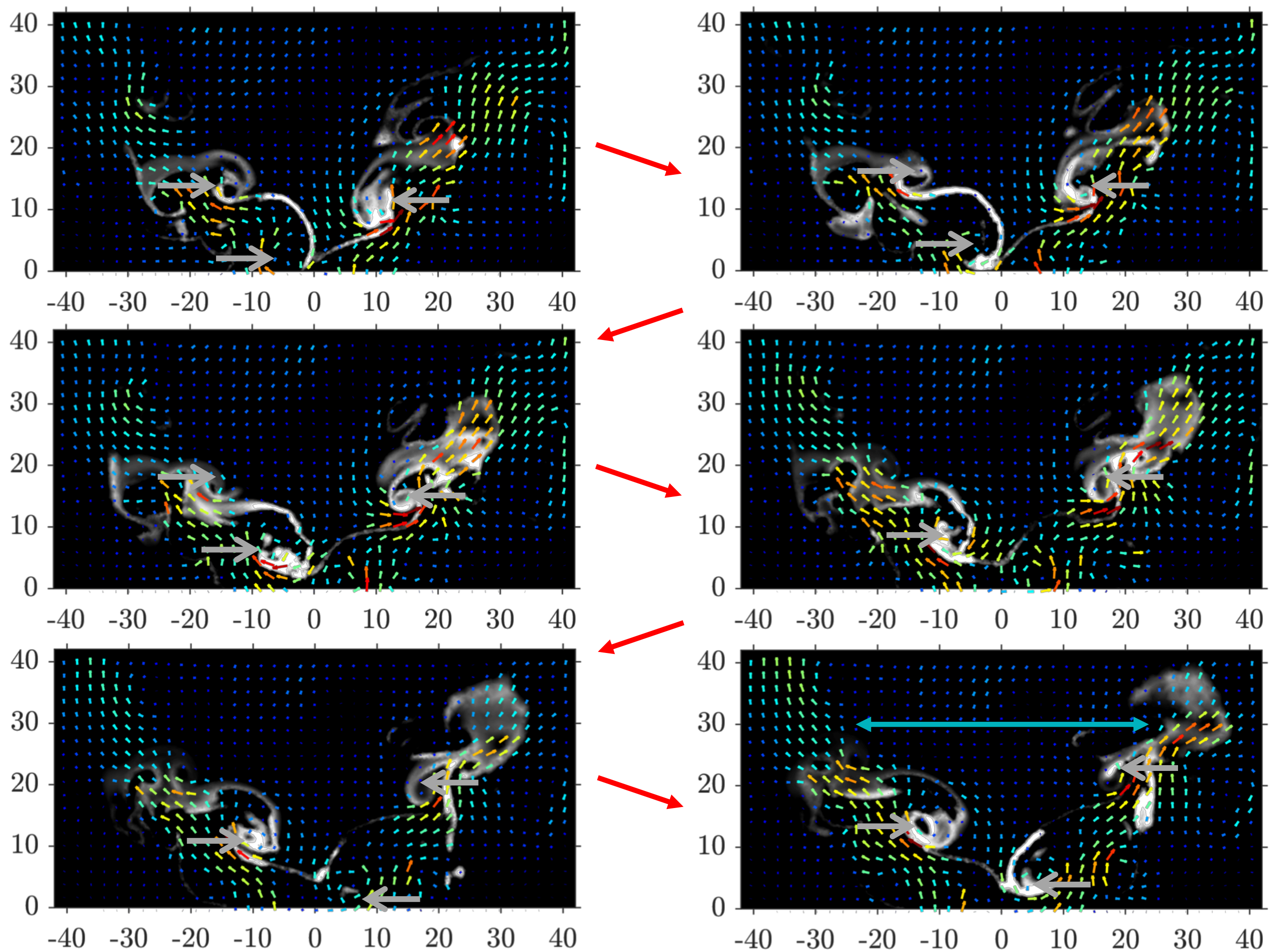




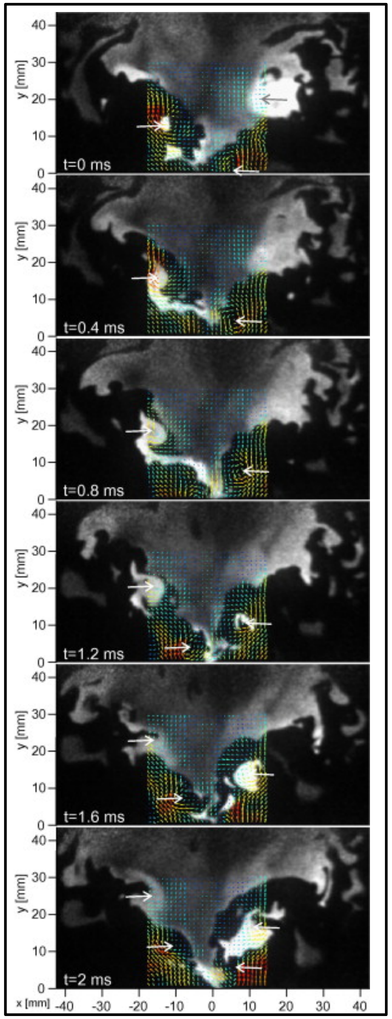
Total length = 45 ms at 10 fps (animation length = 60 s).

3. Results

