Correlation of Heat Loss with Quenching Distance During Transient Flame-Wall Interaction

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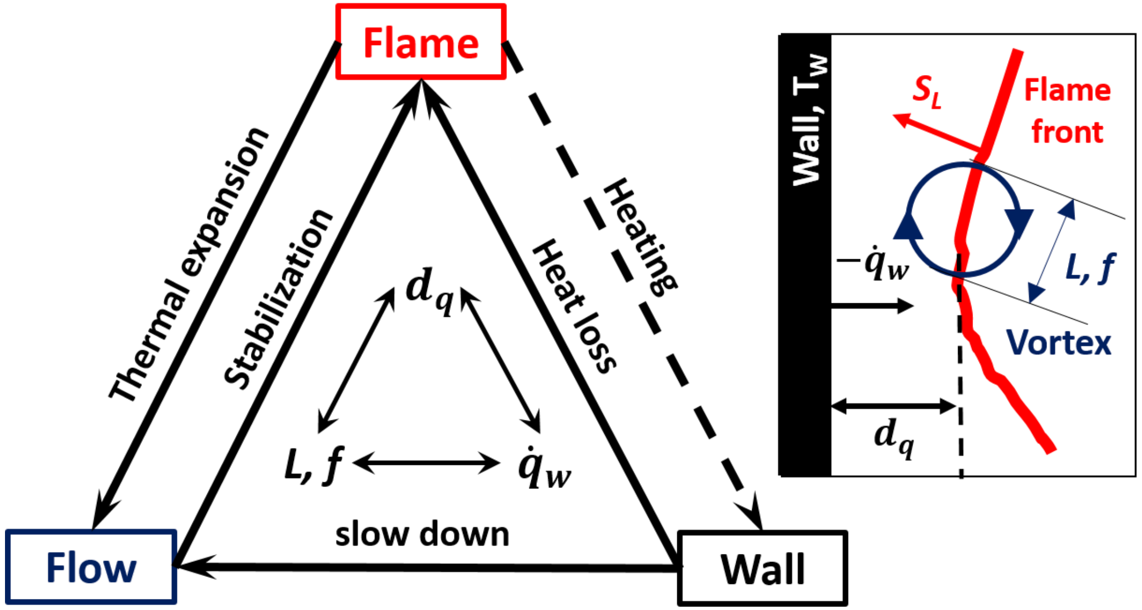
Motivation

Flame – Turbulence – Wall Interaction

- Turbulent combustion in confined spaces
  - Flame quenching close to walls leads to problems with flame stabilization and pollutant formation
  - High computational cost using finite rate chemistry
  - Uncertainties with tabulated chemistry
  - Need for advanced modelling concepts for **turbulent** FWI

Effect of flow unsteadiness on FWI?

