Dr.-Ing. Matthias Steinhausen

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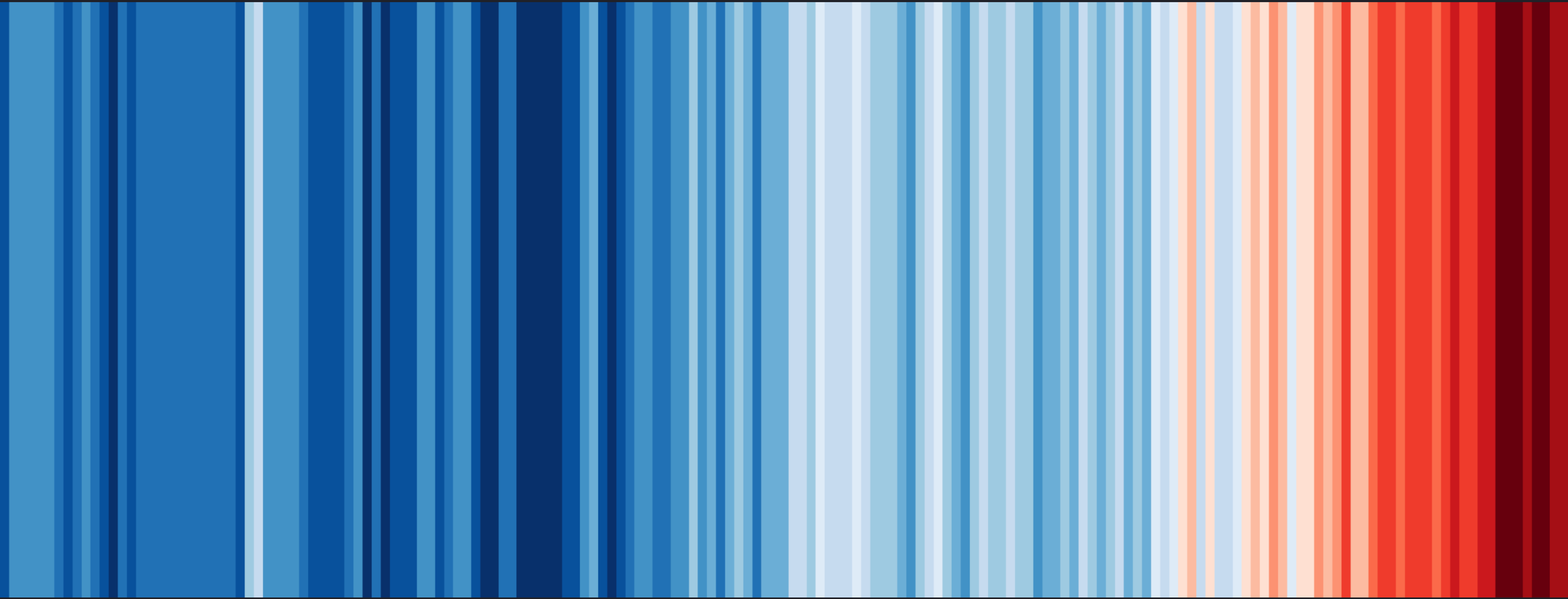
Modeling of near-wall flame dynamics in laminar and turbulent combustion

19th DaVinci Competition

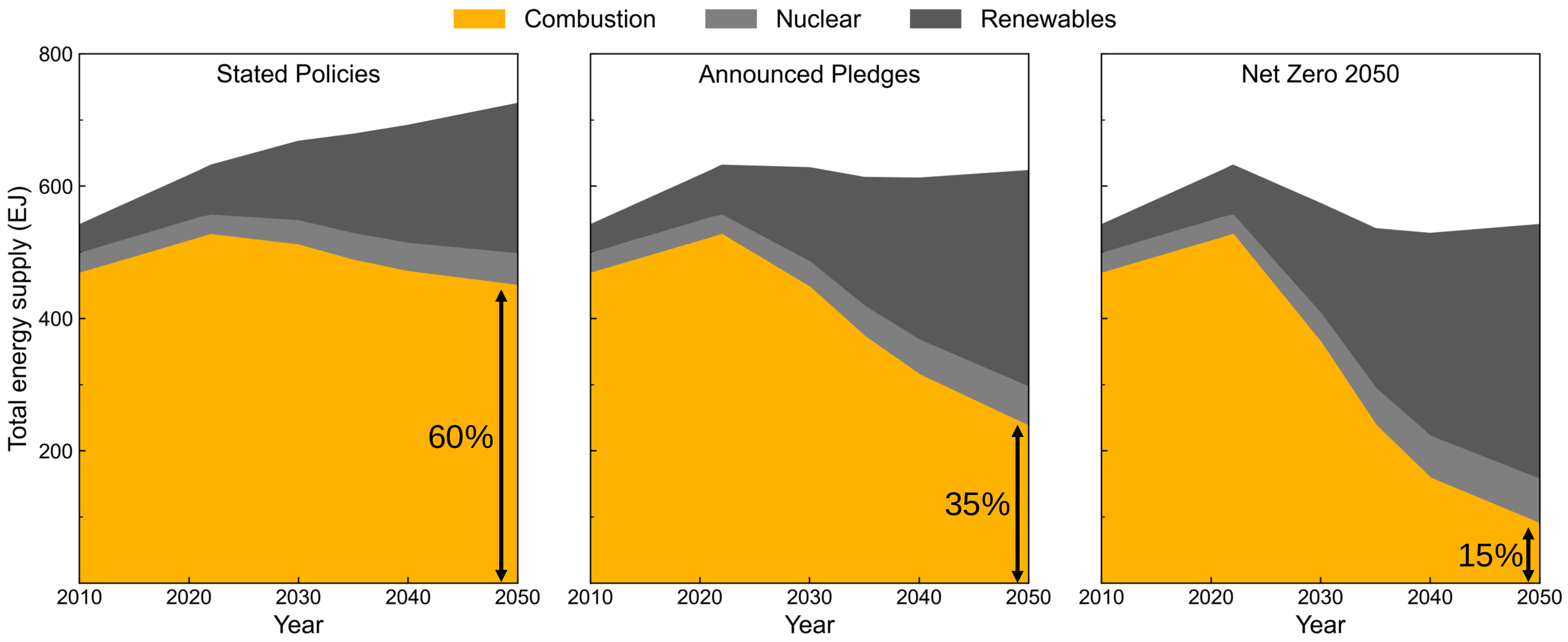
21.10.2024

Source of video: A. Gruber



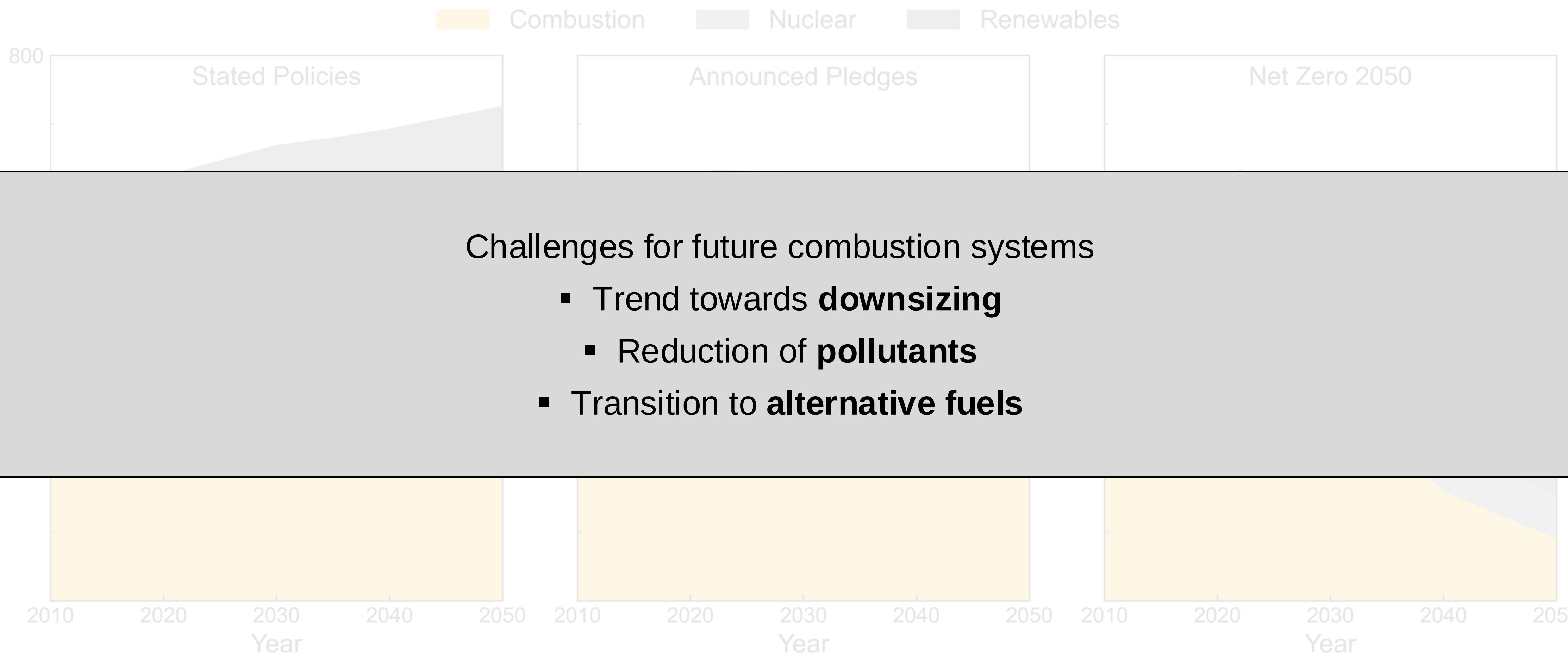
Source: Ed Hawkins “Climate stripes 1850-2022.” https://showyourstripes.info/

Outlook on future energy system



Source: IEA World Energy Outlook 2023 Free Dataset

Outlook on future energy system

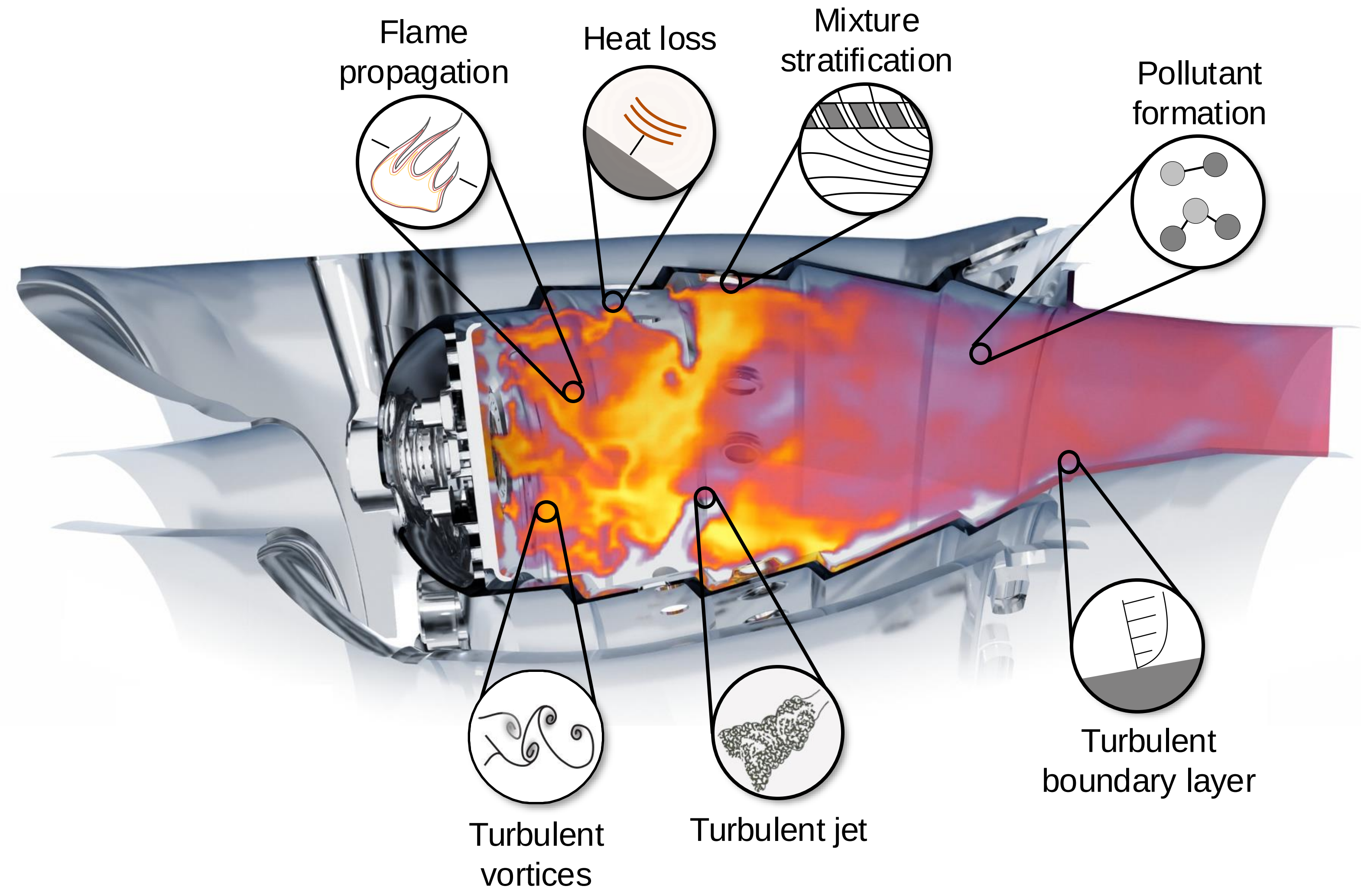


Challenges for future combustion systems

- Trend towards **downsizing**
- Reduction of **pollutants**
- Transition to **alternative fuels**

