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Non-Adiabatic Flamelet Modelling of a Lean Swirl-Stabilised Flame Close to Blow-Off

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Outline

1. Introduction
2. Numerical modelling
3. Results
4. Summary

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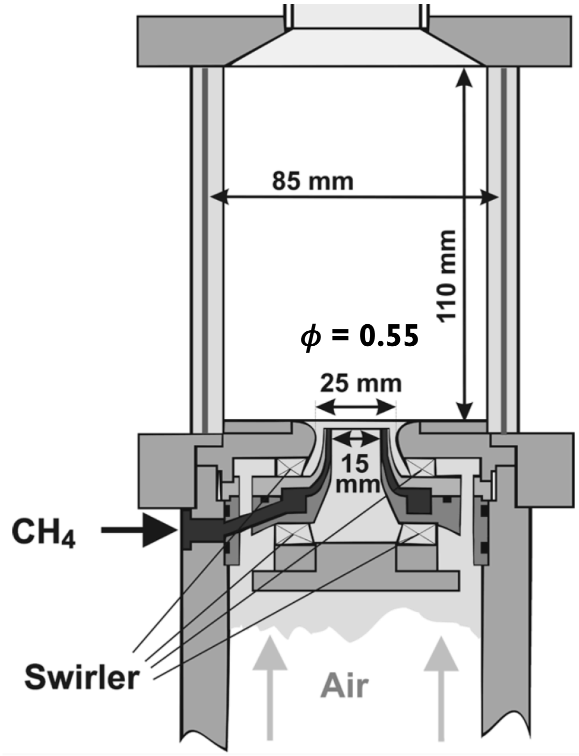
1. Introduction
Motivation

- Lean combustion is used in modern gas turbine combustors to reduce pollutants.
- Flames operating within lean conditions are prone to local extinction and blow-off.
- The mechanisms that lead to blow-off are not well understood.
- The local burning rates become weaker and heat loss can play an influential role with local extinction and flame blow-off.

I. Introduction
Test case

- Gas turbine model combustor (GTMC) with dual swirlers, developed at DLR Stuggart, Germany [1,2].
- LDV, PIV and Raman measurements taken for three methane-air flames
- Unstable flame close to blow-off has been experimentally observed in [3].
    - 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] Weigand P. *et al.* (2006) *Combust. Flame.*
[2] Meier W. *et al.* (2006) *Combust. Flame..*
[3] Stöhr M. *et al.* (2011) *Proc. Combust. Inst.*

1. Introduction

Aims & objectives

- Long-term objective is to investigate whether including heat loss within the modelling affects the flame's stabilisation.

- The main aim is to implement a non-adiabatic flamelet approach and simulate the flame close to blow-off in the DLR GTMC.

- Two simulations are compared to a previous fully adiabatic case that use:

  1. Non-adiabatic wall conditions and adiabatic flamelets.

  2. Non adiabatic wall conditions with a non-adiabatic flamelet approach.

Adiabatic case: Massey, J.C., Chen, Z.X. & Swaminathan, N., *Combust. Sci. Tech*. (2019).

Outline

2. Numerical detail
LES equations

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

$$\frac{\partial \overline{\rho}\widetilde{\boldsymbol{\varphi}}}{\partial t} + \boldsymbol{\nabla} \cdot \left(\overline{\rho}\widetilde{\boldsymbol{U}}\widetilde{\boldsymbol{\varphi}}\right) = \boldsymbol{\nabla} \cdot \left(\overline{\rho \mathcal{D}_{\text{eff}}}\boldsymbol{\nabla}\widetilde{\boldsymbol{\varphi}}\right) + \overline{\boldsymbol{S}_{\boldsymbol{\varphi}}^{+}} - \overline{\boldsymbol{S}_{\boldsymbol{\varphi}}^{-}}$$

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

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

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

2. Numerical detail

Previous non-adiabatic modelling approaches

- Many previous studies have use fixed temperature boundary conditions.
- Coupled heat transfer approaches also exist.
- Various approaches have been proposed for non-adiabatic flamelets.

Approach	
Enthalpy deficit approach through radiation	Bray & Peters, *Turbulent Reacting Flows* (1994) Marracino & Lentini, CST (1997)
Burner stabilised approach	Van Oijen & de Goey, *CST* (2000) Fiorina et al., *CTM* (2003)
Heat release damping approach	Proch & Kempf, *PROCI* (2015) Wollny et al., *Fuel* (2018)
Wall heat transfer model	Ma et al. *AIAAJ* (2018)
PSR approach	Chen et al., *Energy Fuel* (2018)

2. Numerical detail

Flamelet equations

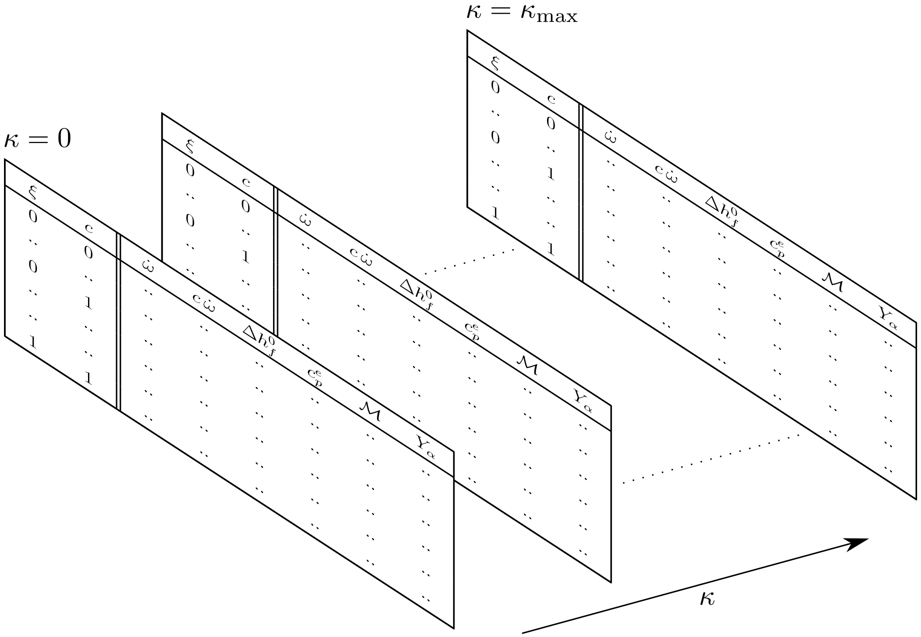
- Progress variable:

$$c = \frac{Y_{\mathrm{CO}} + Y_{\mathrm{CO2}}}{Y^{\mathrm{b}}_{\mathrm{CO}}(\xi, h^*) + Y^{\mathrm{b}}_{\mathrm{CO2}}(\xi, h^*)}$$

- Normalised enthalpy:

$$h^* = \frac{h - h_{\mathrm{min}}(\xi, c)}{h_{\mathrm{ad}}(\xi, c) - h_{\mathrm{min}}(\xi, c)}$$

- 1D flamelet equations:



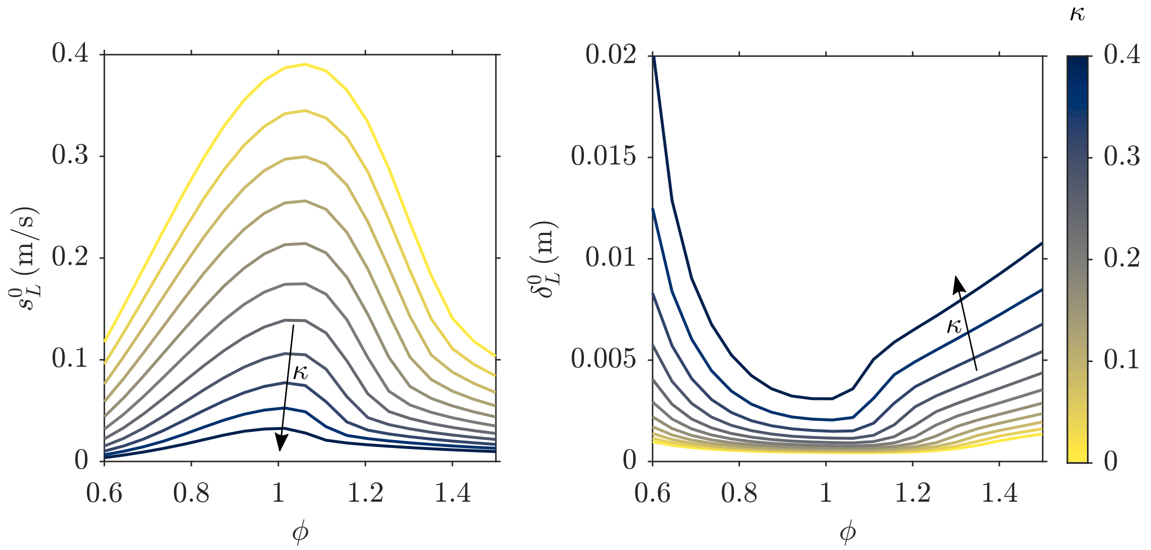
$$\rho U \frac{\mathrm{d}Y_\alpha}{\mathrm{d}x} = \dot{\omega}_\alpha + \frac{\mathrm{d}}{\mathrm{d}x}\left(\rho \mathcal{D}_\alpha \frac{\mathrm{d}Y_\alpha}{\mathrm{d}x}\right)$$

$$\rho c_p U \frac{\mathrm{d}T}{\mathrm{d}x} = \frac{\mathrm{d}}{\mathrm{d}x}\left(\lambda \frac{\mathrm{d}T}{\mathrm{d}x}\right) + \rho \frac{\mathrm{d}T}{\mathrm{d}x}\left(\sum_{\alpha=1}^{N} c_{p,\alpha} \mathcal{D}_\alpha \frac{\mathrm{d}Y_\alpha}{\mathrm{d}x}\right) - (1-\kappa)\sum_{\alpha=1}^{N} h_\alpha \dot{\omega}_\alpha$$

2. Numerical detail

Non-adiabatic flamelet table

- Flamelet solutions are undertaken using Cantera v2.3.0.
- 11 flamelets are calculated at equal heat loss factor increments of 0.04 for 20 equivalence ratios across the flammability range.
- For the maximum heat loss factor, the flame speed did not exceed 8% of the adiabatic value.