Swirl-stabilized combustion in a confined chamber



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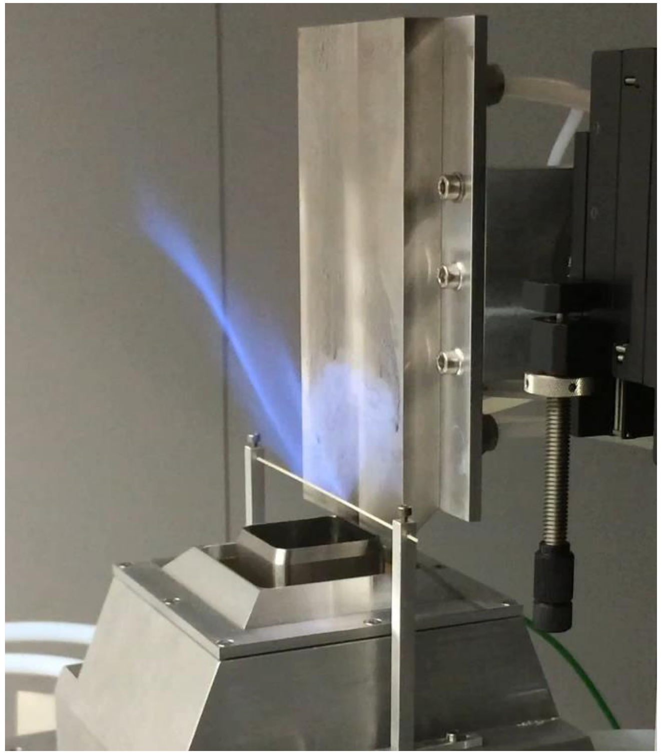
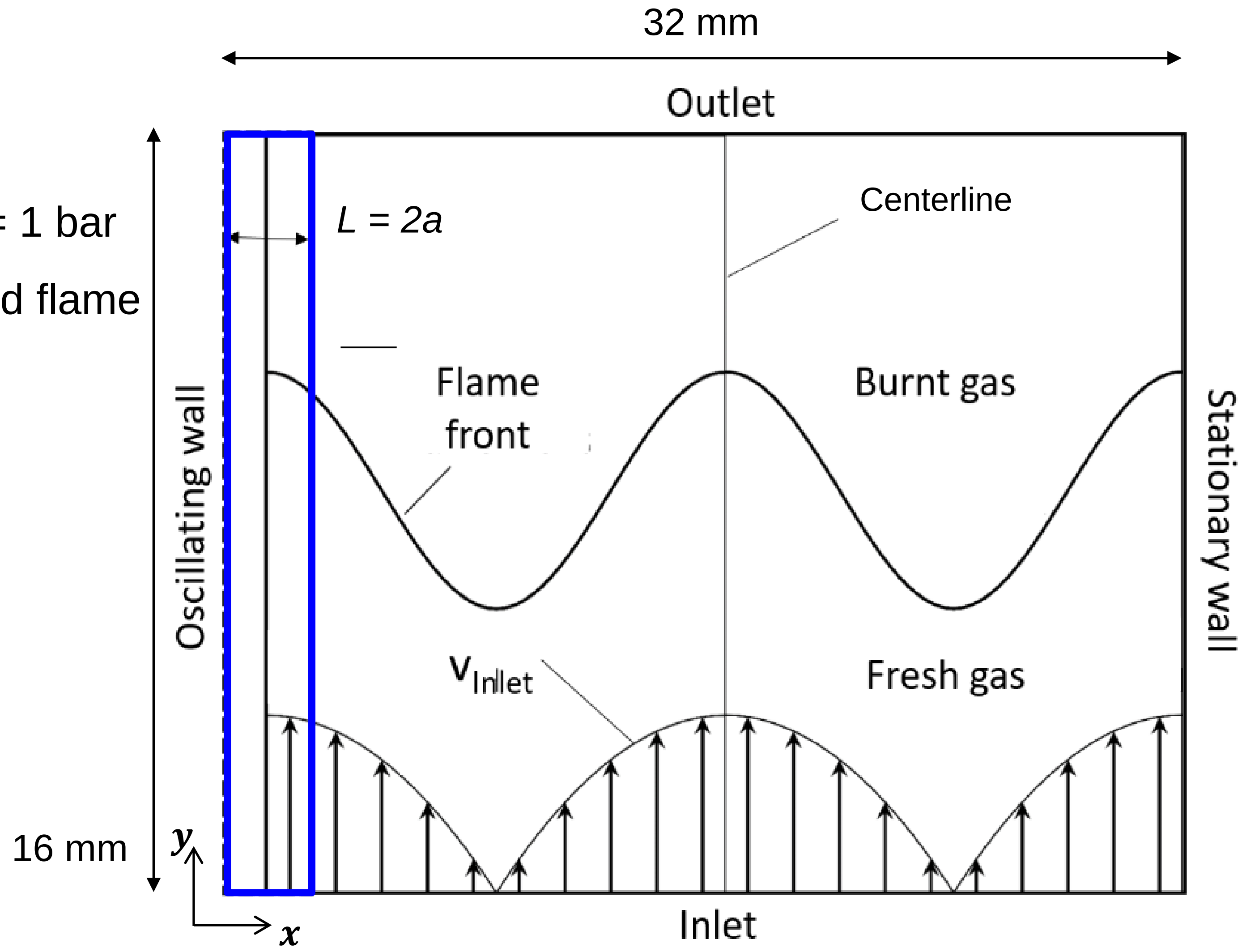