Source: IEA World Energy Outlook 2023 Free Dataset

Simulation of a turbulent combustion system



Turbulence & mixing

Turbulence chemistry interaction

Chemistry

Source: doi.org/10.48328/tudatalib-1286

Chemistry closure approaches

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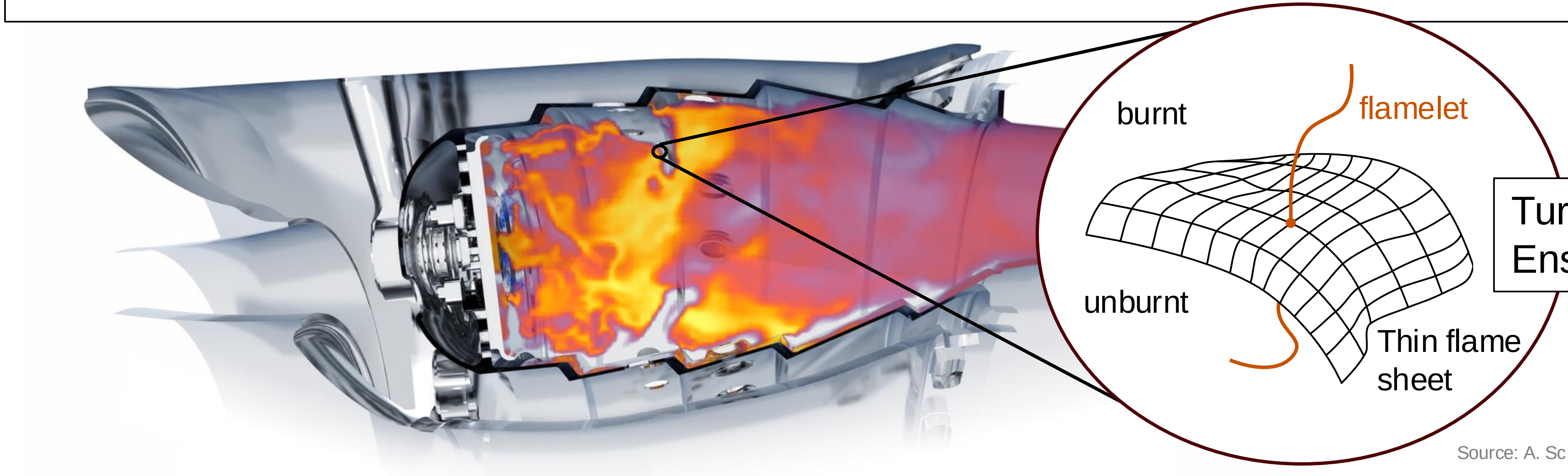
The chemical system is described by the **thermochemical state** $\boldsymbol{\Psi} = [\boldsymbol{p}, \boldsymbol{h_s}, \boldsymbol{Y_1}, \dots, \boldsymbol{Y_N}]$.
Given $\boldsymbol{\Psi}$ the flame reactivity, pollutant formation and mixture properties $(\rho, \mu, \dots)$ can be determined.



Turbulent flames ≈
Ensembles of 1D flamelets

Source: A. Scholtissek, PhD thesis, 2018

Finite rate chemistry

- **Direct calculation** of the thermochemical state
- *O*(100) species and *O*(1000) reactions
- High computational costs

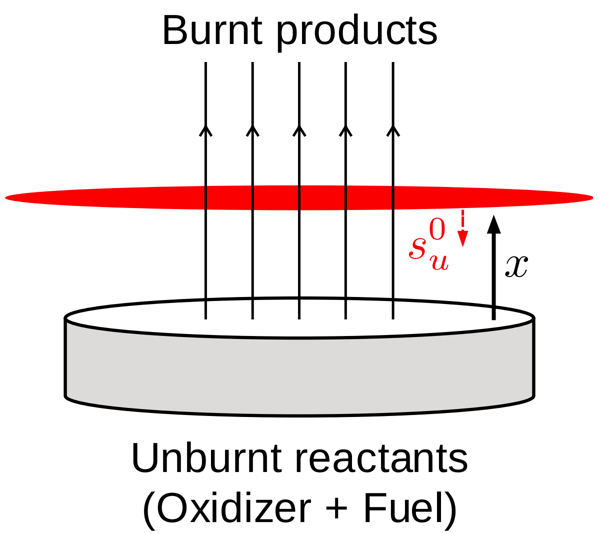
Chemistry manifolds

- **Approximation** of the thermochemical state
- Combustion chemistry is fast compared to flow
- Orders of magnitude lower computational costs