2. Numerical detail

Filtered reaction rate closure

- Partially premixed reaction rate is treated as a sum of premixed and non-premixed modes:

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

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

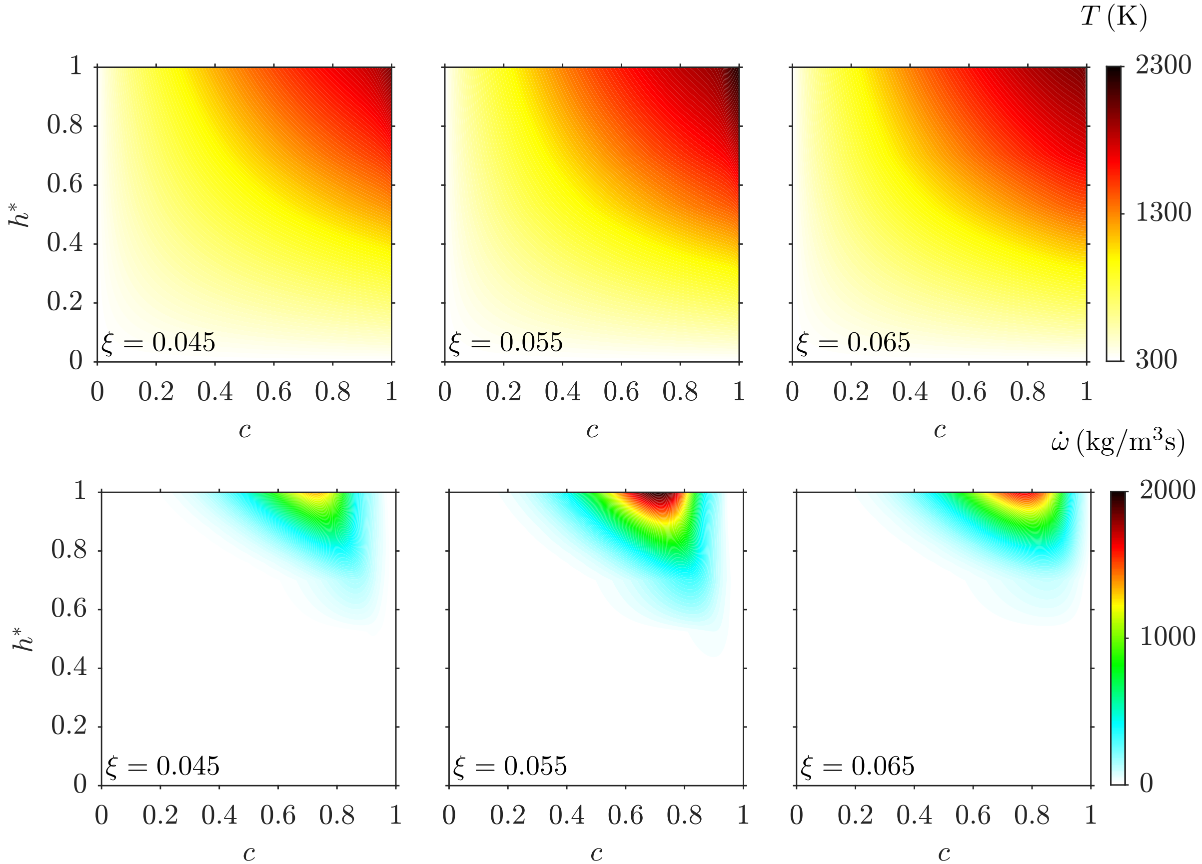
$$\widetilde{P}(\eta, \zeta, \mathcal{H}) \approx \widetilde{P}_\beta(\eta\,;\, \widetilde{\xi}, \sigma^2_{\xi,\mathrm{sgs}}) \times \widetilde{P}_\beta(\zeta\,;\, \widetilde{c}, \sigma^2_{c,\mathrm{sgs}}) \times \delta(\mathcal{H} - \widetilde{h}^*)$$

$$\overline{\dot{\omega}}_{\mathrm{np}} = \overline{\rho}\, \widetilde{c}\, \widetilde{\chi}_\xi \int_0^1 \frac{1}{\psi^{\mathrm{eq}}(\eta)} \frac{\mathrm{d}^2 \psi^{\mathrm{eq}}(\eta)}{\mathrm{d}\eta^2} \widetilde{P}(\eta) \, \mathrm{d}\eta$$

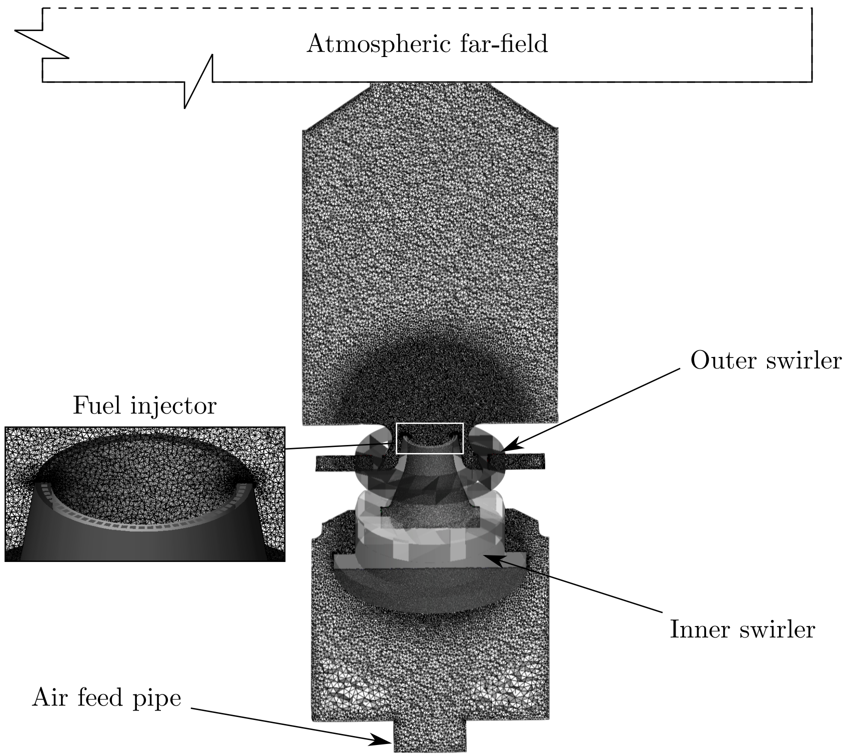
2. Numerical detail

Non-adiabatic flamelet table contours

- Similar contours to the study Wollny et al., *Fuel* (2018).