Numerical setups

Detailed simulation of unsteady SWQ

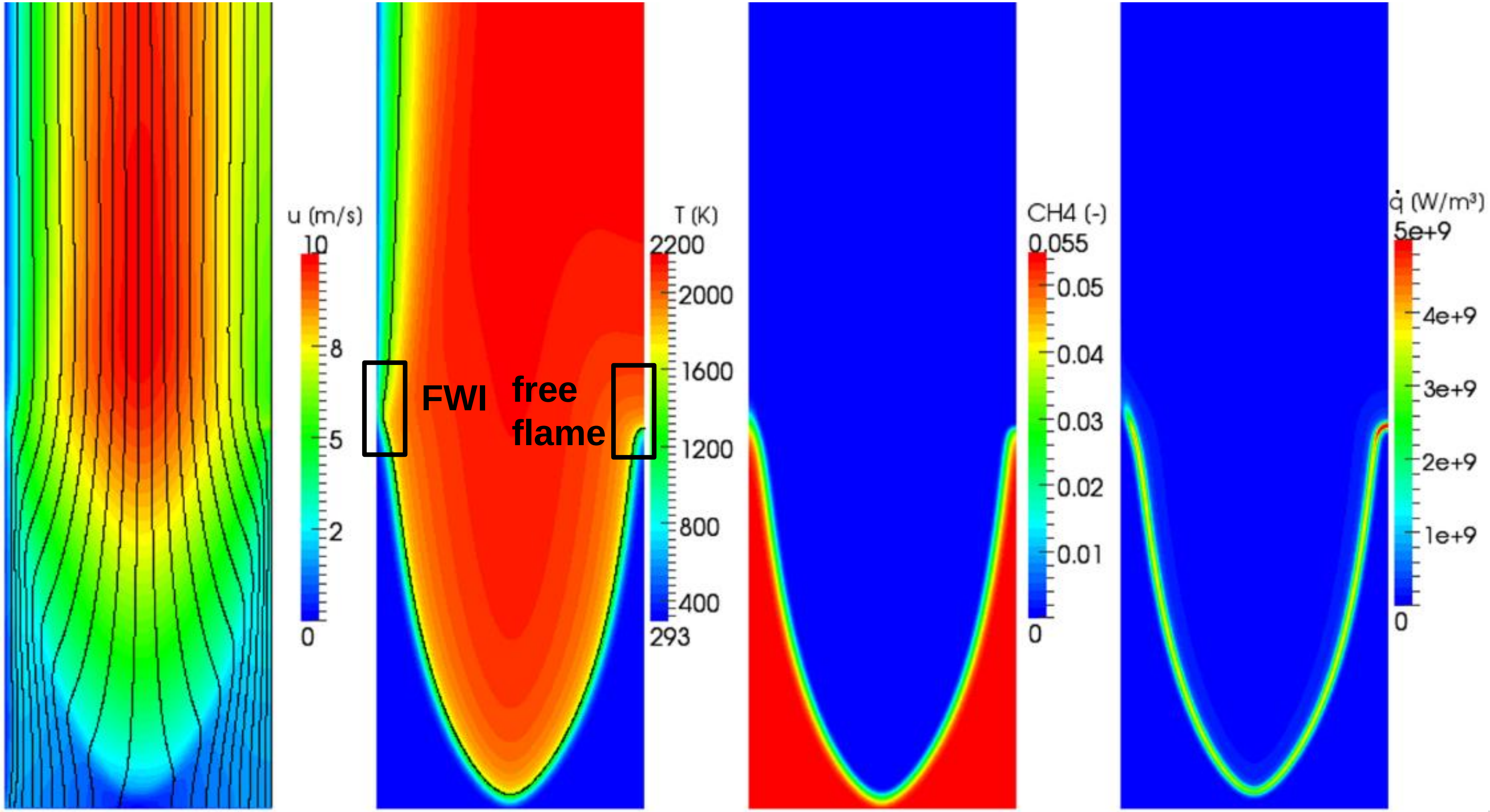
- OpenFOAM/2D, compressible
- Mixture-averaged transport
- Finite rate chemistry (GRI-3.0)
- Premixed CH_4/air at $\Phi = 1$, $T_0 = 20$ °C, $p_0 = 1$ bar
- Parabolic inlet velocity profiles → W-shaped flame
- **Left: oscillating moving wall**
- Right: stationary wall
- $T_{w,left} = T_{w,right} = 20$ °C
- $x_{w,left} = -a \cdot sin\left(2\pi f t + \frac{\pi}{2}\right)$
  - $f = 0, 50, 100, 200, 400$ Hz
  - $a = 1\,\text{mm}, 2\,\text{mm}$
- Equidistant grid: $\Delta = 40$ µm