Construction of chemistry manifolds

1D flamelet

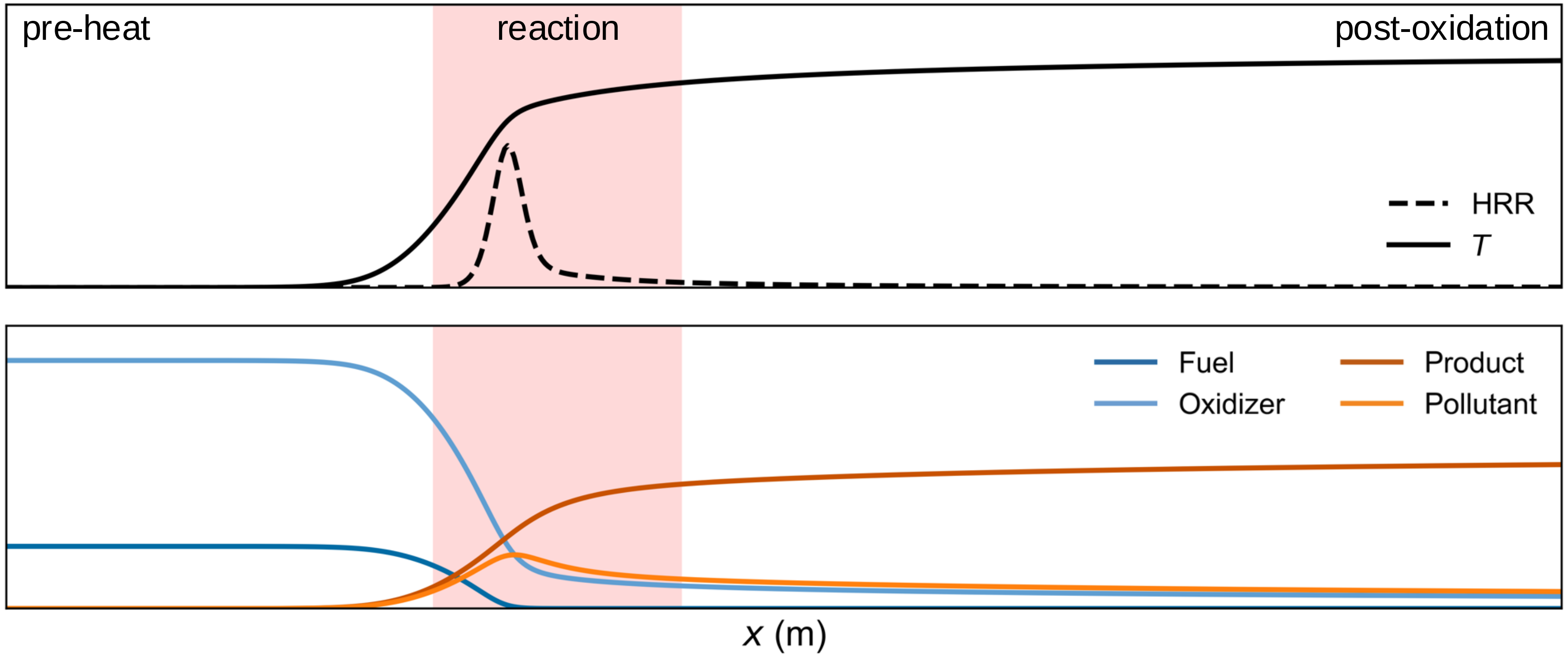
Premixed flame



Flame structure

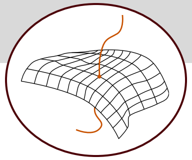
Full thermochemical state

$\Psi = [p, T, Y_1, \dots Y_N]$

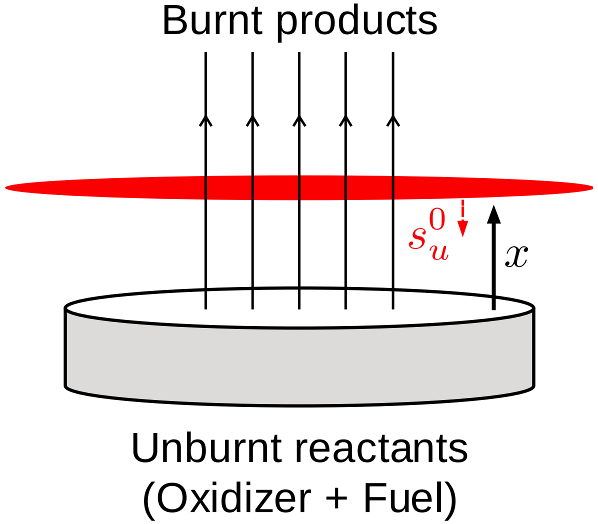


Construction of chemistry manifolds

1D flamelet



Premixed flame

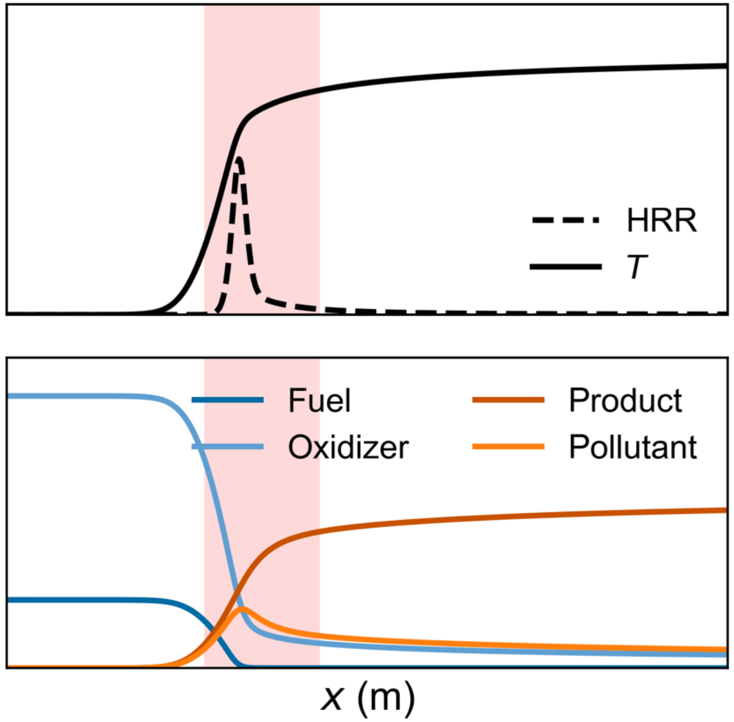


Tabulation →

Flamelet database

Full thermochemical state

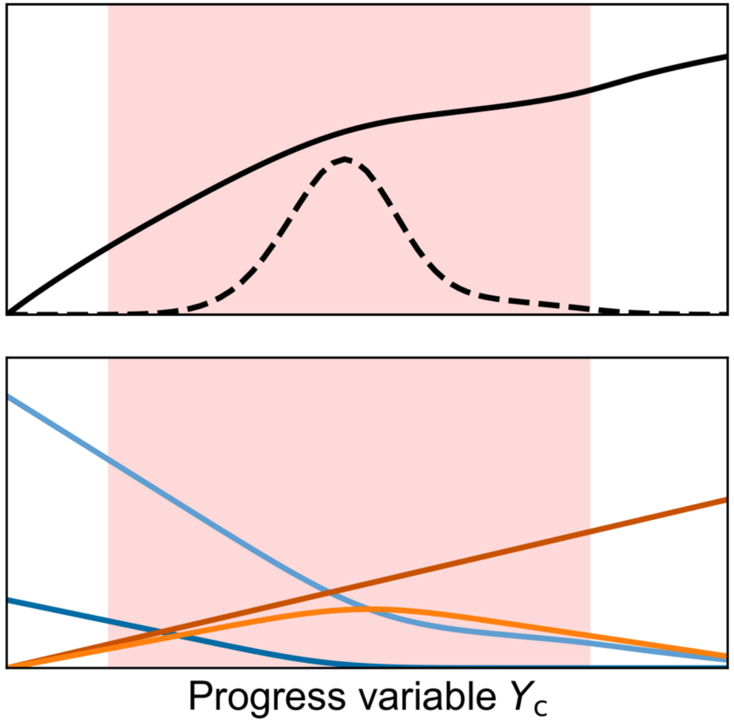
$\Psi = [p, T, Y_1, \ldots Y_N]$



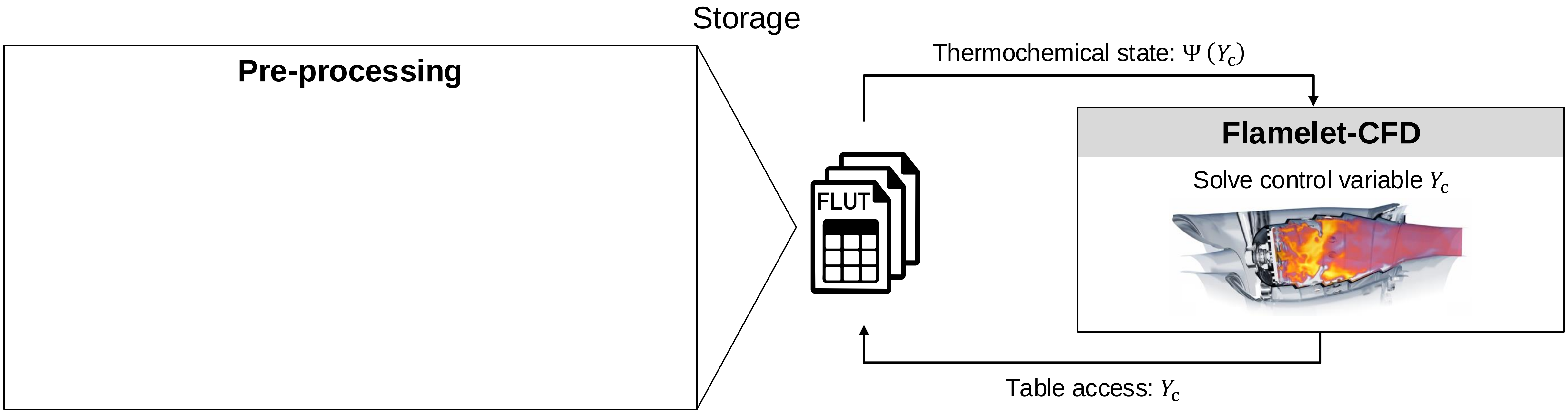
Chemistry manifold

Reduced order representation

$\Psi = \Psi\,(Y_c)$



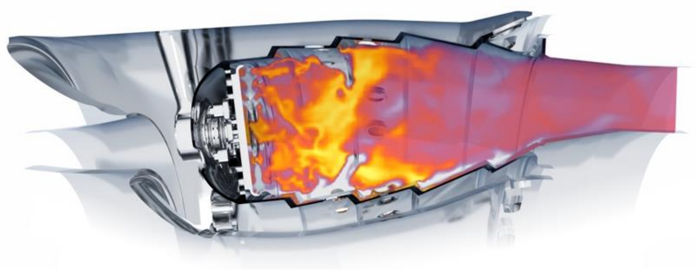
Usage of chemistry manifolds



Development of combustion models

Simplify **Understand**

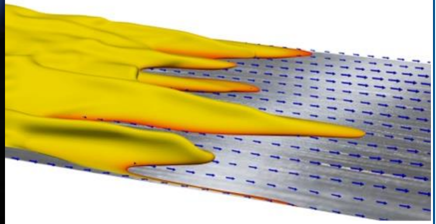
Complex application



Large eddy simulation[1]
(Chemistry manifolds)

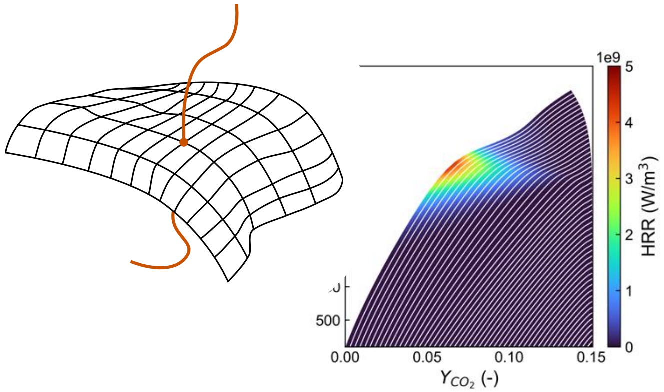
Benchmark configuration

Experiment[2]



Reference simulation
(Finite-rate chemistry)

Combustion model



Model and knowledge transfer

[1] doi.org/10.48328/tudatalib-1286 [2] Provided by F. Zentgraf from RSM

Challenges of flame-wall interaction

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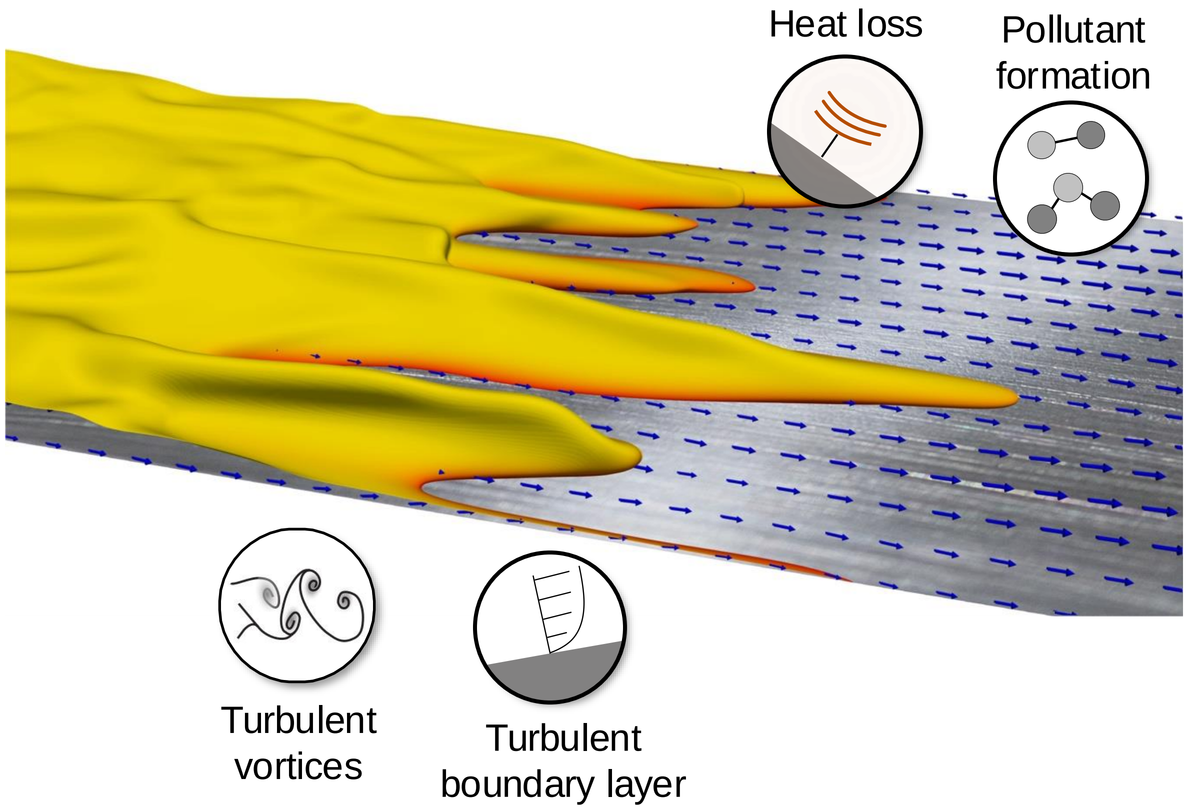
Heat loss to the wall affects flame chemistry leading to

- flame extinguishment
- incomplete combustion
- pollutant formation

These effects cannot be captured by standard combustion models[1-3]



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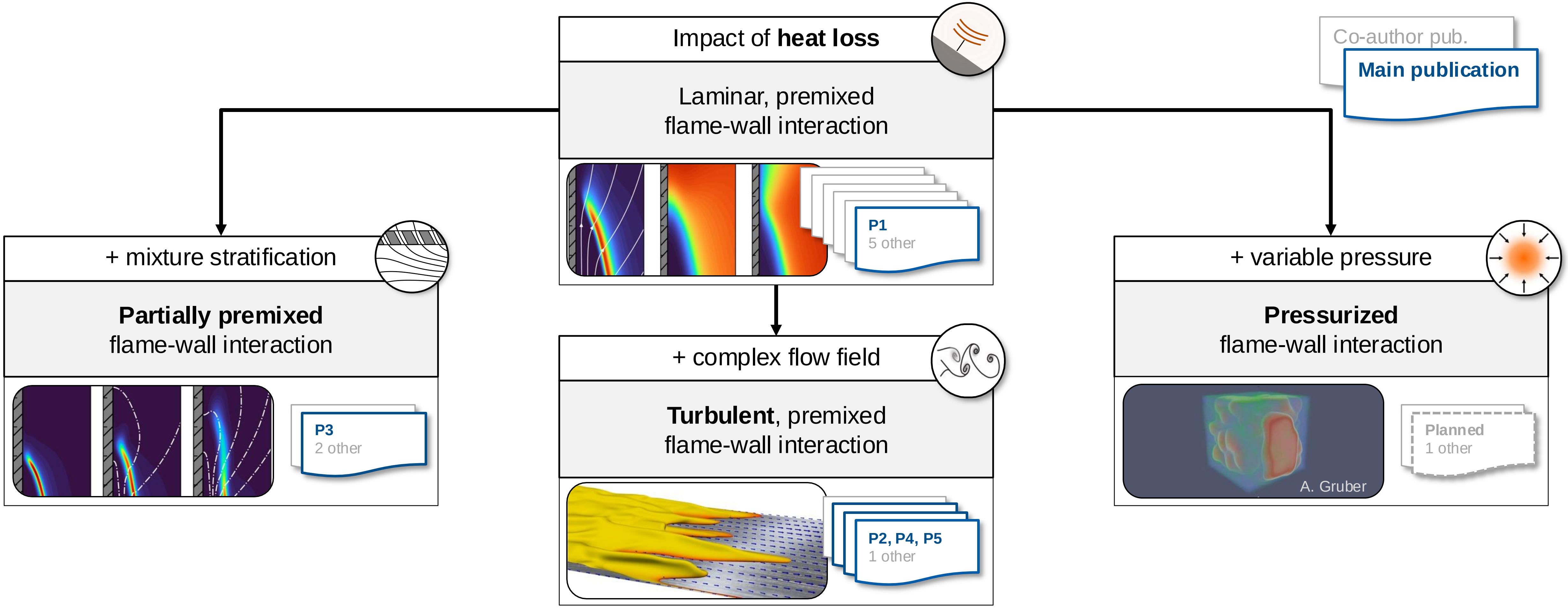
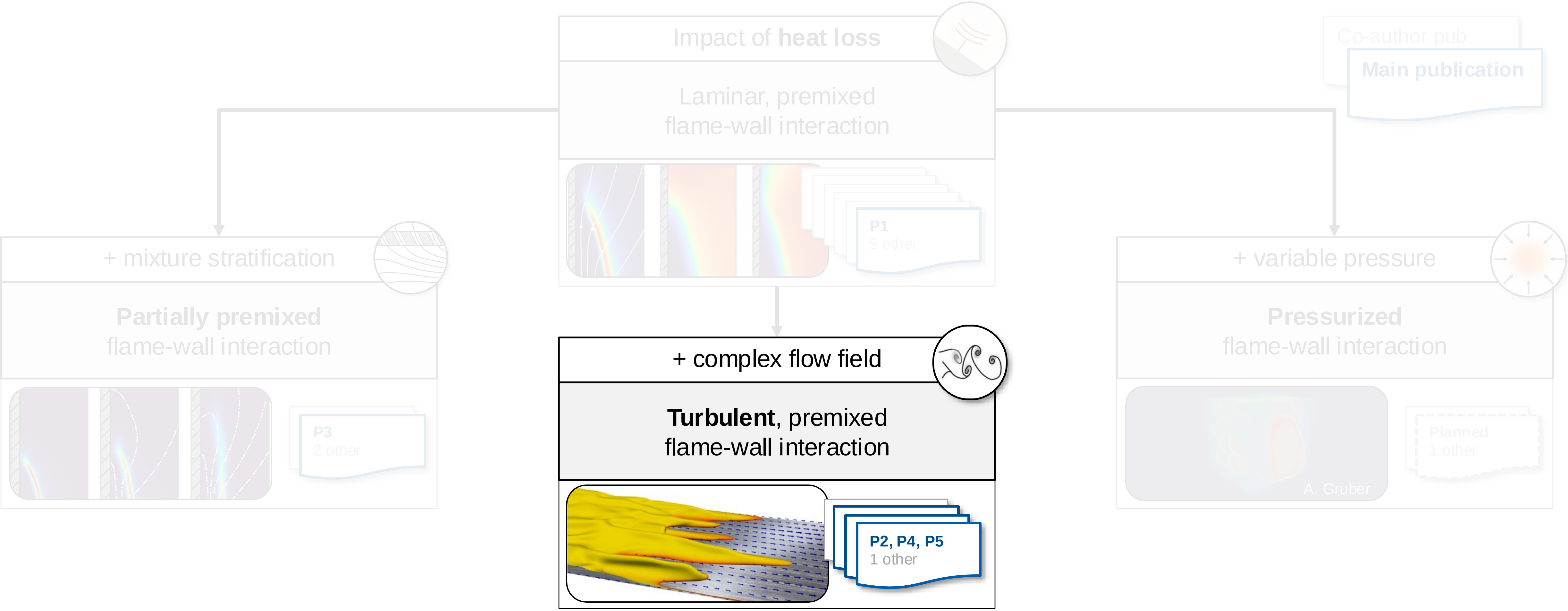
[1] Ganter et al., Combust. Flame 186, 2017
[2] Ganter et al., Int. J. Heat Fluid Flow 70, 2018
[3] Efimov et al., Combust. Theory Model. 24, 2020