Stable burning event (1.875 ms, dt = 0.375 ms)



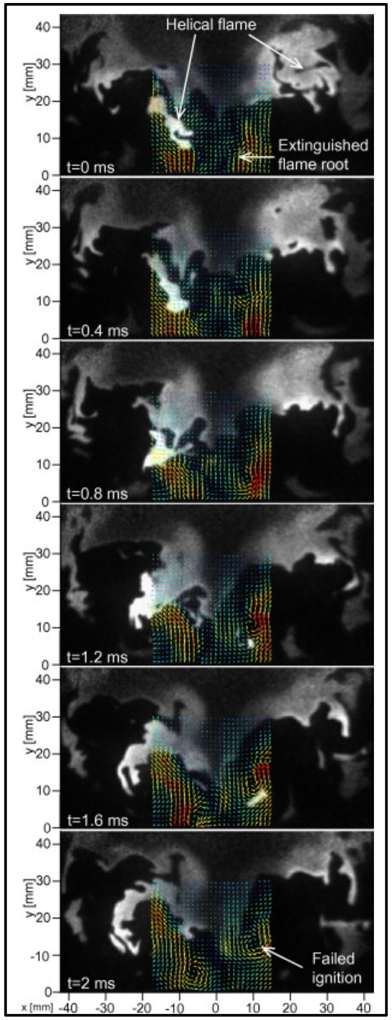
LES contours of reaction rate and velocity vectors, coloured by the magnitude.