Steady – state solution

Steady – state solution

Streamwise velocity | Temperature | Mass fraction of CH_4 | Heat release rate



Free flame vs. SWQ flame

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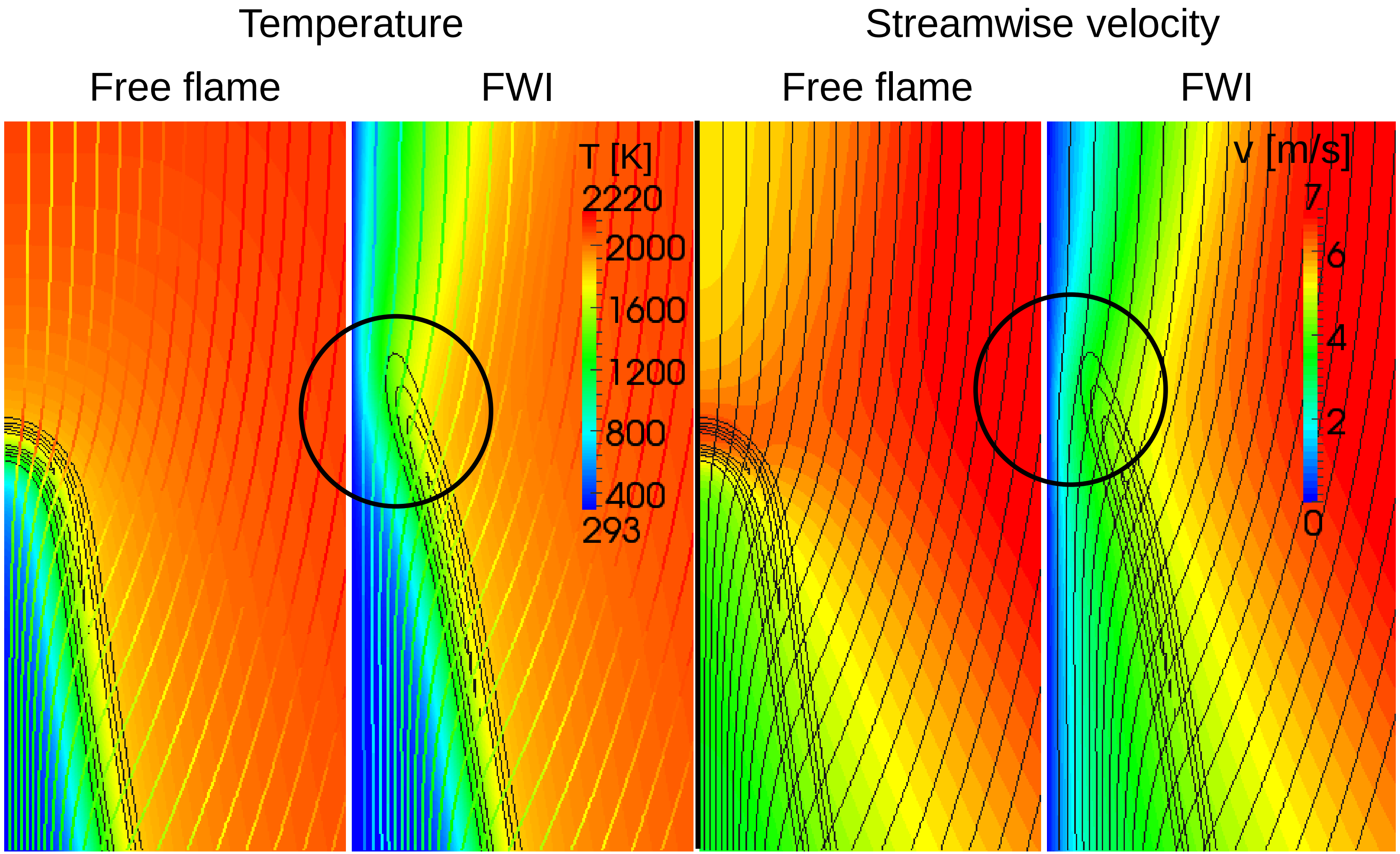
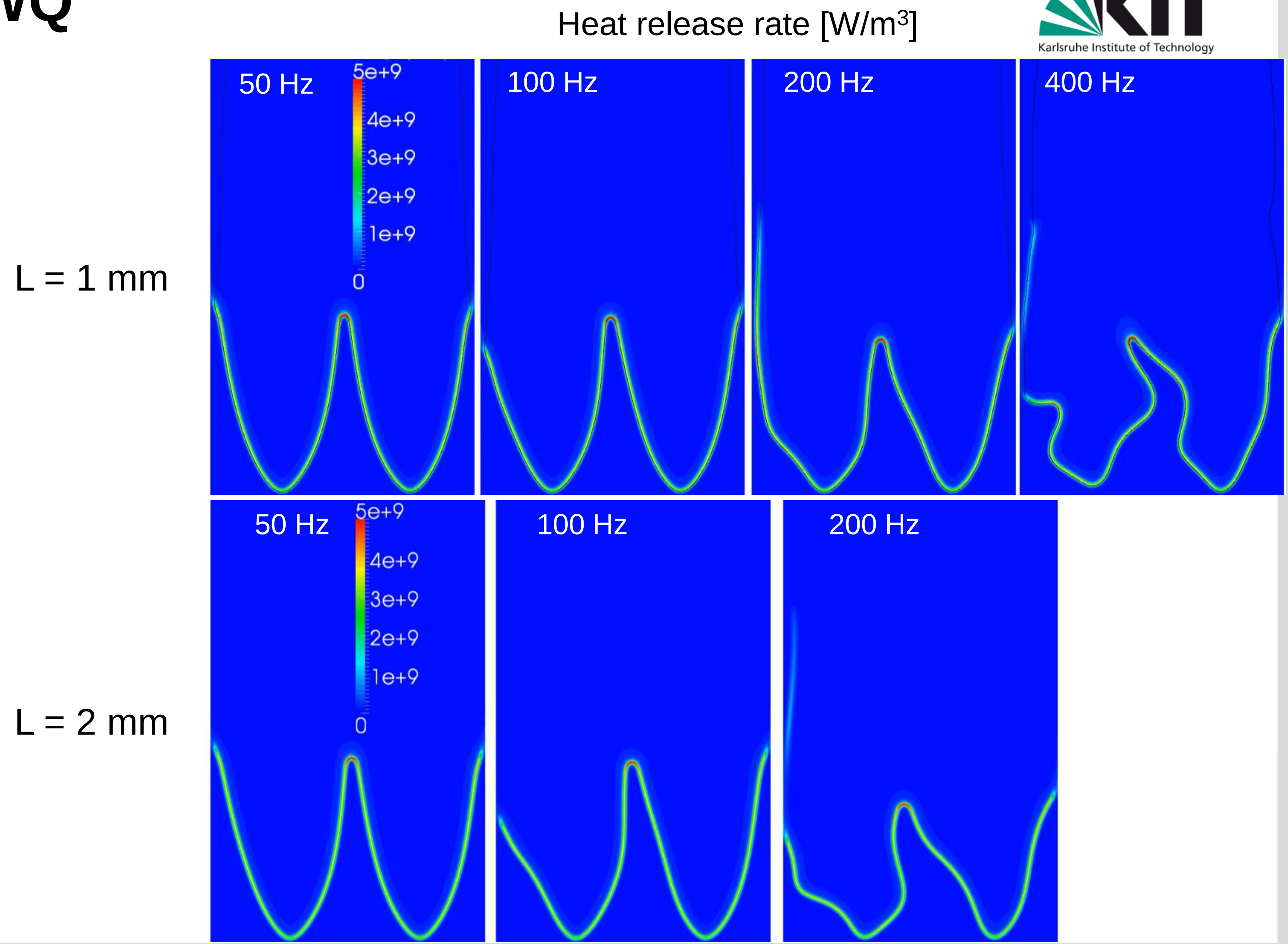
- Local balance between flame dynamics/propagation speed and near-wall flow