Overview of the thesis



Overview of the thesis



Turbulent, premixed flame-wall interaction

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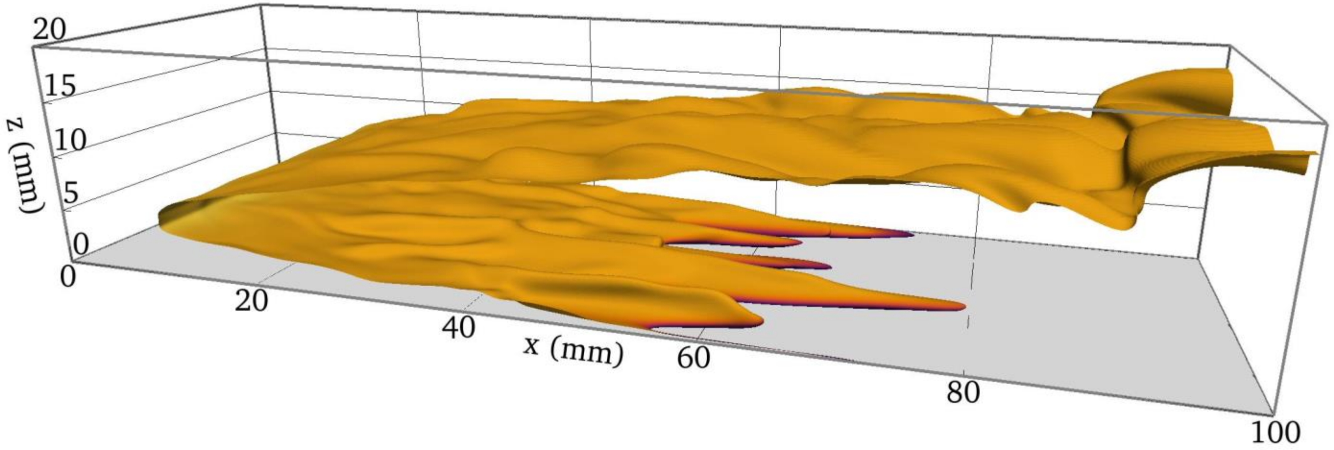
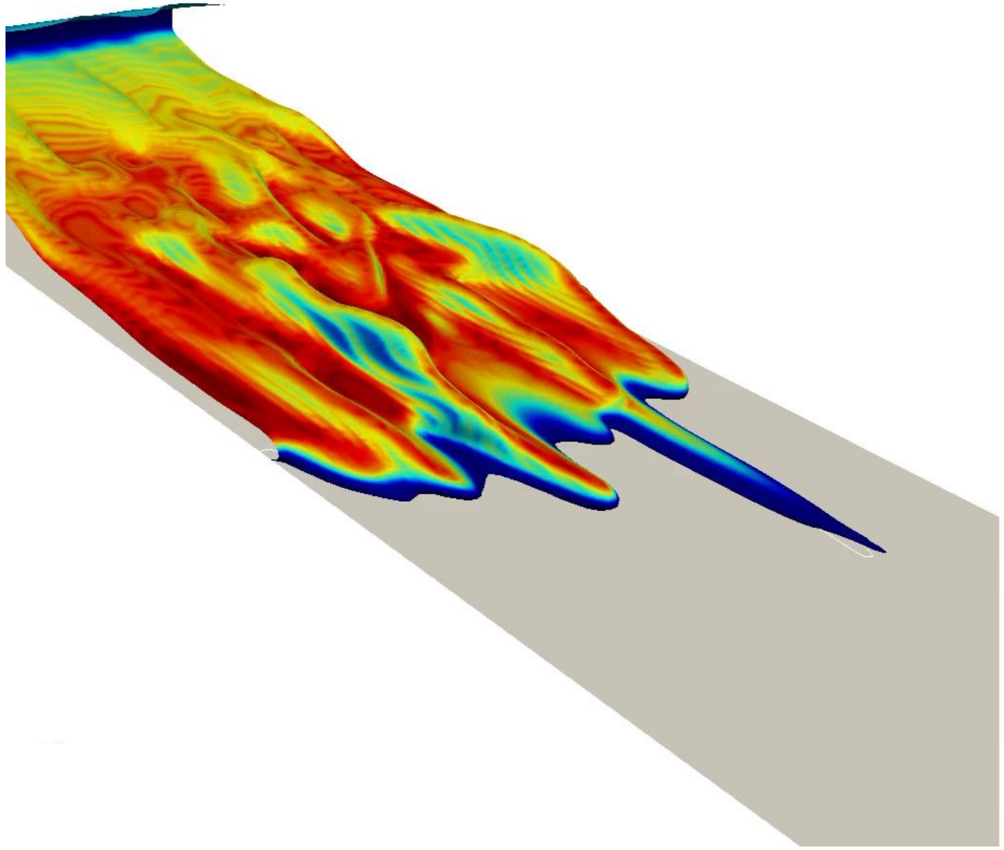
Benchmark configuration

- Complex, turbulent flow field
- Premixed methane-air flame
- **Direct numerical simulation** with finite-rate chemistry
- Simulation results are published as a dataset[1]





[1] https://doi.org/10.48328/tudatalib-673

Turbulent, premixed flame-wall interaction

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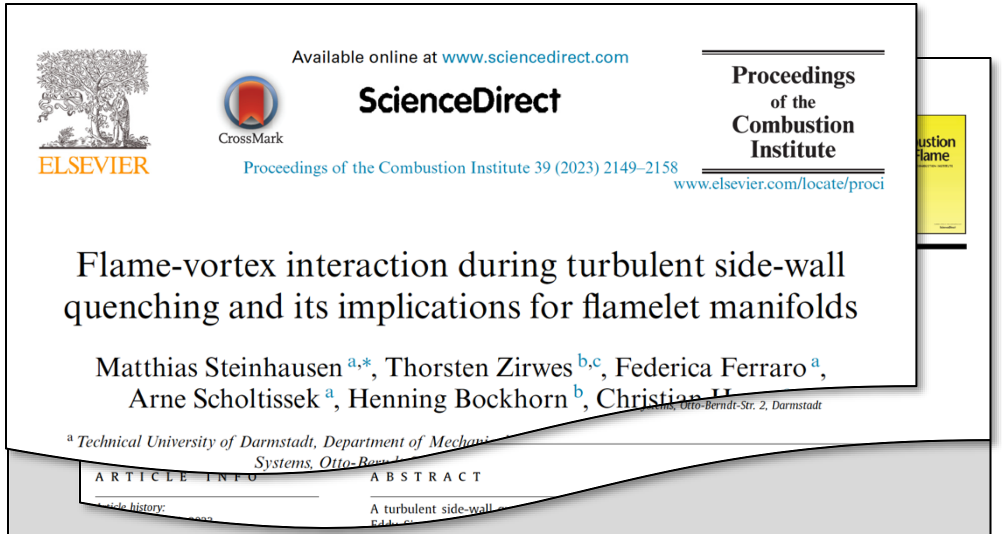
Benchmark configuration

- Complex, turbulent flow field
- Premixed methane-air flame
- **Direct numerical simulation** with finite-rate chemistry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Flame-vortex interaction during turbulent side-wall quenching and its implications for flamelet manifolds

Matthias Steinhausen [a,*], Thorsten Zirwes [b,c], Federica Ferraro [a], Arne Scholtissek [a], Henning Bockhorn [b], Christian H...

Understand

What is the effect of a turbulent flow field on the near-wall flame structure?

Validate and Model

How to model these effects in a chemistry manifold?

