Entwicklung eines optischen Detektionssystems für die Anwendung der 3D-Chemilumineszenz-Tomographie in industriellen Hochtemperatur-Prozessen (Tomo-Pro)

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in cooperation with

Gastechnologisches Institut

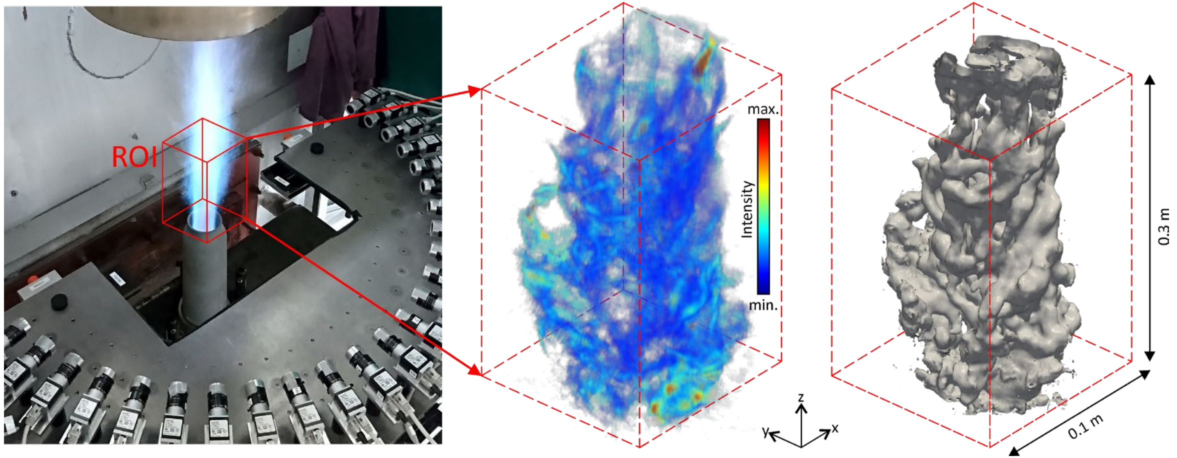
Offen im Denken

Seminar GWI, 10.07.2025

Motivation

in cooperation with

- Non-intrusive, low-cost 3D combustion diagnostics for the industrial sector
- Specially resolved reaction zone visualization via chemiluminescence detection
- Better understanding of industrial gas firing systems facilitates optimization (CFD, LES)
- Camera-based flame and process monitoring (industry 4.0)
- Tomographic reconstruction of an optically accessible industrial flame, 2018:



Computed tomography of chemiluminescence

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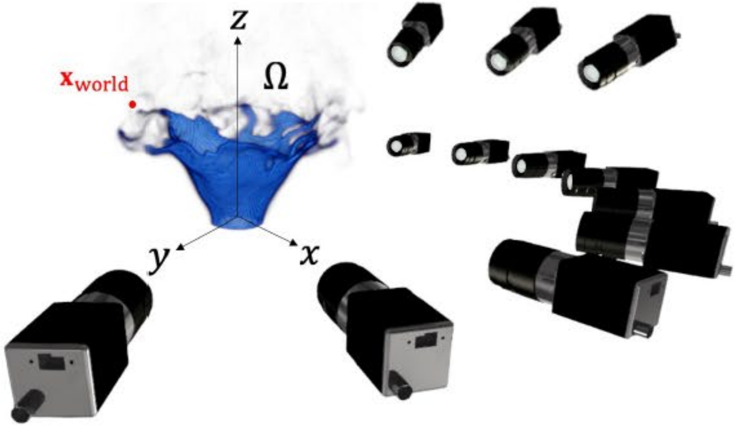
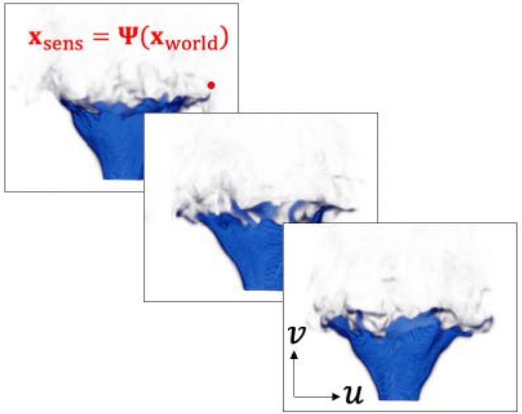
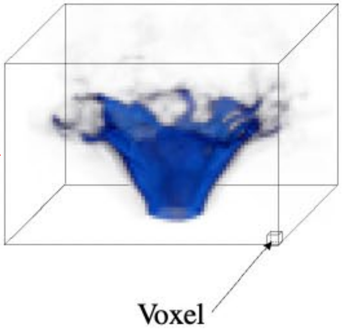
Imaging setup[1]