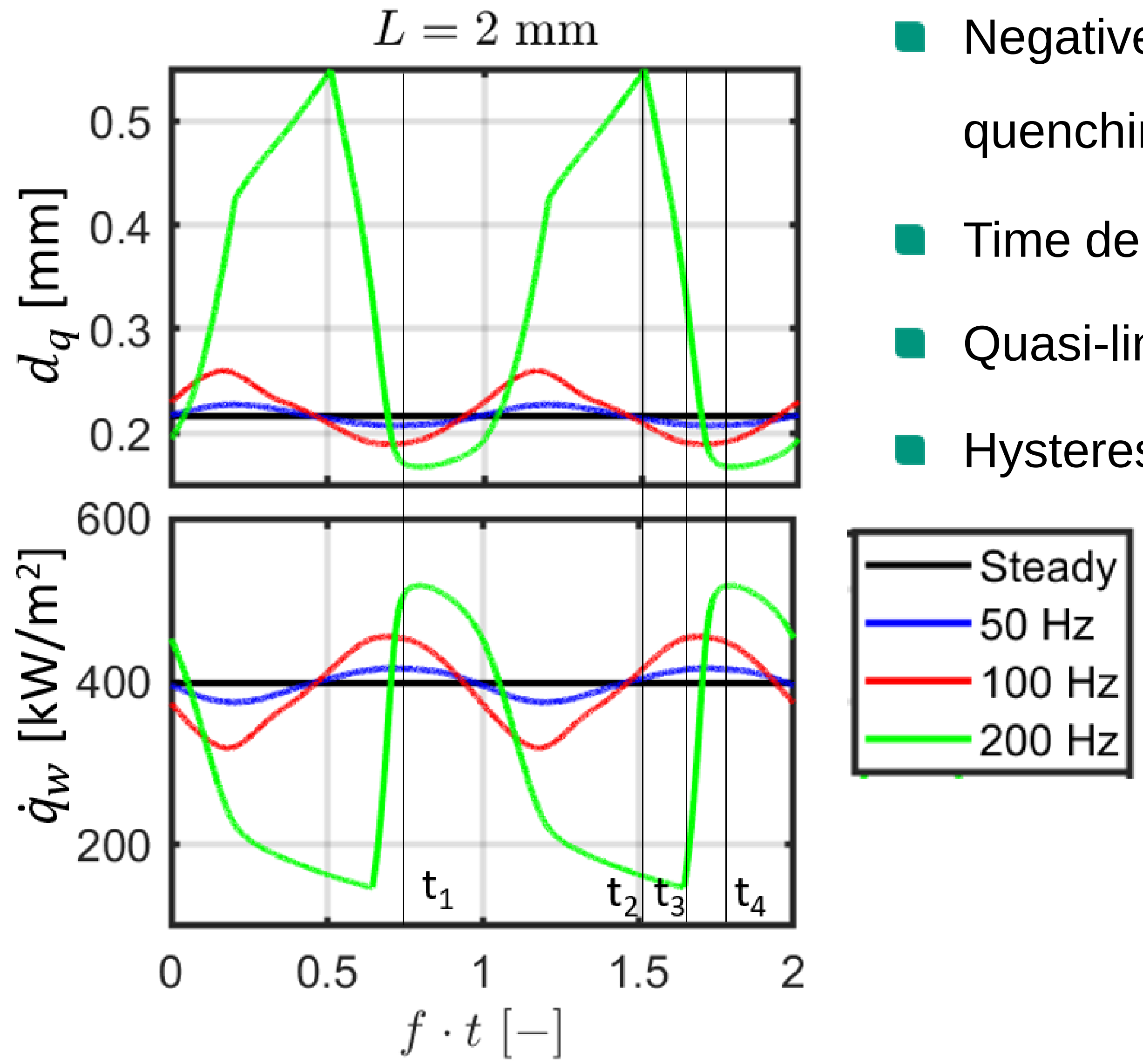
Unsteady FWI

DNS of unsteady SWQ

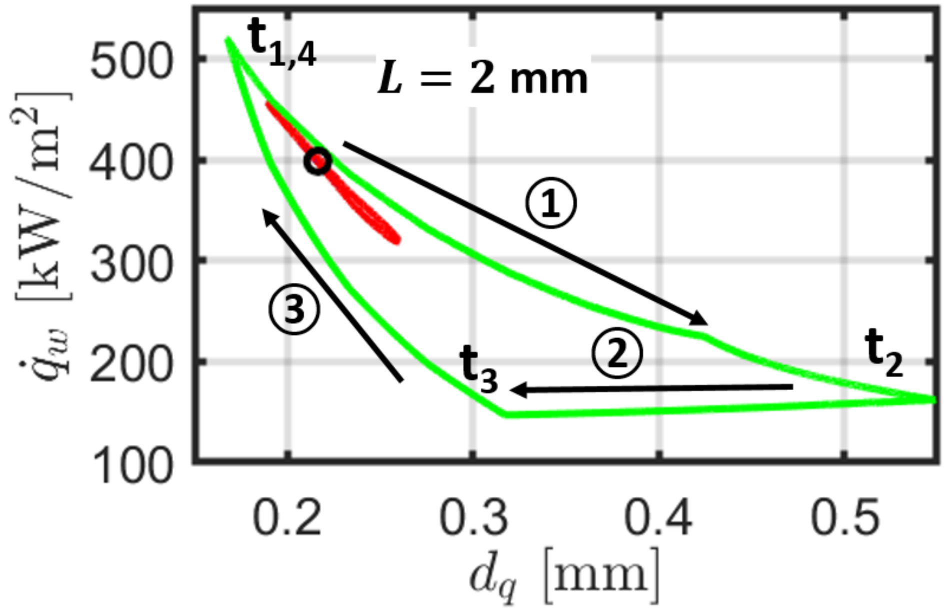
- Unsteady relative motion between flame and wall
- left flame branch interacts with the moving wall and right flame branch with the stationary wall
- Wrinkling of flame with multiple FWI zones in case of large f



Quenching distance and wall heat flux