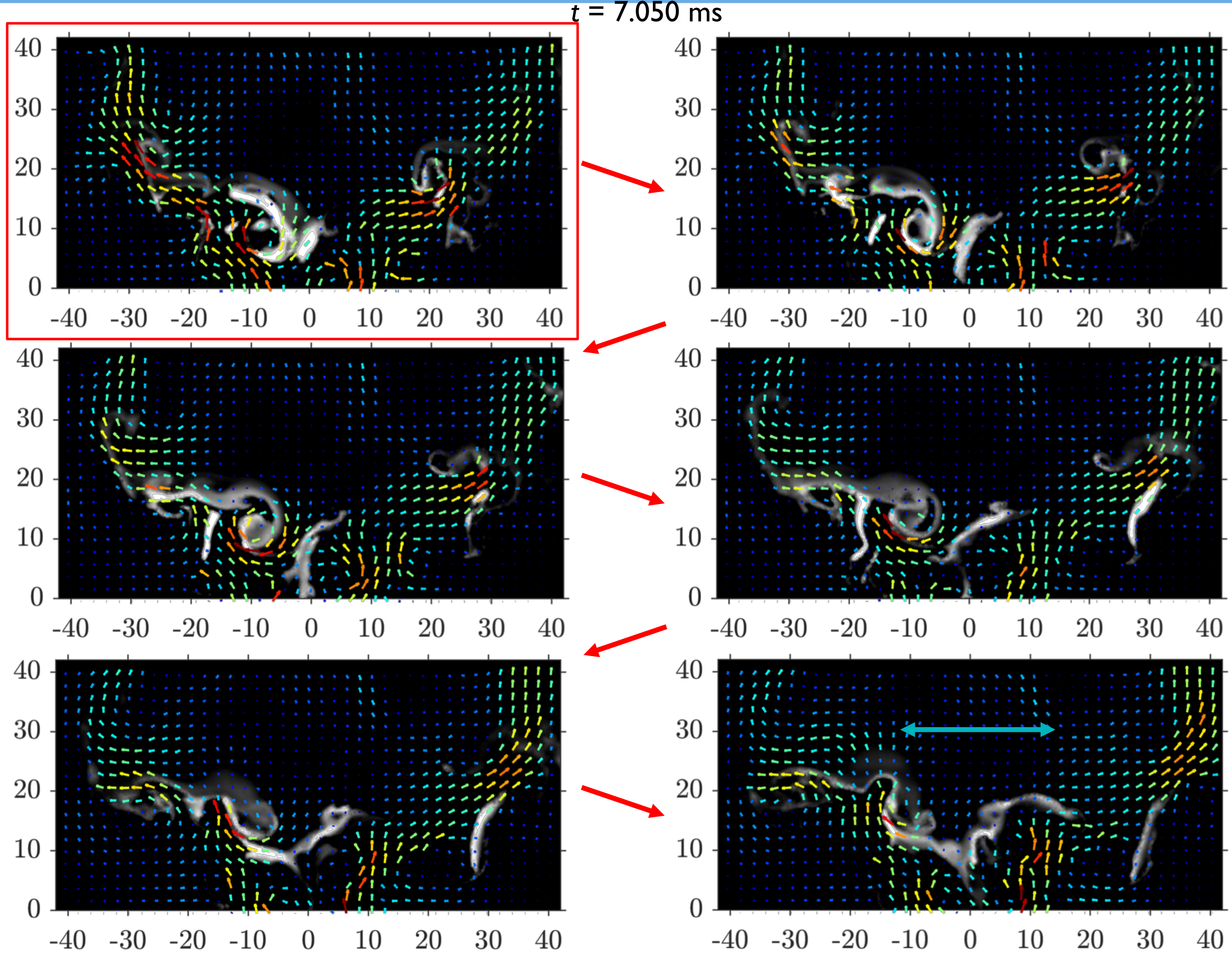


OH-PLIF and PIV

3. Results

A local extinction event (1.875 ms, dt = 0.375 ms)

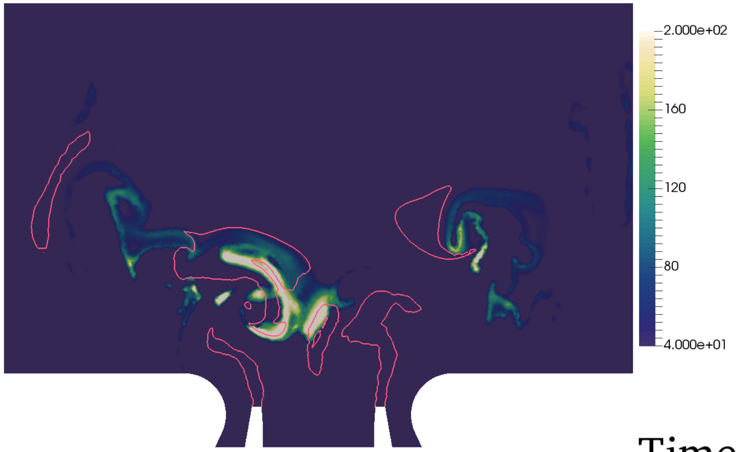




LES contours of reaction rate and velocity vectors, coloured by the magnitude.