2. Numerical detail
Computational grid and solver details

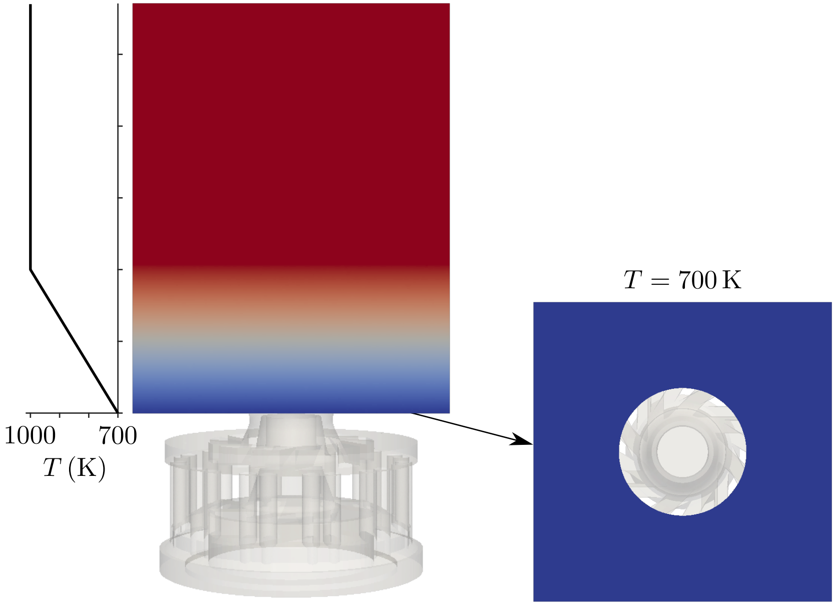


- Unstructured grid with 20 million tetrahedral cells is used.
- Pressured based solver in OpenFOAM is used with the PIMPLE algorithm for pressure-velocity coupling.

2. Numerical detail
Cases and boundary conditions

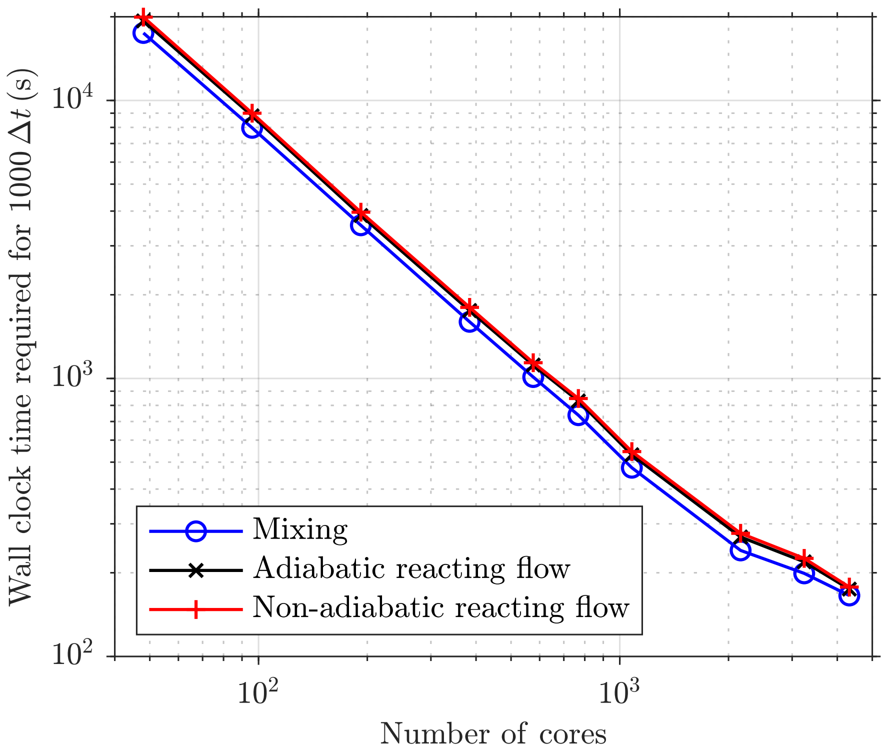
- A time-step of 0.15 μs is used, to ensure the CFL number does not exceed 0.4.
- Second-order schemes are used for spatial derivatives and an Euler scheme for time derivatives.
- Statistics for each case are collected over a time sample of 24 ms.