- Negative correlation for wall heat flux $\dot{q}_w$ vs. quenching distance d_q
- Time delay between $\dot{q}_w$ and d_q for $f = 200$ Hz
- Quasi-linear correlation for small f (50 and 100 Hz)
- Hysteresis loop for $\dot{q}_w$ vs. d_q for $f = 200$ Hz



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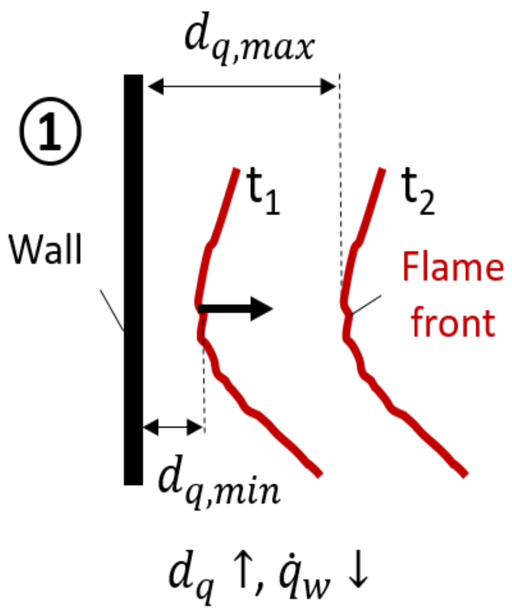
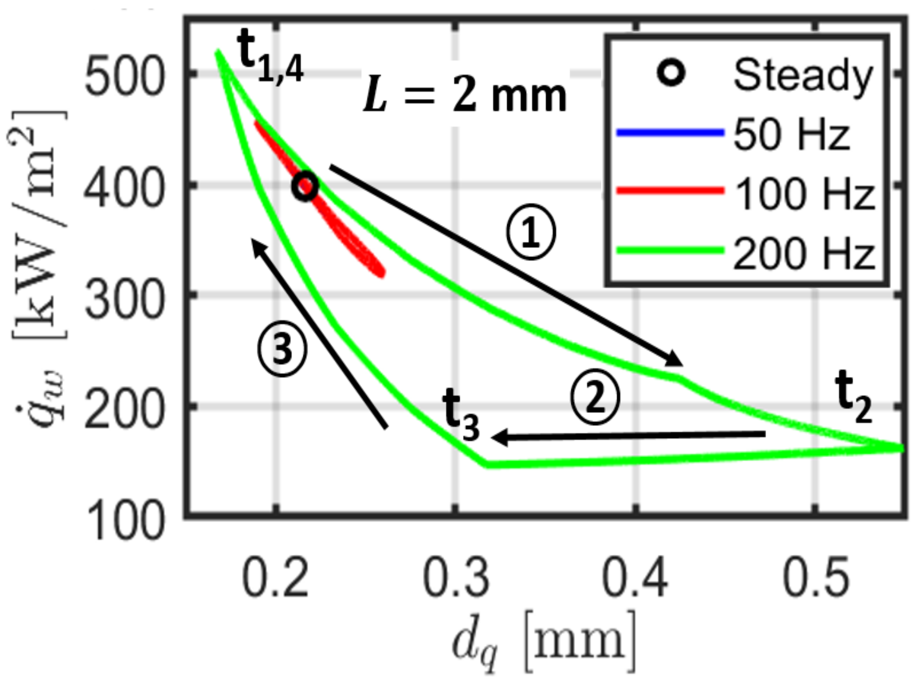
Flame dynamics