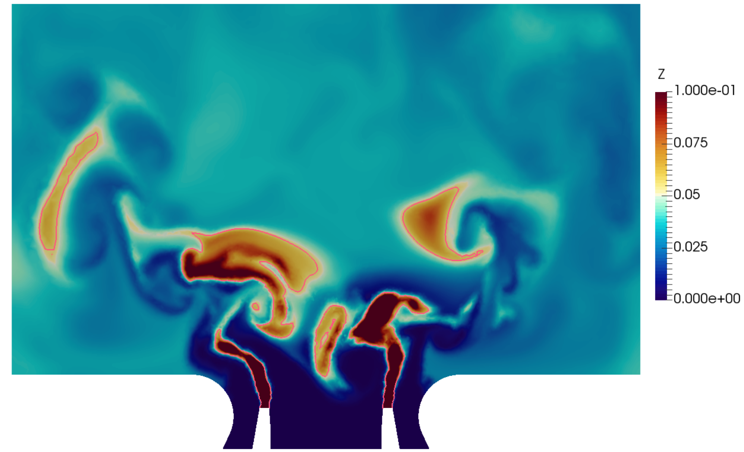
3. Results

Failed ignition event

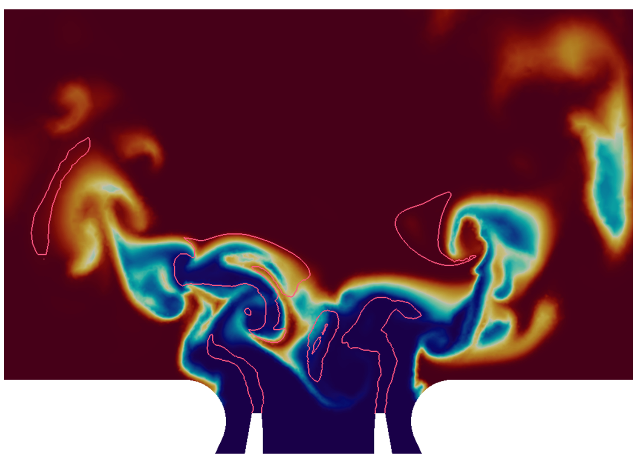


Reaction rate

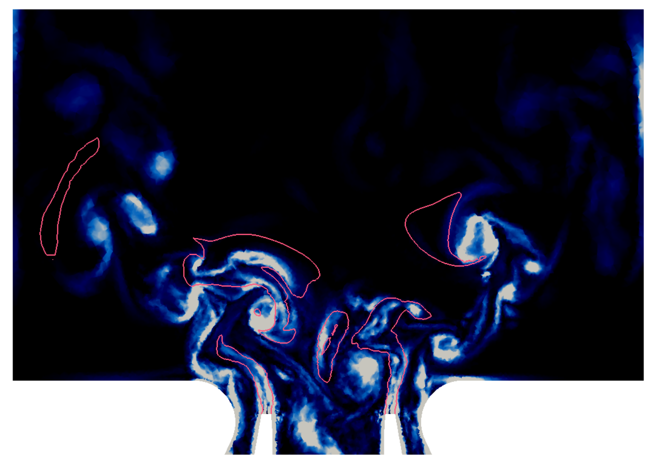
Time: 7.050 ms



Mixture fraction



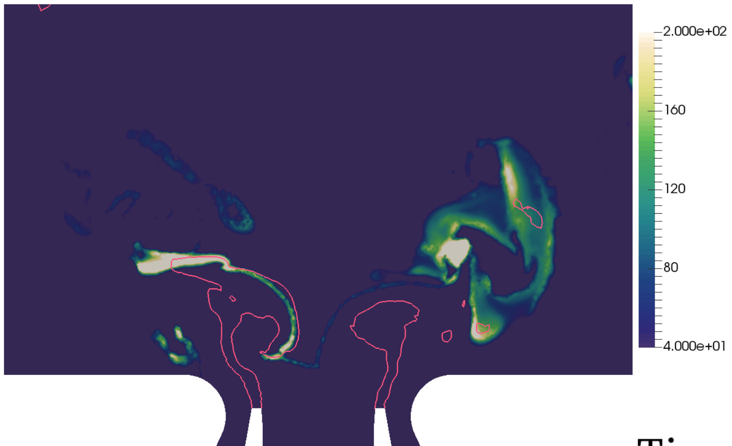
Progress variable



Vorticity

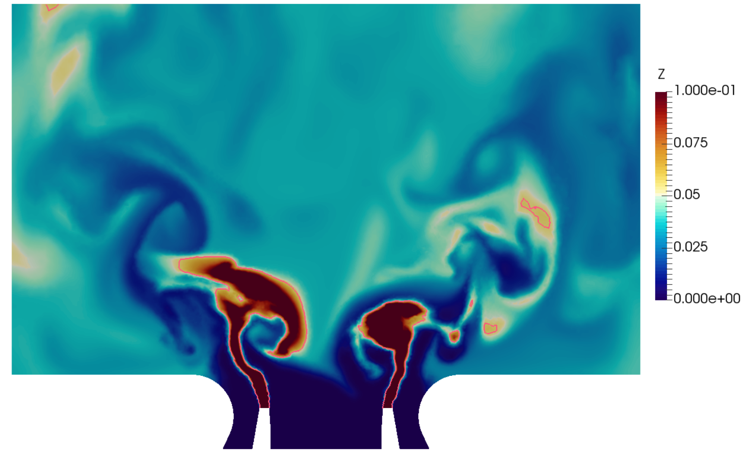
3. Results

Failed ignition event

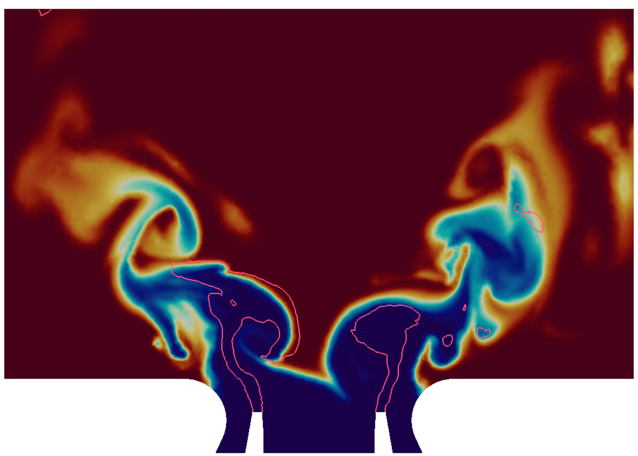


Reaction rate

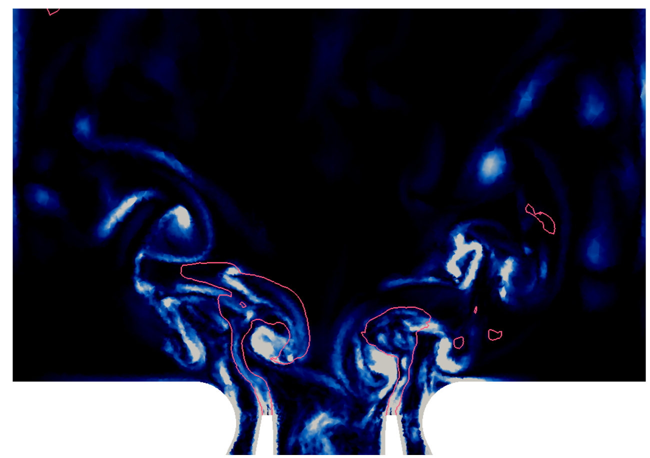
Time: 4.050 ms



Mixture fraction



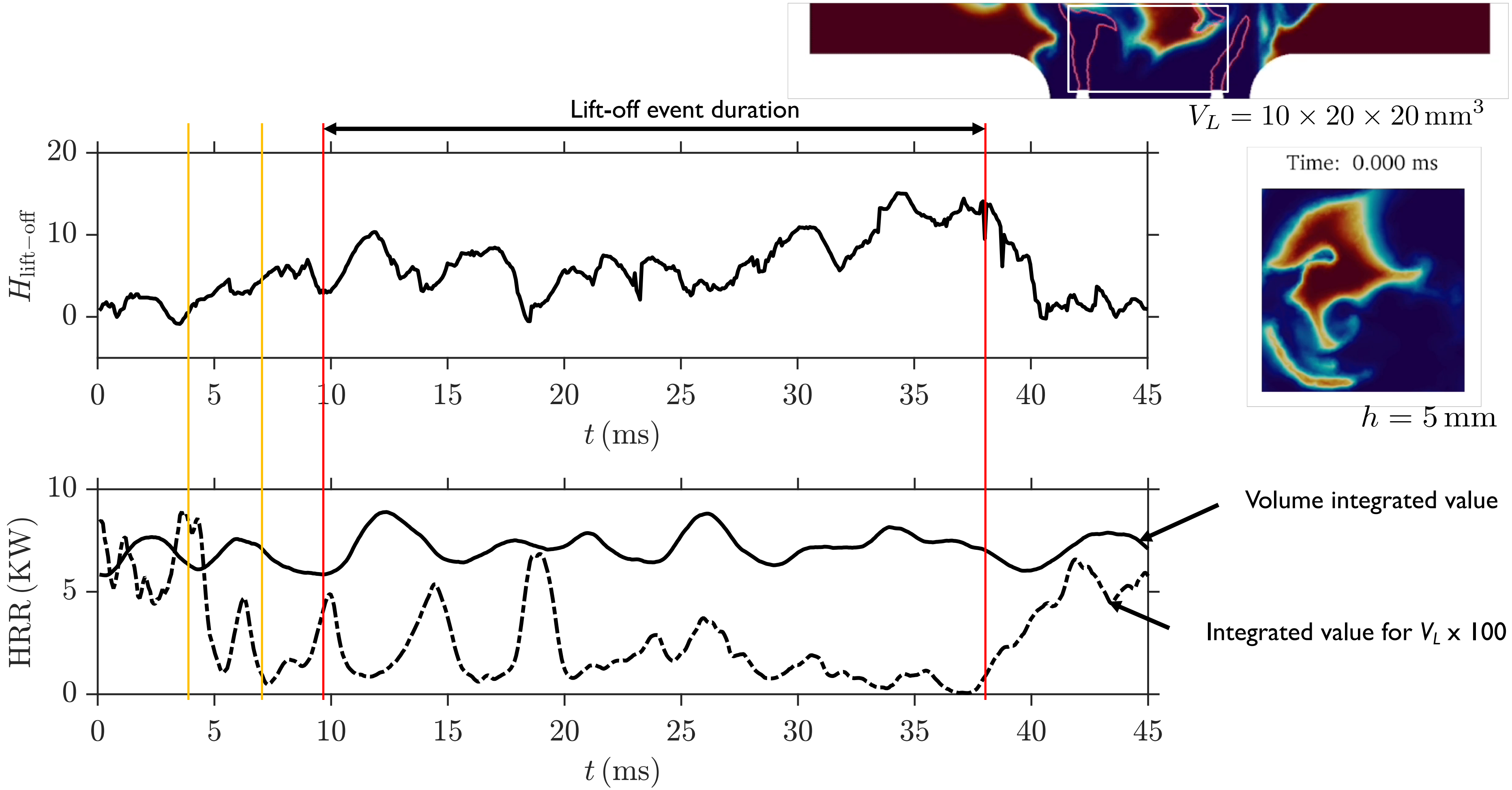
Progress variable



Vorticity

3. Results

Lift-off and heat release rate



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3. Results

4. Summary

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Take away messages