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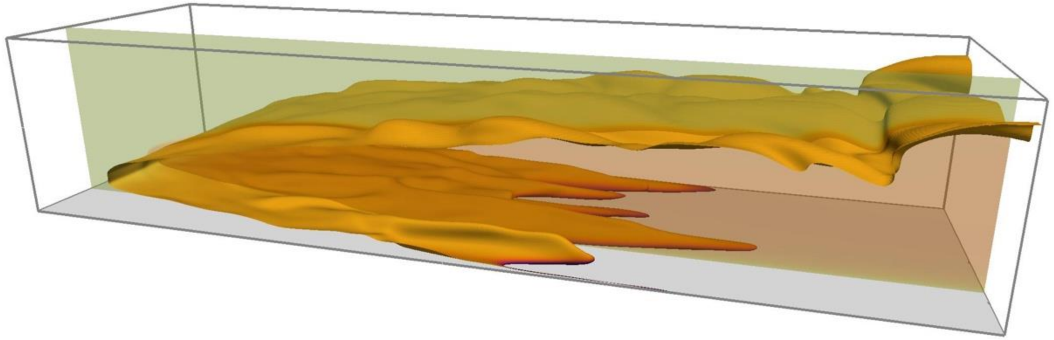
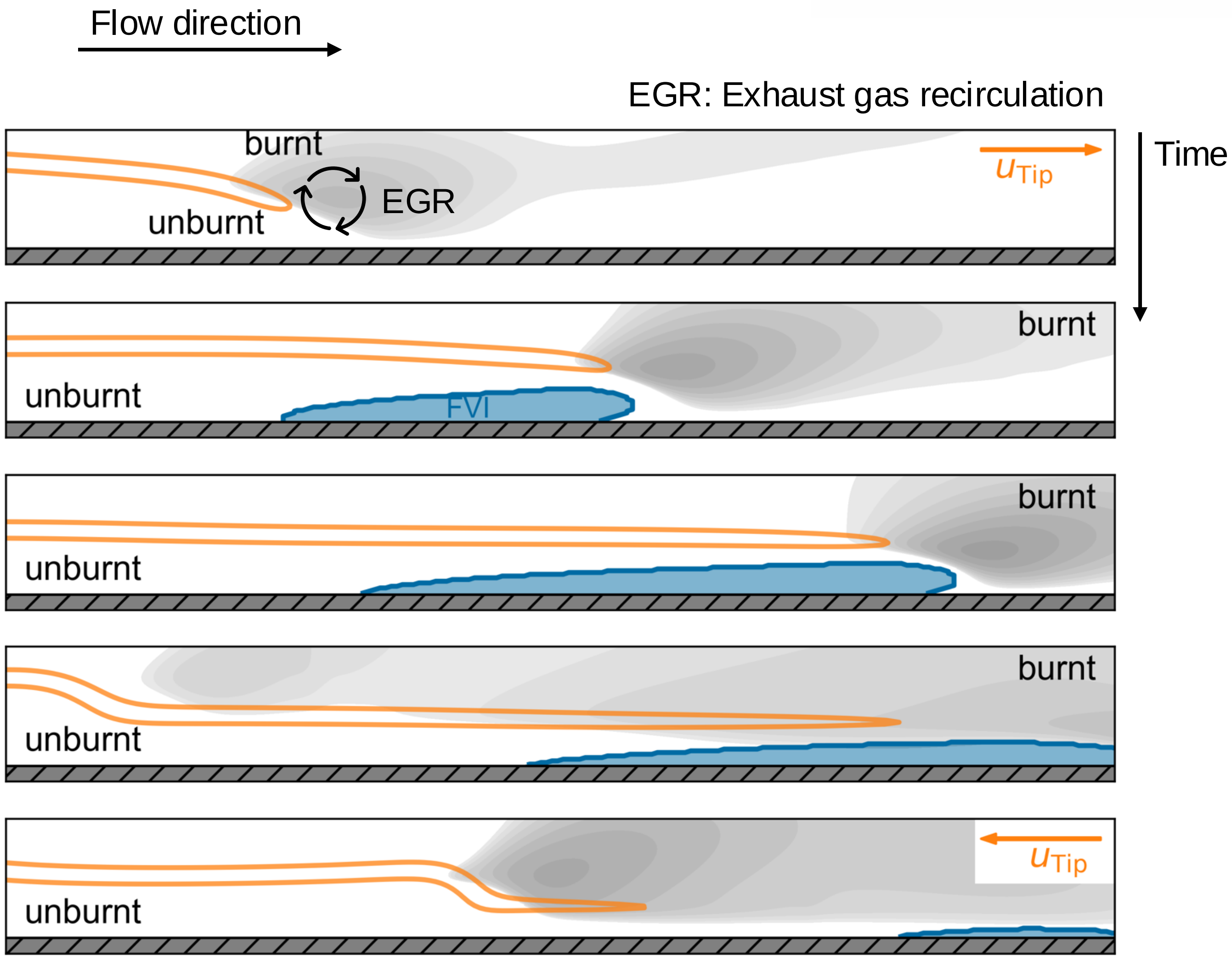
Flame-vortex interaction

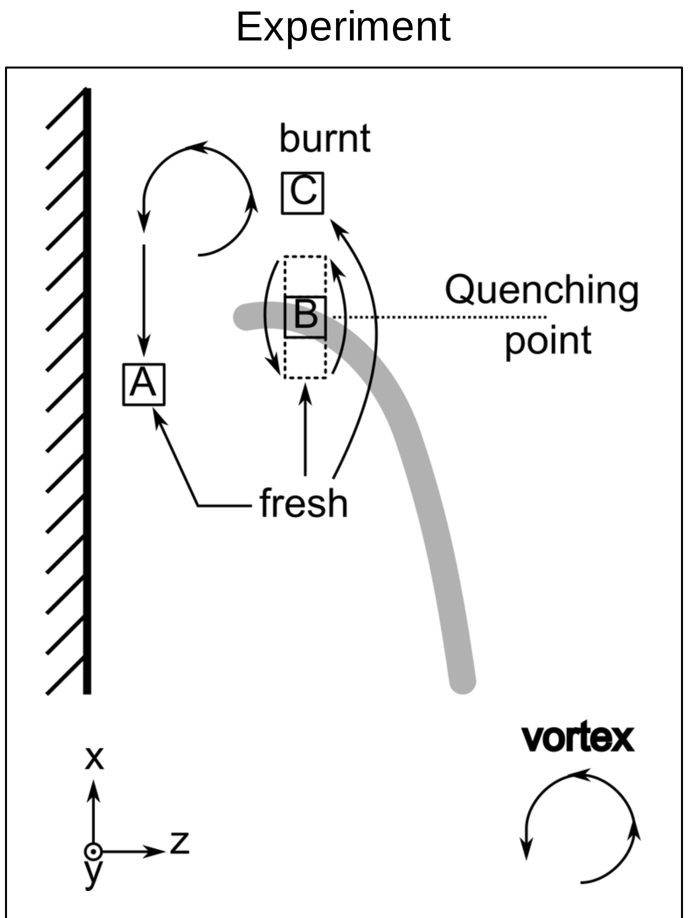
Flame-vortex-interaction mechanism

- Vortex pushes burnt gases to the wall
- Flame front propagates over the burnt gases
- Mixing of fresh and cold burnt gases (blue area)
- Flame tip is extinguished at the wall

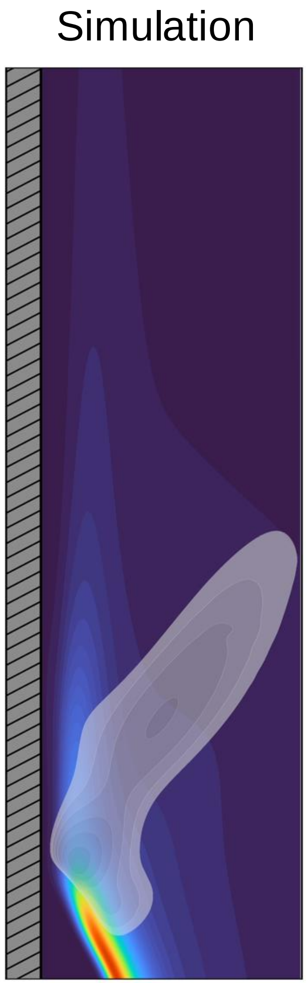


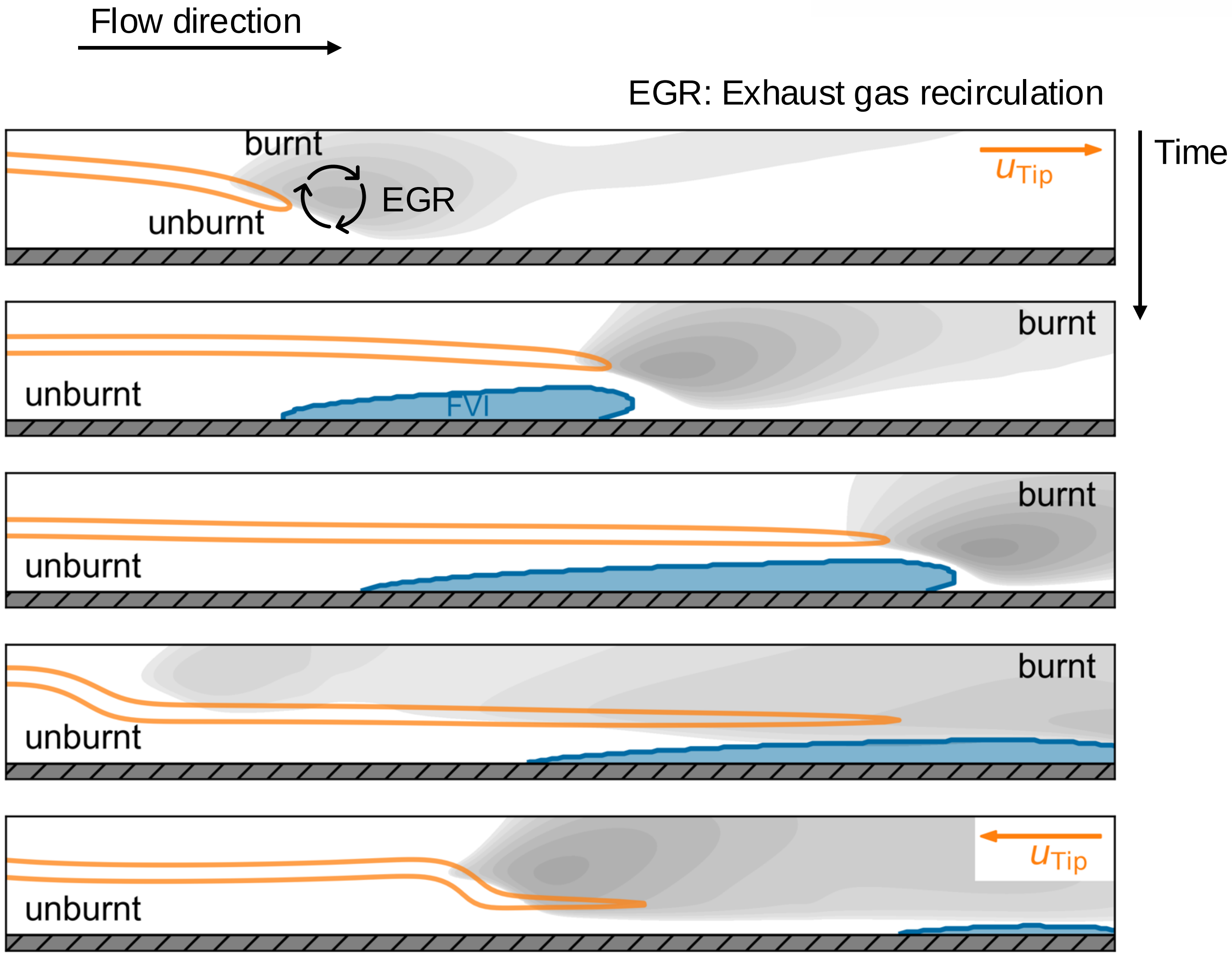


Flame-vortex interaction

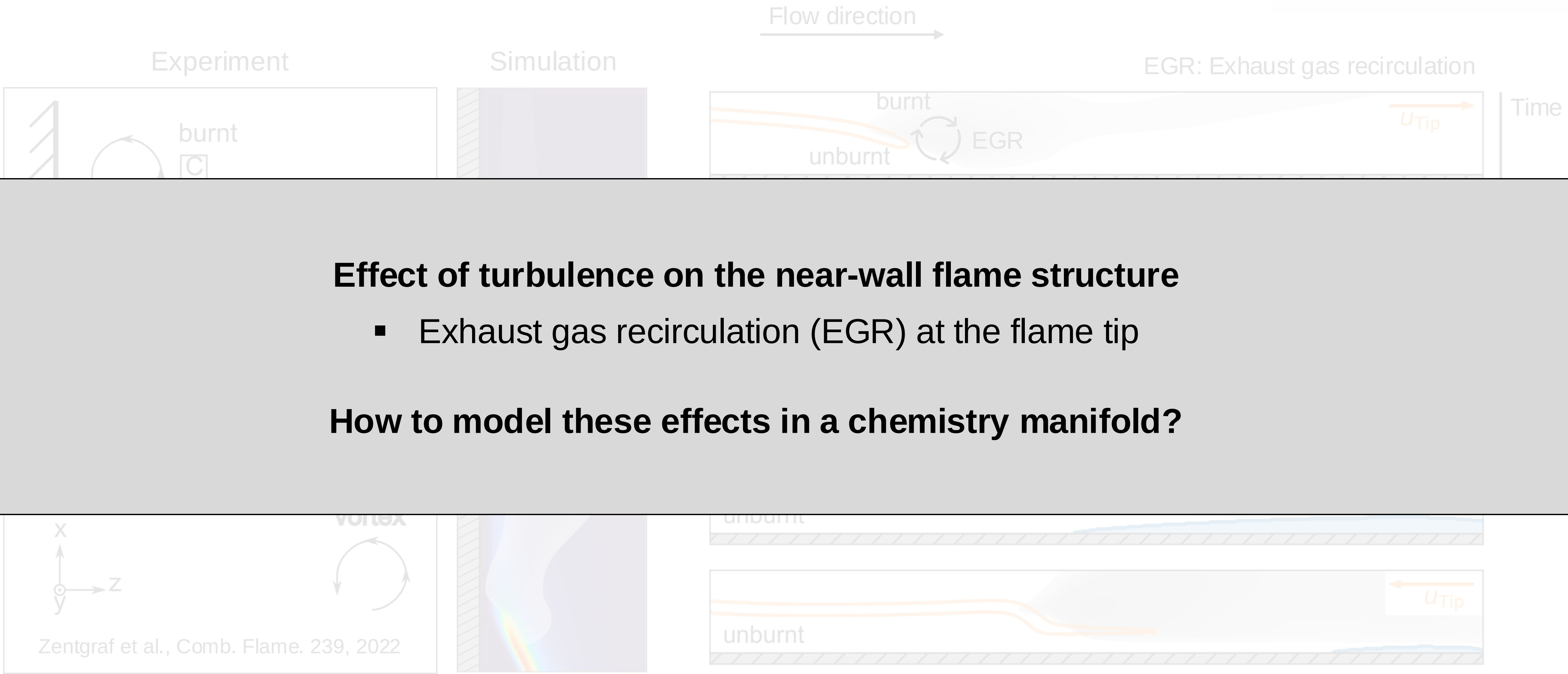


Zentgraf et al., Comb. Flame. 239, 2022





Flame-vortex interaction



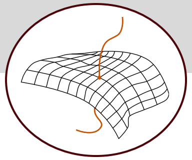
Effect of turbulence on the near-wall flame structure

- Exhaust gas recirculation (EGR) at the flame tip

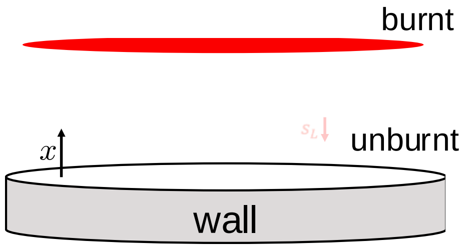
How to model these effects in a chemistry manifold?