2D images



3D reconstruction



- **Measurements and their mathematical modeling:**
  spontaneous or triggered activity (transmission, emission etc.)
- **Reconstruction algorithms:** algebraic reconstruction technique (ART), Bayesian, Metaheuristic, filtered back projection
- Include characteristics of the optical detection system

[1]Grauer, Mohri, Yu, Liu and Cai, Progress in Energy and Combustion Science 94 (2023)

gwi

Investigation of industrial-scale flames

Case 1: high-speed burner

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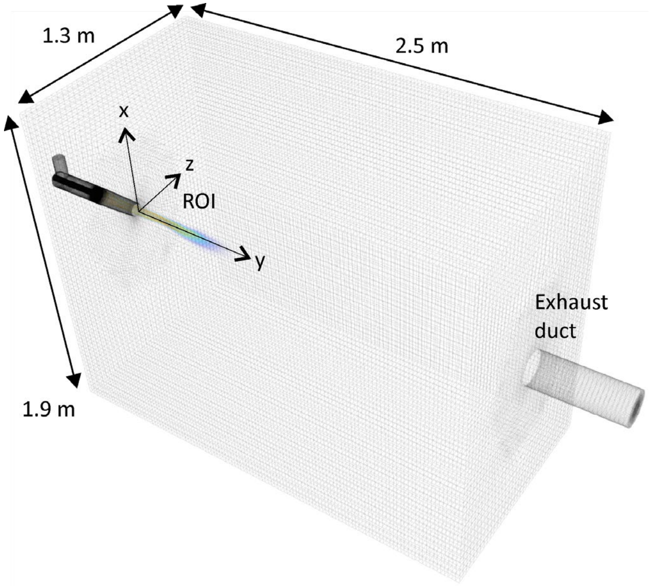
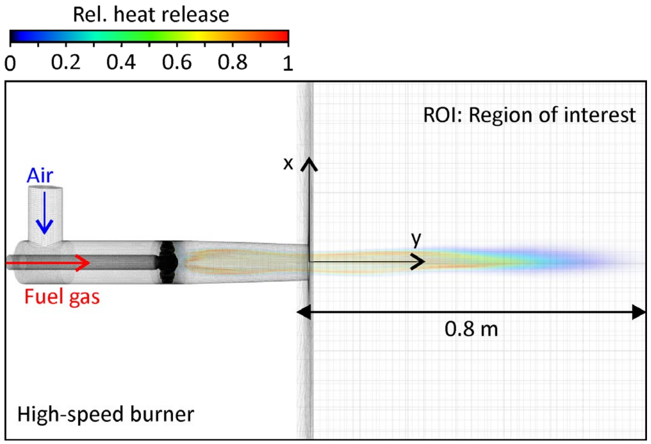
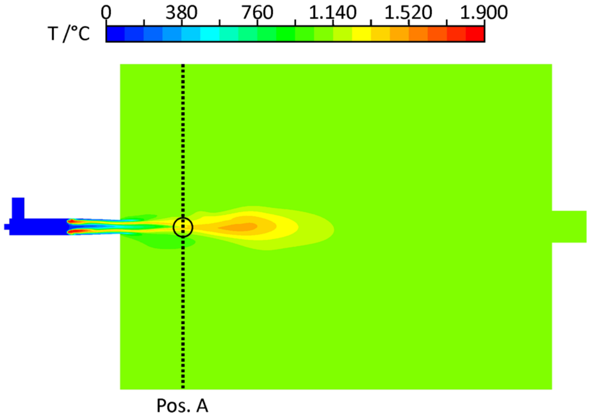
- 160-kW non-premixed industrial burner
- Natural gas /air combustion
- High flow velocity
- Pronounced recirculation or backflow of hot exhaust gas
- CFD-Simulation: RANS, PDF model