- The unstrained flamelet closure is used for modelling the flame close to blow-off for the DLR gas turbine model combustor.
- Time-averaged statistics are well-captured, along with the dynamics of the flame burning prior to a lift-off event.
- A lift-off event is observed, which lasted ~30 ms, and is caused by the loss of the flame root.
- This loss is caused by the entrainment of air between the hot products in the recirculation zone and the reactant mixture.

4. Summary
Suggested further work

- To run this case for longer, in order to observe the frequency of this lift-off event – it was reported that this event occurred 1-2 times every second.

- To run this case with a lower fuel mass flow rate and see if complete blow-off occurs or not.

Thank you for listening. Any questions?

We acknowledge the support from an EPSRC DTP award.

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Appendix
Further LES modelling detail

- Unstrained flamelet reaction rate is obtained using PDFs for mixture fraction and progress variable for premixed and non-premixed contributions [6].

$$\overline{\dot{\omega}^{*}} = \overline{\dot{\omega}}_{\mathrm{fp}} + \overline{\dot{\omega}}_{\mathrm{np}}$$

where: $$\overline{\dot{\omega}}_{\mathrm{fp}} = \overline{\rho} \int_0^1 \int_0^1 \frac{\dot{\omega}\left(\eta,\zeta\right)}{\rho\left(\eta,\zeta\right)} \widetilde{P}\left(\eta,\zeta\right)\,\mathrm{d}\eta\,\mathrm{d}\zeta$$