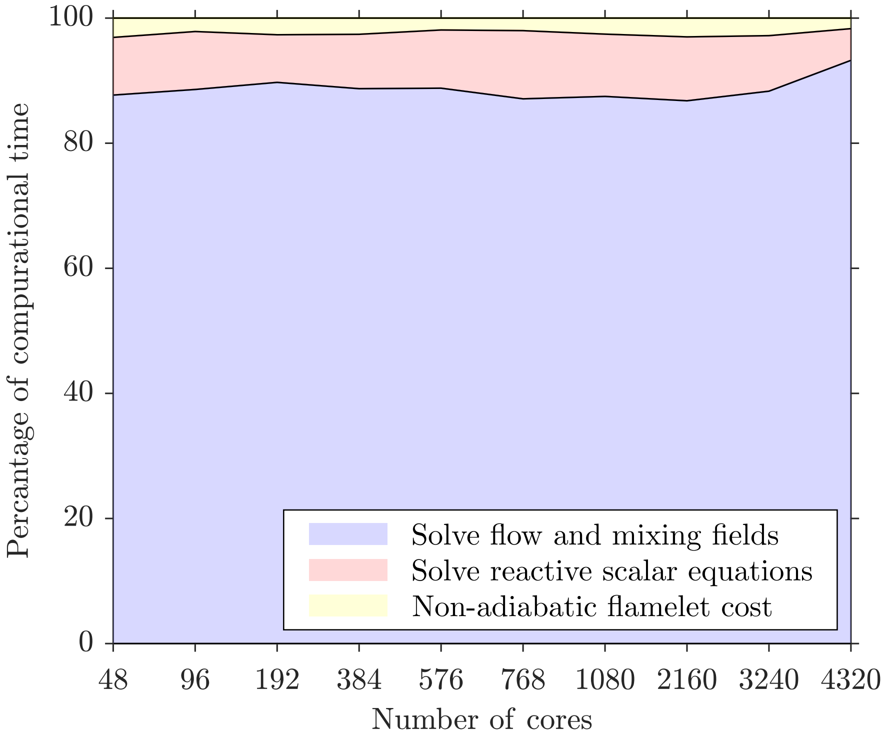
Case	AD	NAW	NAF
Fixed temperature BCs	N	Y	Y
Non-adiabatic flamelets	N	N	Y



2. Numerical detail

ARCHER UK scaling



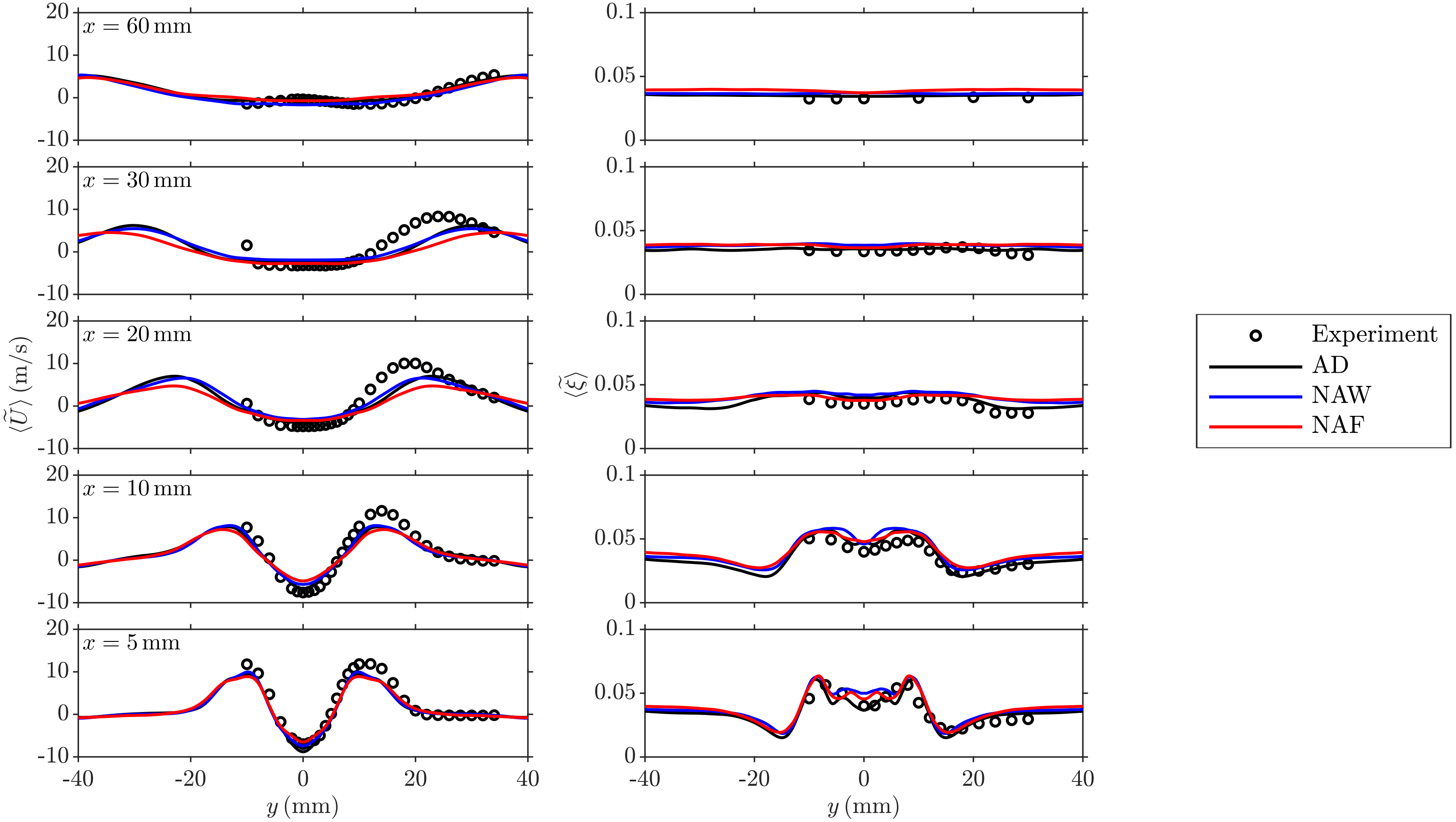


- A 1080 core 24 hr job is approximately 400 kAU, which gives 24 ms of statistics.