Conditions:
$P = 120$ kW
$\lambda = 1.1$
$T_{Furnace} = 800$ °C

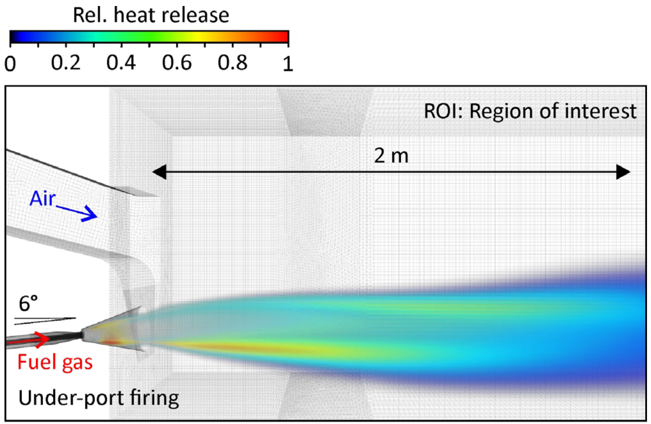


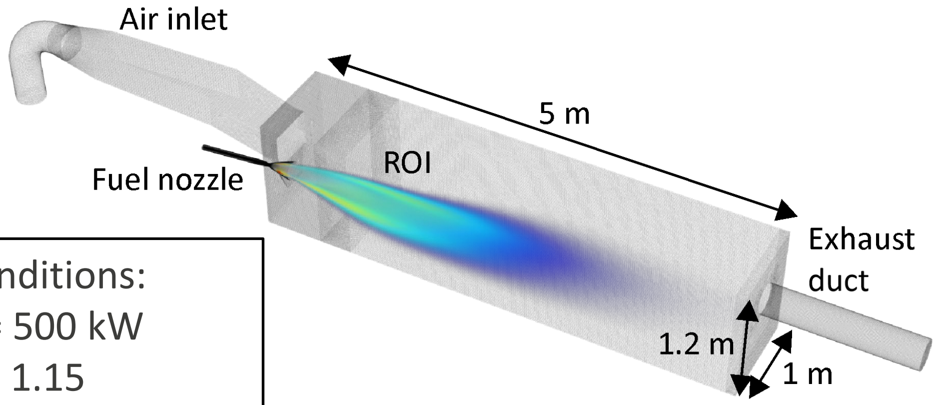


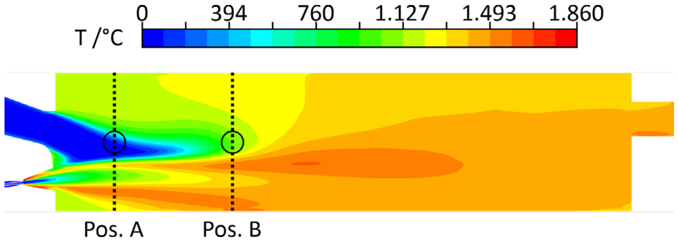
Investigation of industrial-scale flames (2)
Case 2: under-port firing

in cooperation with DBI GTI Gastechnologisches Institut; Universität Duisburg Essen – Offen im Denken

- 1.2-MW under-port firing (natural gas / air)
- Air pre-heating up to 1250 °C
- Low flow velocity
- Interaction of chemical reaction and turbulent flow
- CFD-Simulation: RANS, PDF model