Chemistry manifolds: Improved laminar model

2D flamelet



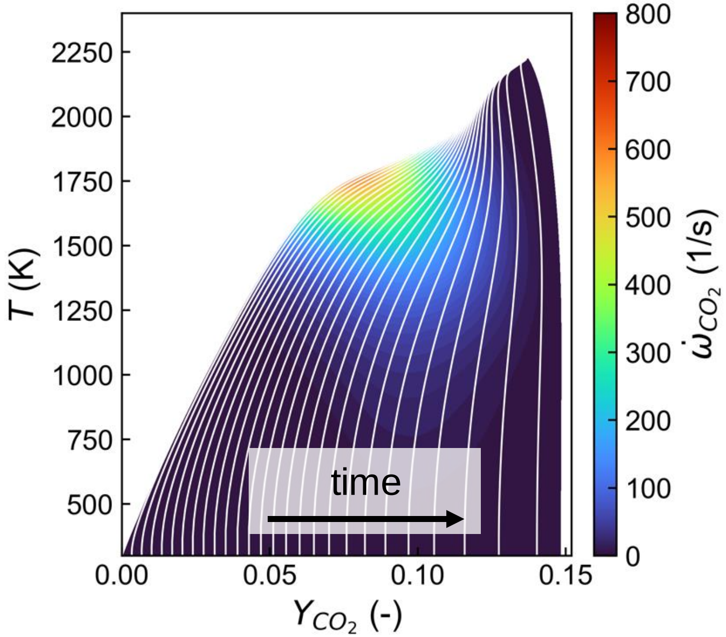
Transient head-on quenching



Flamelet database

Full thermochemical state

$\Psi = [p, T, Y_1, \dots Y_N]$

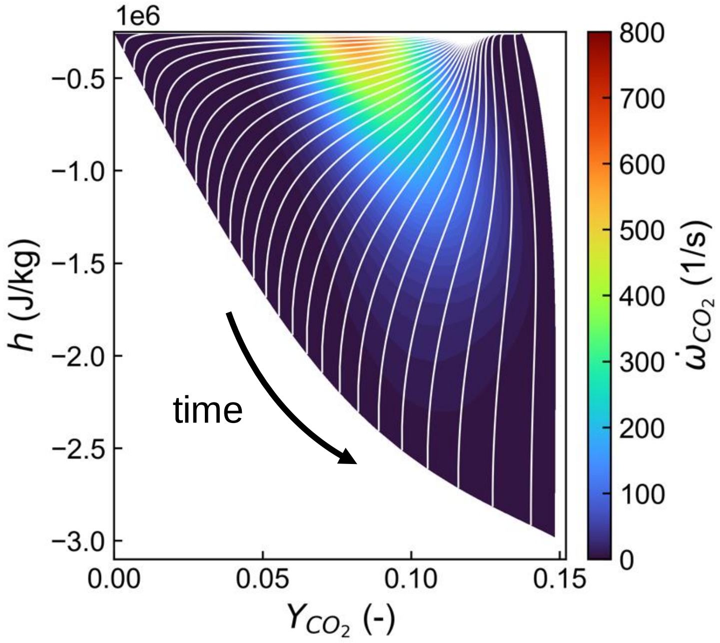


Tabulation

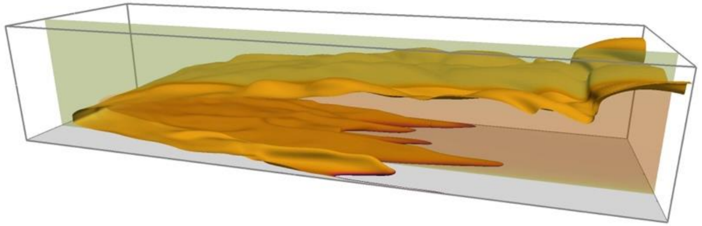
Chemistry manifold

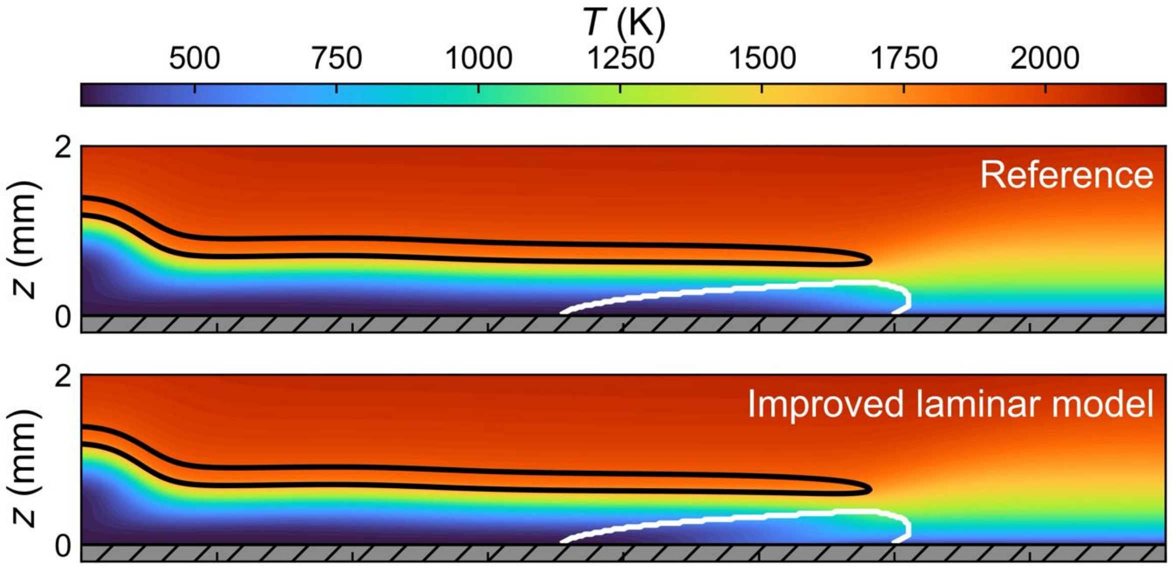
Reduced order representation

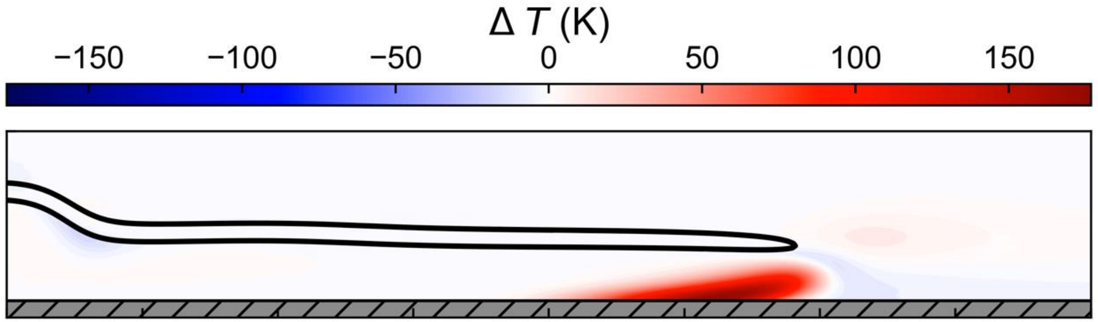
$\Psi = \Psi\left(Y_{CO_2}, h\right)$



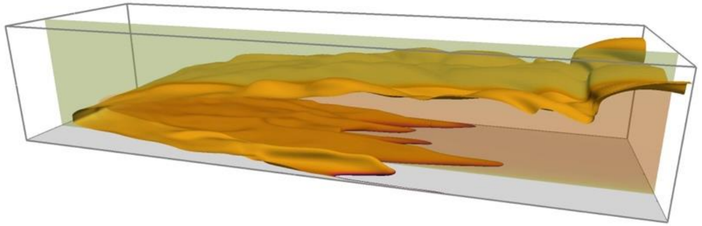
Model validation: Global flame properties