Outline

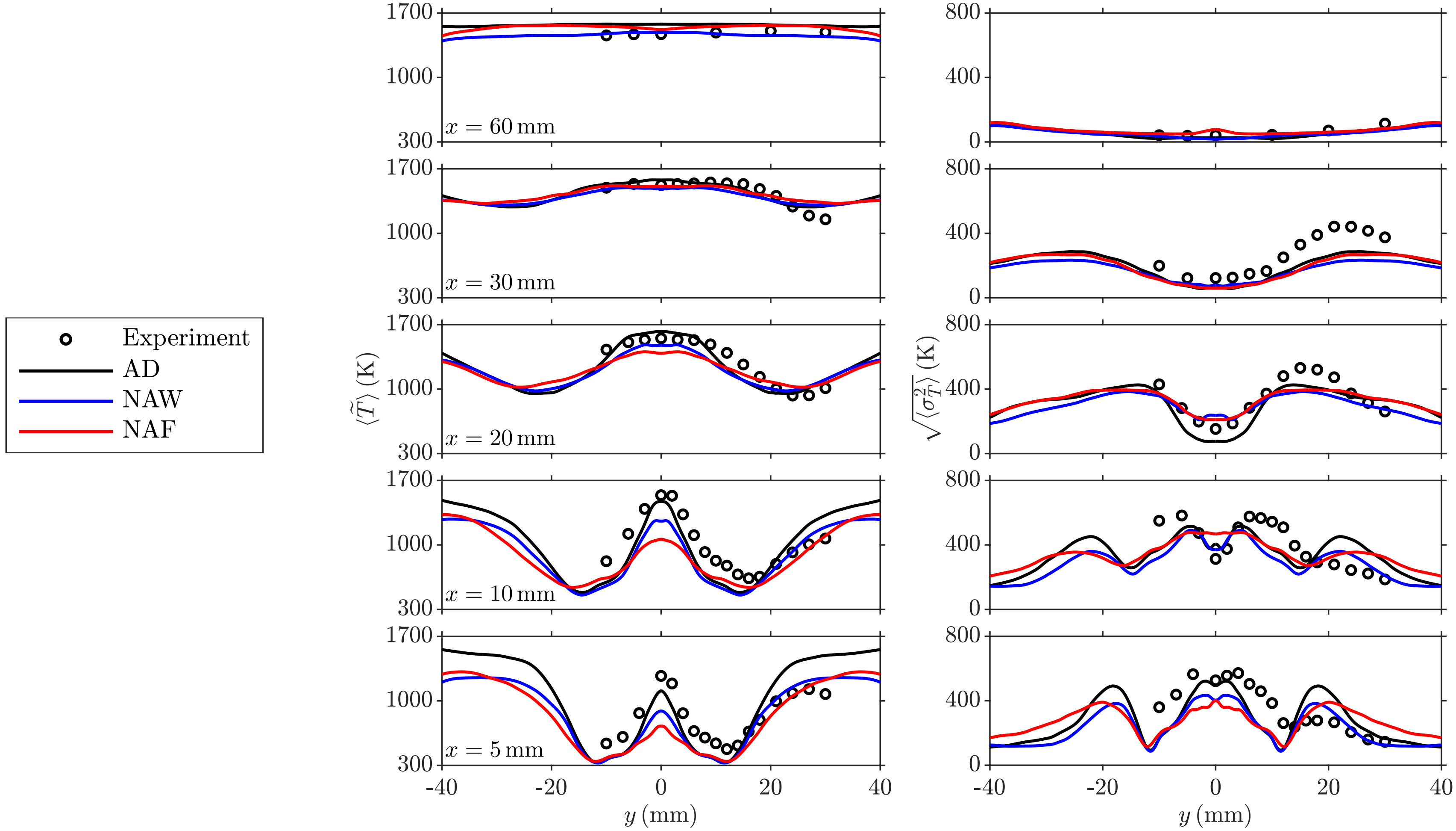
3. Results

Axial velocity and mixture fraction profiles



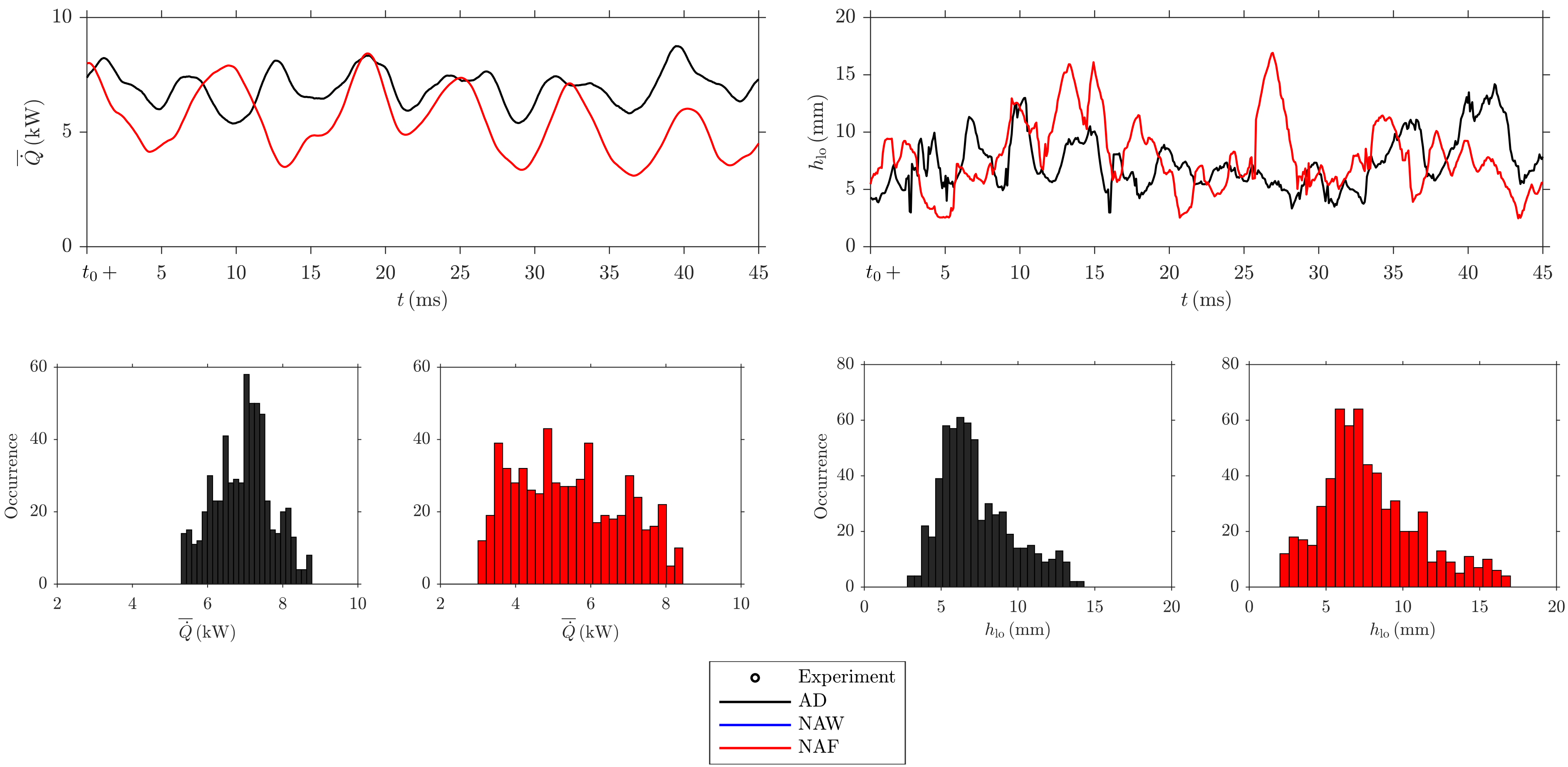
3. Results

Temperature profiles



3. Results

Heat release rate and lift-off height



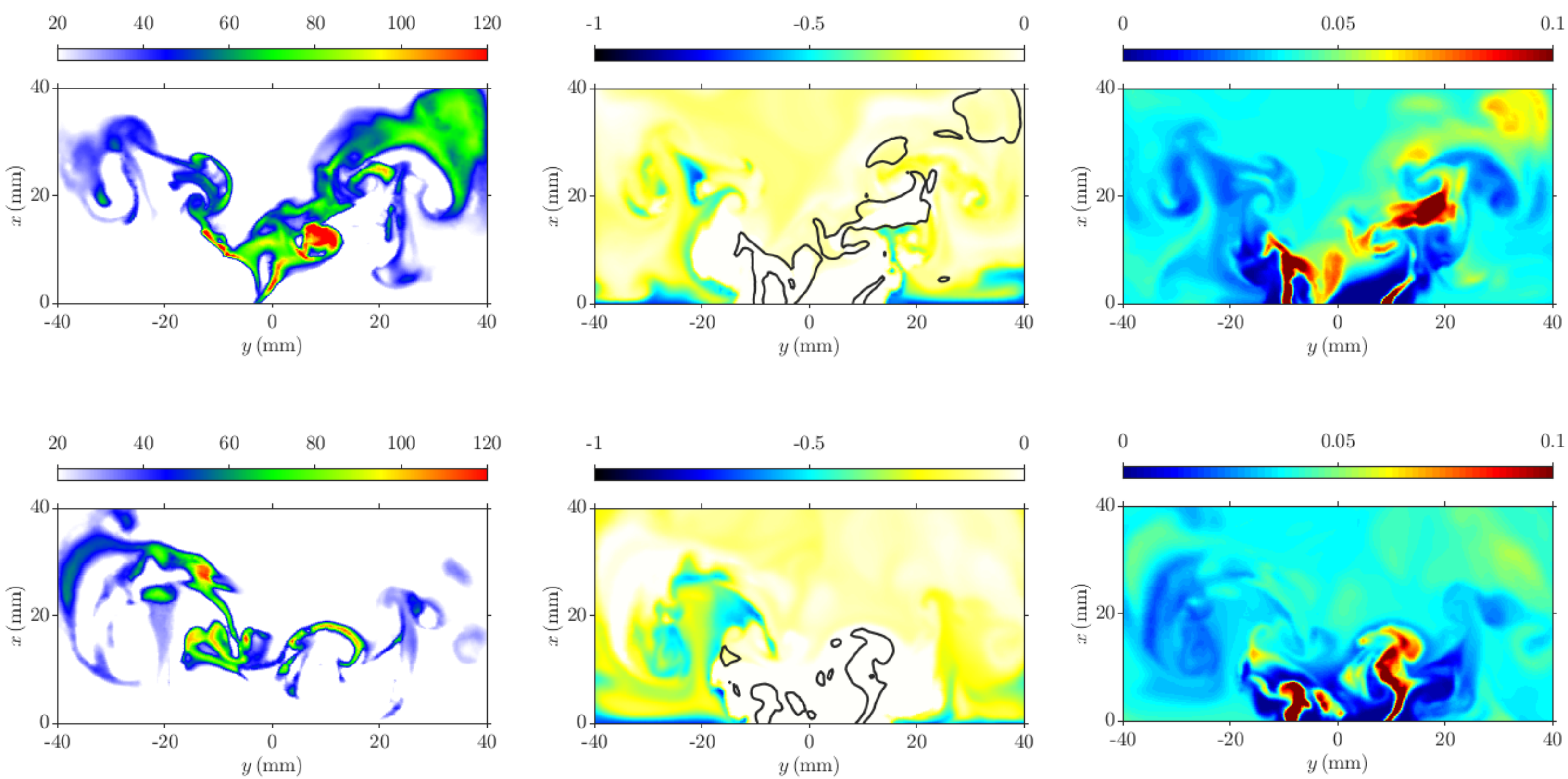
3. Results

Established flame root vs. maximum lift-off height

Reaction rate | Enthalpy deficit | Mixture fraction

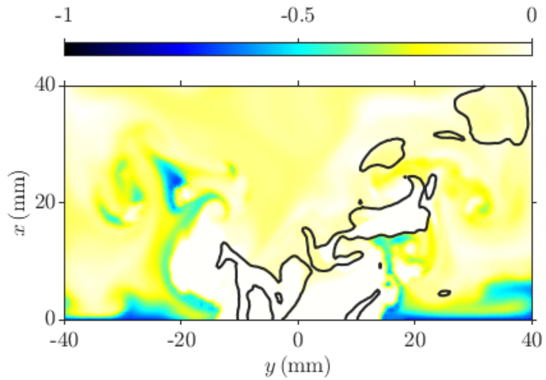