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

- Scalar dissipation rate for *c* is modelled using the algebraic expression [7]:

$$\widetilde{\chi}_{c,\mathrm{sgs}} = \mathcal{F}\left[2K_c\frac{s_L}{\delta_{\mathrm{th}}} + \left(C_3 - \tau C_4 \mathrm{Da}_\Delta\right)\left(\frac{2\,u'_\Delta}{3\,\Delta}\right)\right]\frac{\sigma^2_{c,\mathrm{sgs}}}{\beta_c}$$

β_c uses a constant value of 7.5 following an earlier study on this burner.

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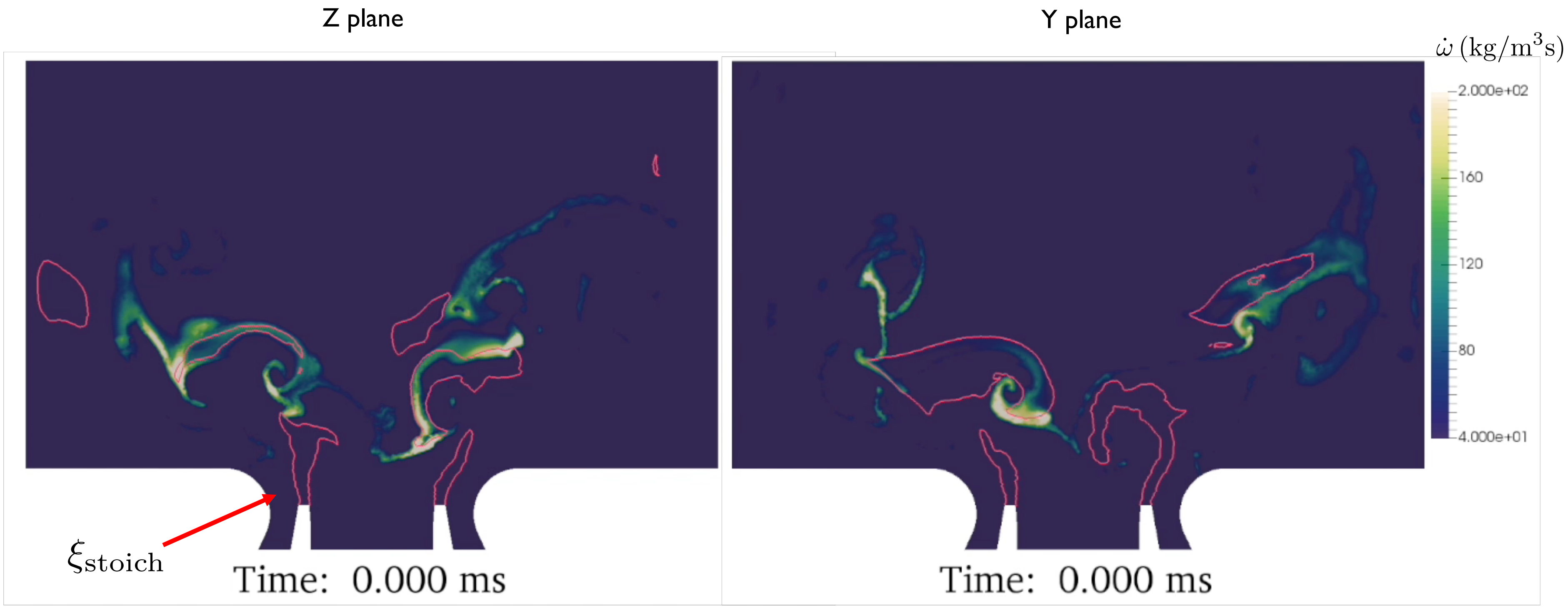
6. Z. Chen, S. Ruan and N. Swaminathan. *Proc. Combust. Inst.*, **36** (2), p. 1645-1652 (2017).
7. T. D. Dunstand, Y. Minamoto, N. Chakraborty and N. Swaminathan. *Proc. Combust. Inst.*, **34** (1), p. 1193-1201 (2013).

Appendix

Two midplanes of the reaction rate



Total length = 45 ms at 10 fps (animation length = 60 s).