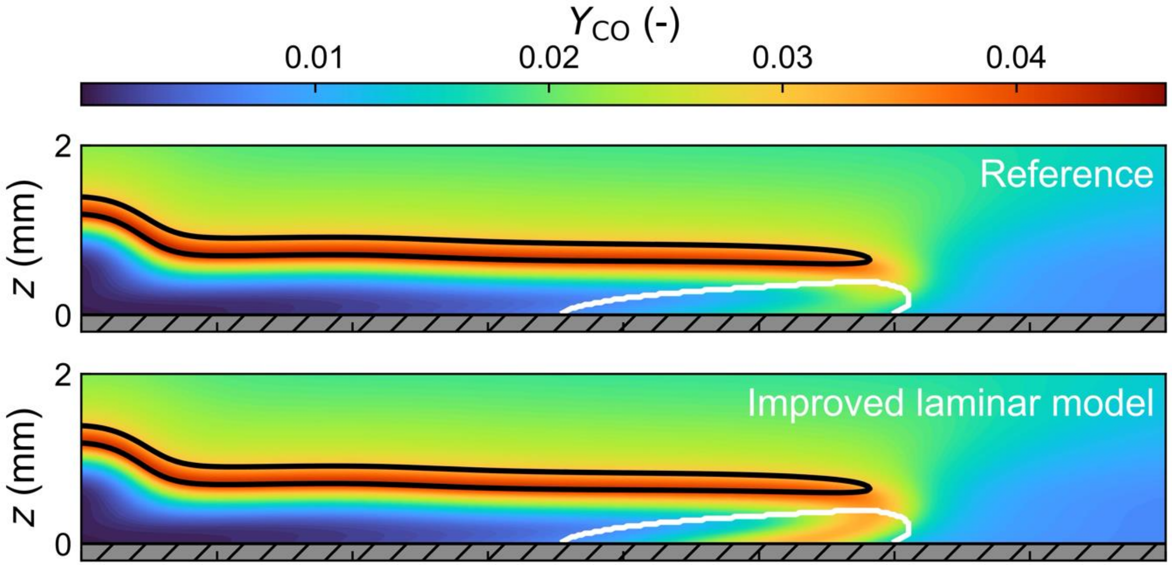


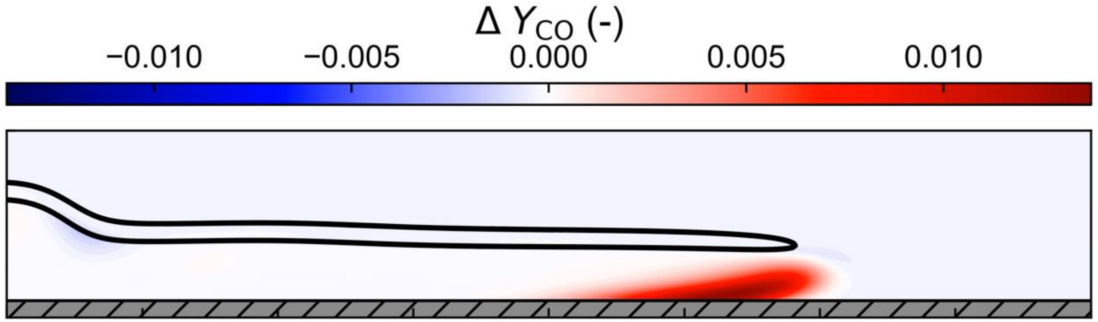




Model validation: Pollutant formation







Chemistry manifolds: Turbulent model

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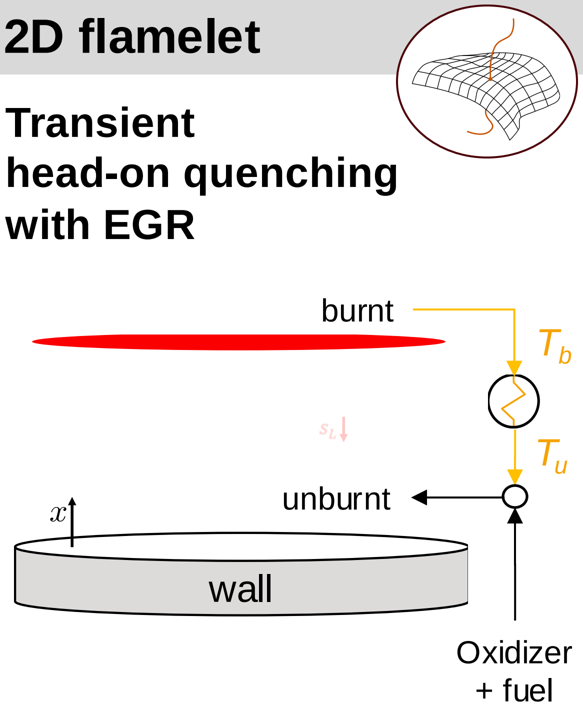
2D flamelet