Mechanism of transient flame-wall interaction

① Flame moves away from wall to the maximum d_q:

prompt response with $d_q \uparrow$, $\dot{q}_w \downarrow$





- Unsteady flow: $u' \rightarrow d_q' \rightarrow T' \rightarrow \dot{q}_w'$

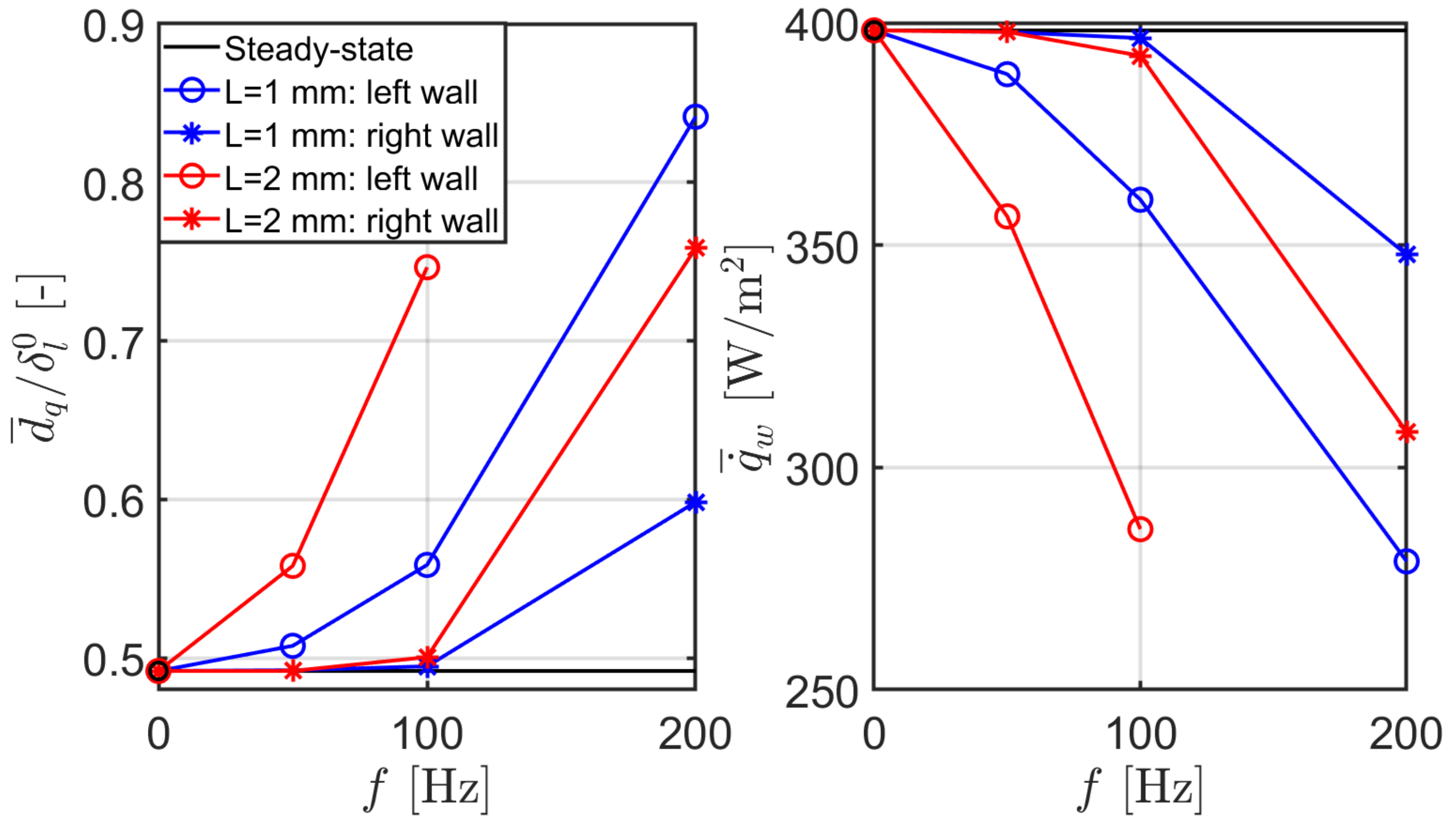
→ Fluctuations of S_L in time

- Delayed response of $\dot{q}_w$ with respect to d_q at maximum d_q

Impact of unsteady FWI

Time-mean quenching distance and wall heat flux

- Increase of $\bar{d}_q$ up to 80% under unsteady conditions compared with steady-state solution
- Stronger impact for increased fluctuation length scales and frequencies