Established flame root

Maximum lift-off height

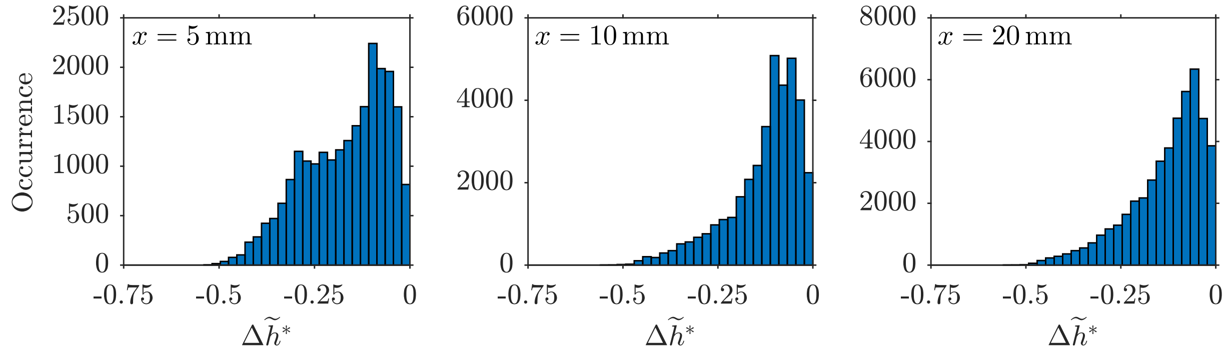


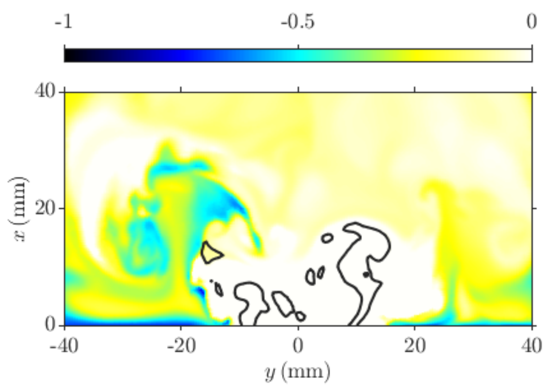
3. Results

Established flame root vs. maximum lift-off height (cont.)

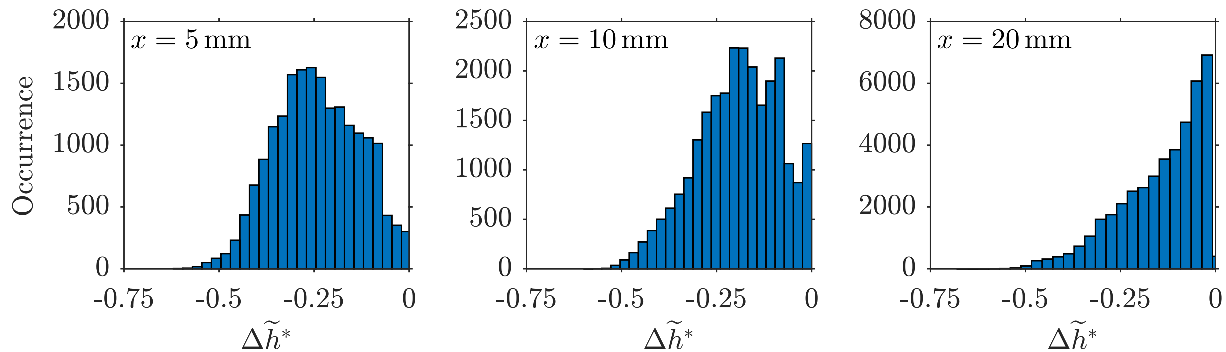


Established flame root





Maximum lift-off height



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4. Summary

- Two simulations with non-adiabatic modelling are compared to a fully adiabatic flame close to blow-off.
- The non-adiabatic flamelet model is implemented using a heat release damping method.
- Differences are seen in the temperature profiles and lift-off height/HRR time series.
- The non-adiabatic flamelet case is highly unstable and further analysis is needed to ascertain its blow-off behaviour.

Thank you for listening. Any questions?

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