Transient head-on quenching with EGR

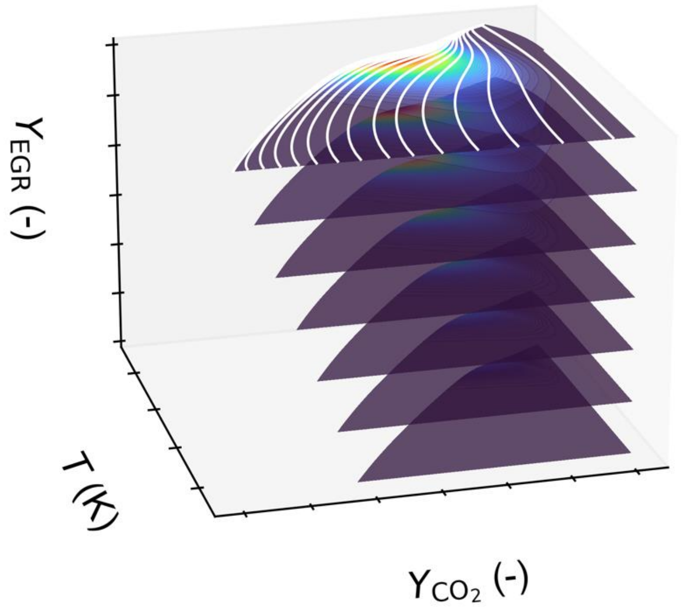


EGR: Exhaust gas recirculation

Flamelet database

Full thermochemical state

$\Psi = [p, T, Y_1, \dots Y_N]$

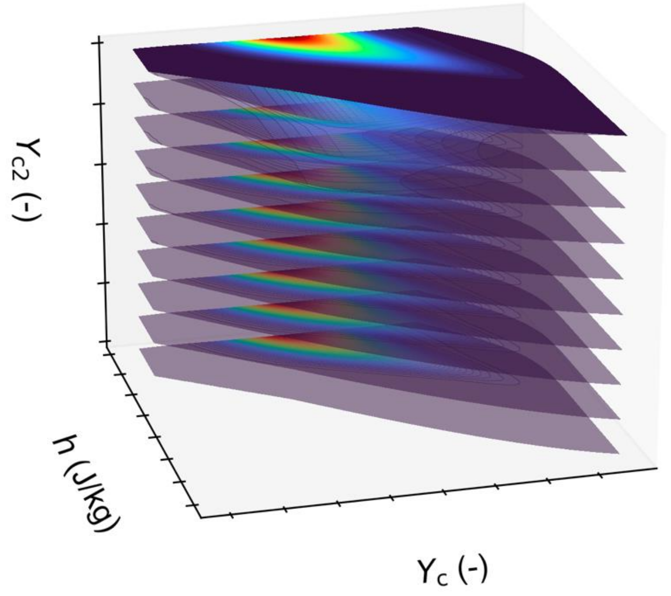


Tabulation →

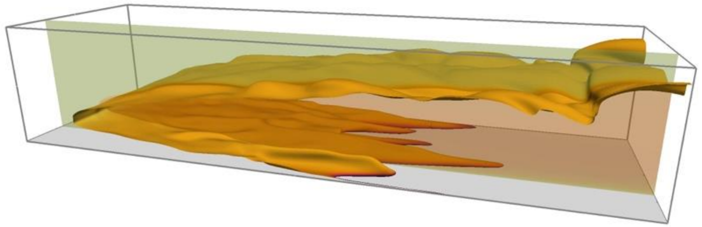
Chemistry manifold

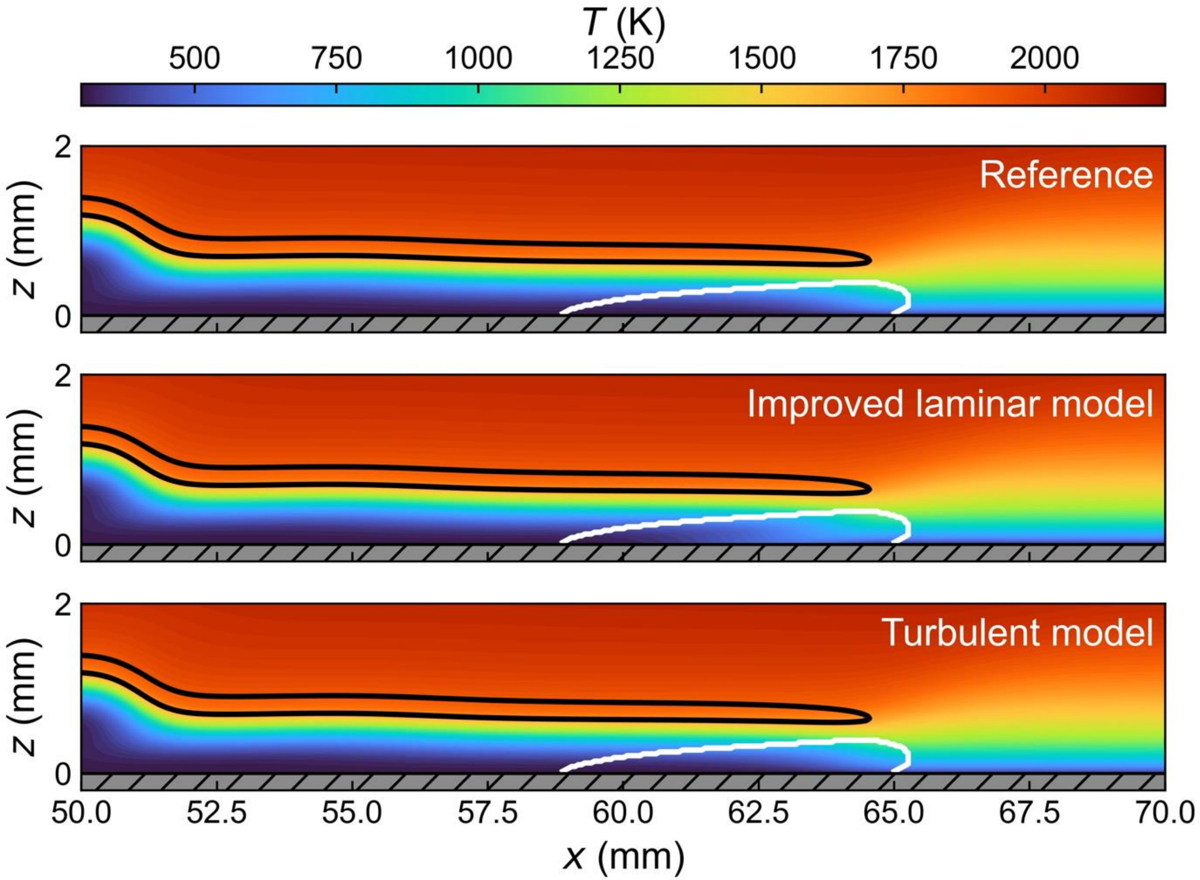
Reduced order representation

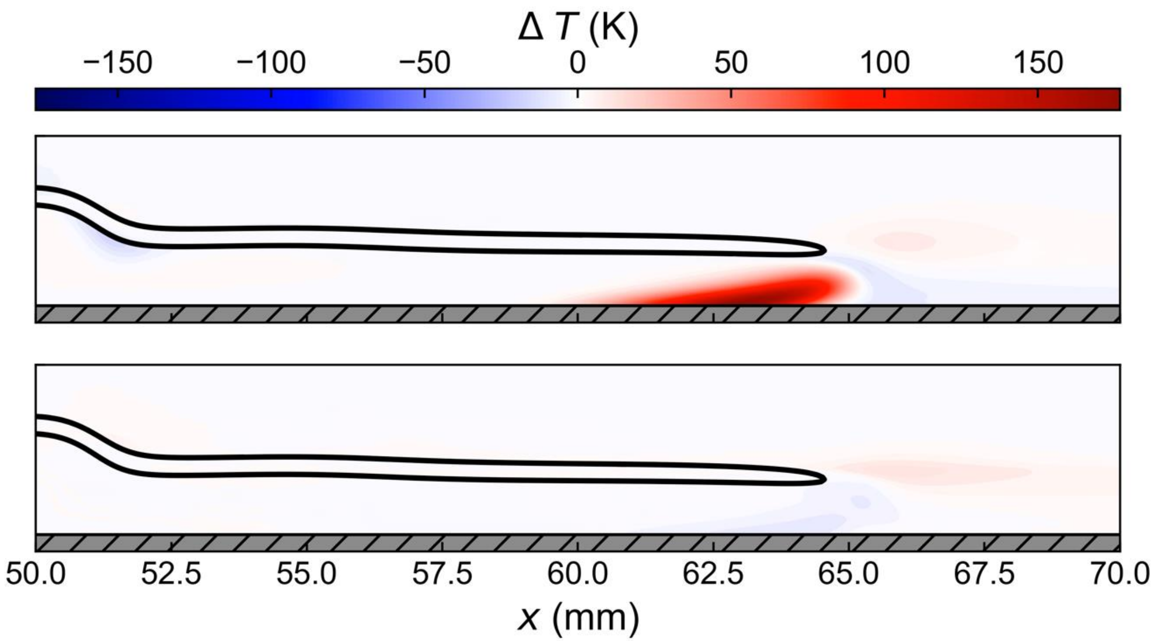
$\Psi = \Psi\,(Y_c, Y_{c2}, h)$



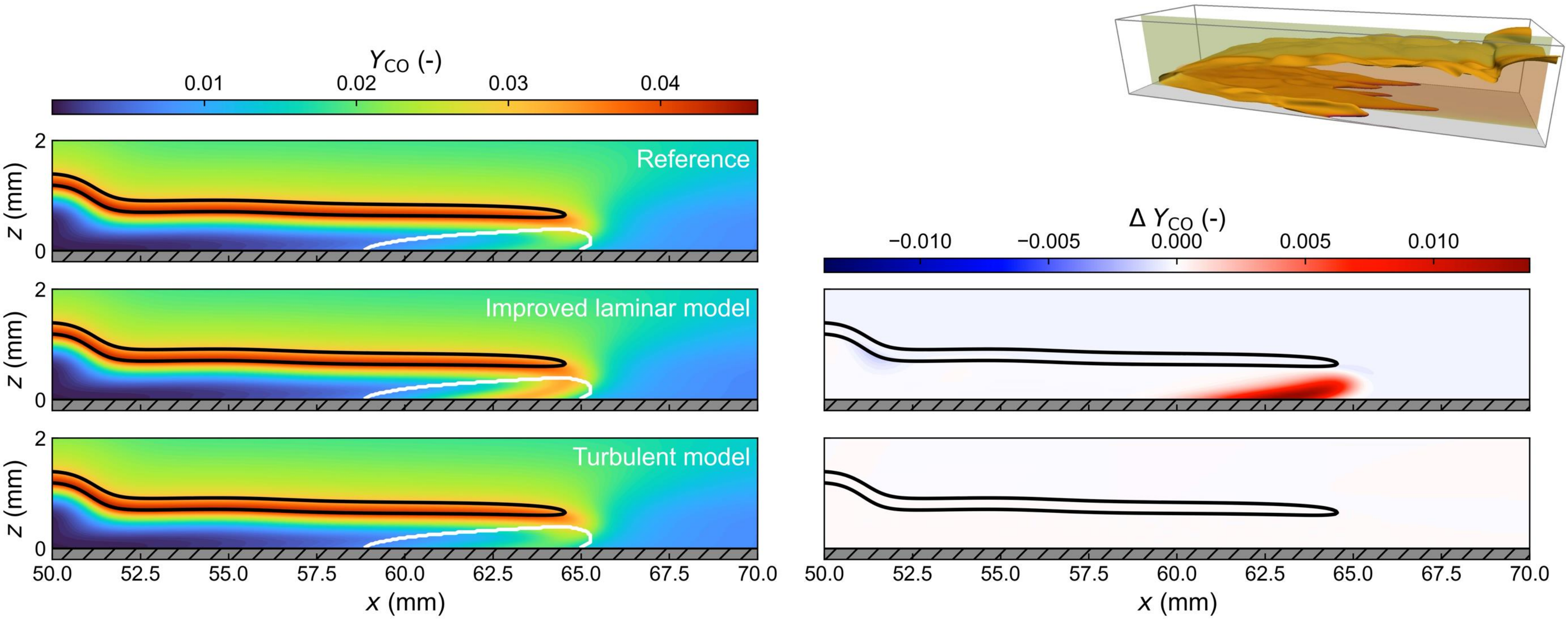
Model validation: Global flame properties







Model validation: Pollutant formation



Model validation: Pollutant formation

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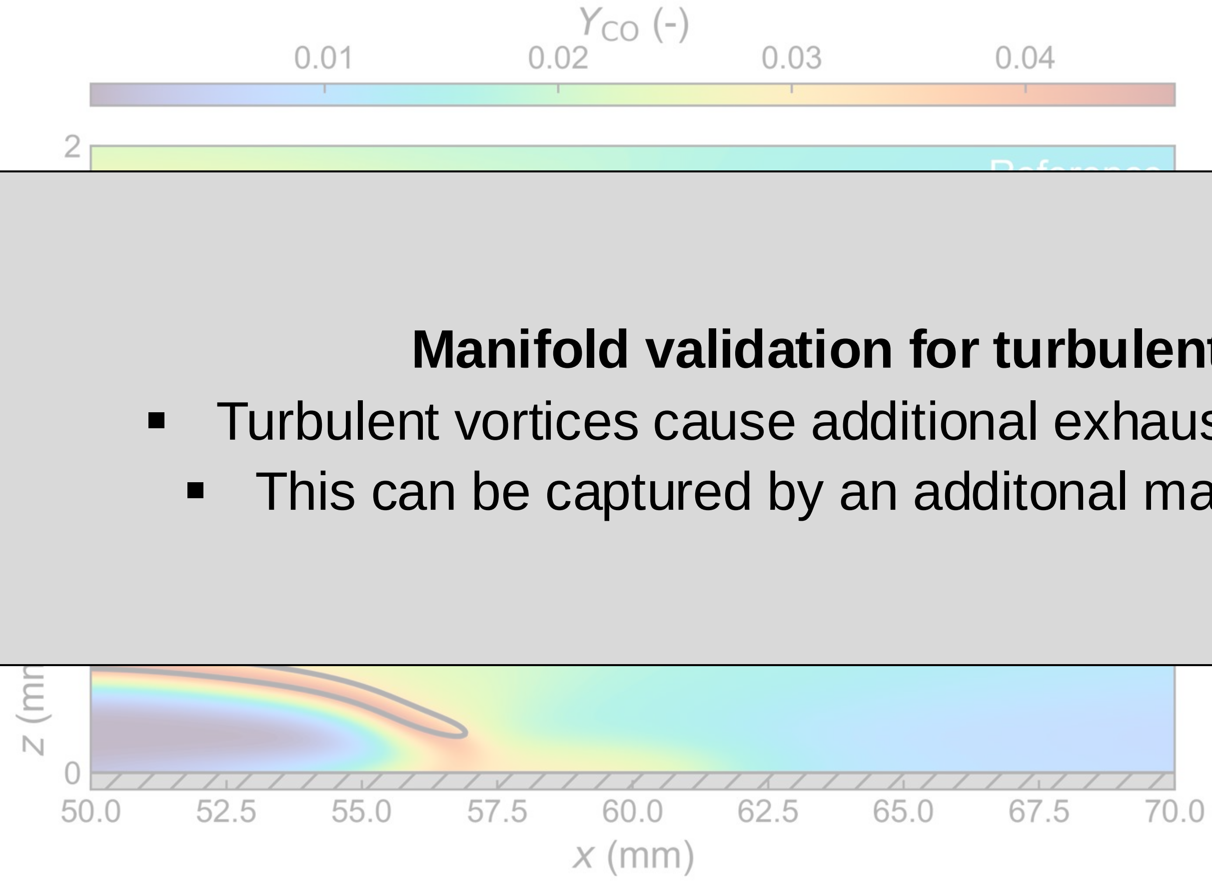
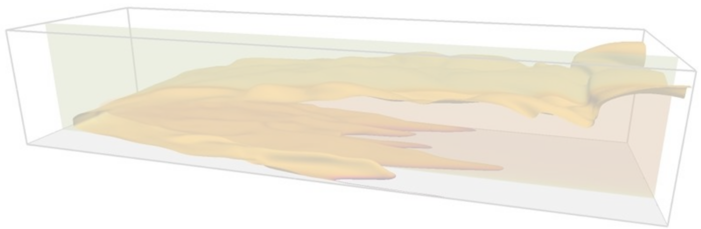
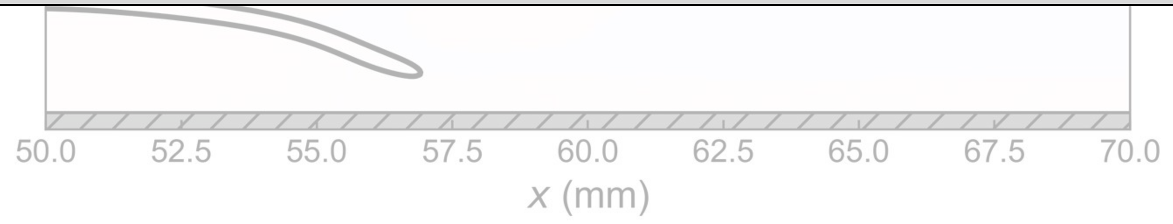
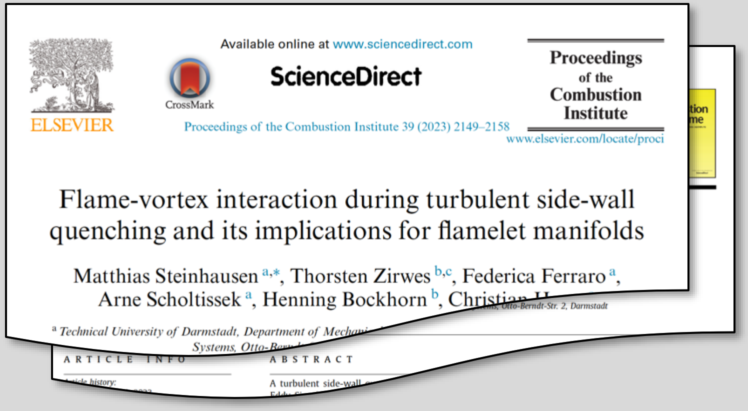






Manifold validation for turbulent flows

- Turbulent vortices cause additional exhaust gas recirculation
  - This can be captured by an additonal manifold dimension



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Flame-vortex interaction during turbulent side-wall quenching and its implications for flamelet manifolds

Matthias Steinhausen [a,*], Thorsten Zirwes [b,c], Federica Ferraro [a], Arne Scholtissek [a], Henning Bockhorn [b], Christian H...

[a] Technical University of Darmstadt, Department of Mechani...

ARTICLE INFO

ABSTRACT

A turbulent side-wall ...

Conclusion and outlook

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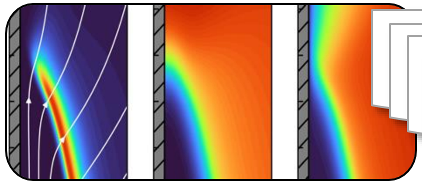
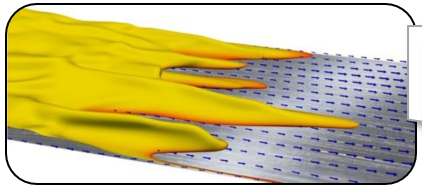
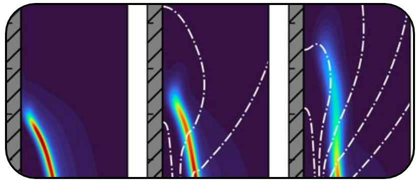
Configurations



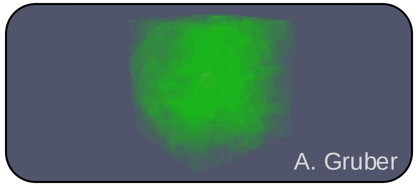
P1
5 others



P2, P4, P5
1 other



P3
2 others



Planned
1 other

Achievements

Development, verification and validation of predictive simulation methods for

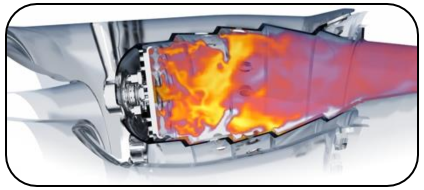
- Oxygenated fuels
- Turbulent flow conditions

Analysis of the **governing physical effects** that need to be incorporated into combustion models for

- Mixture stratification
- Pressure effects

Follow up projects

Rolls-Royce



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Conclusion and outlook

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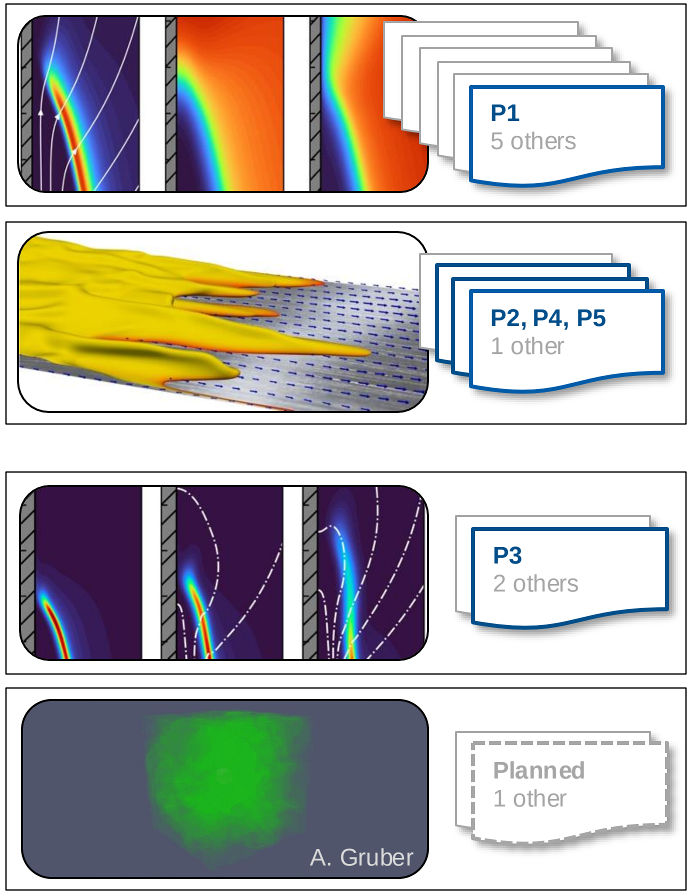

This thesis advances the **understanding and modeling** of flame-wall interactions,

paving the way to simulate real combustors with sustainable fuels.

SFB/Transregio 150
Turbulente, chemisch reagierende Mehrphasenströmungen in Wandnähe

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