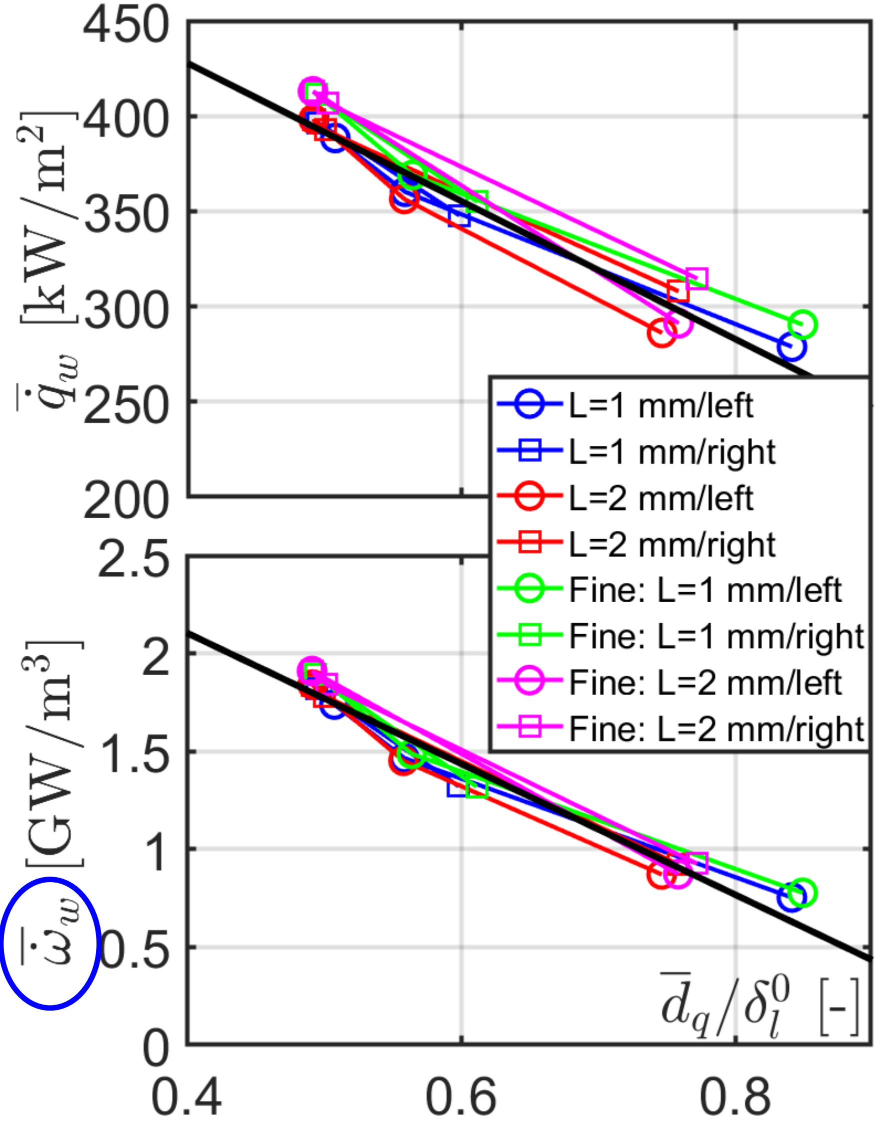


Wall heat loss

- Quasi-linear correlation between wall heat loss and quenching distance
- near-wall Peclet number: $Pe = \overline{d}_q / \delta_{L0}$
- Wall heat loss within FWI: $\overline{\dot{\omega}}_w = \overline{\dot{q}}_w / \overline{d}_q$
- Validation of grid resolution
- Modelling effect of unsteady FWI

$$\frac{\partial \overline{\rho} \widetilde{H}}{\partial t} + \nabla \cdot \left(\overline{\rho} \widetilde{\vec{u}} \widetilde{H} \right) - \frac{\partial \overline{p}}{\partial t} =$$

$$-\nabla \cdot \overline{\vec{j}}_q + \overline{\dot{q}}_r + \rho \widetilde{\vec{u}} \cdot \vec{g} + \overline{\dot{\omega}}_w$$



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Summary

- Unsteady motion in wall-normal direction has a significant impact
  - Increase of time-mean d_q and decrease of time-mean $\dot{q}_W$ due to unsteady FWI
- Physical mechanism during flame-flow-wall interaction under unsteady condition
  - Delayed responses between d_q and $\dot{q}_W$ in high frequency range
- Quasi-linear correlation between time-mean wall heat loss and Peclet number, which could be used for modeling unsteady FWI

Thank you for your attention!