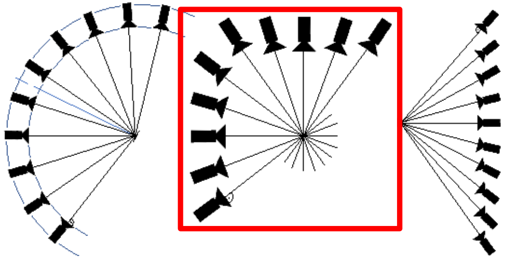


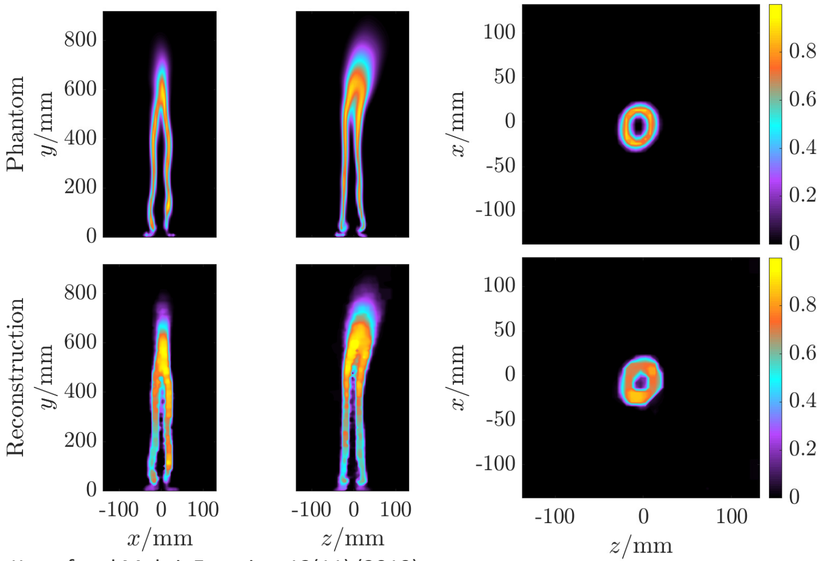
Conditions:
P = 500 kW
λ = 1.15

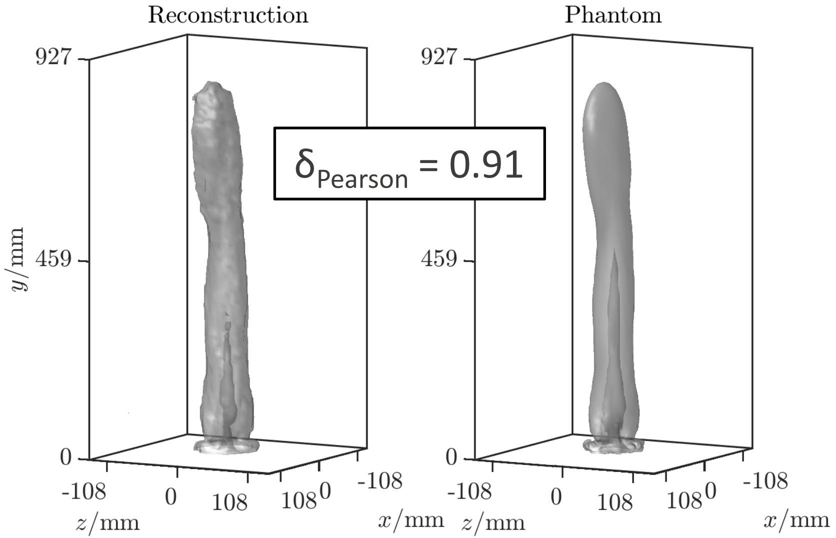
Investigation of industrial-scale flames (3)
Phantom studies (Case 1)

- Numerical investigation and optimization optical arrangement
- 3 different camera arrangements containing 10 cameras
- Flame length of 0.8 m and distance 0.5 – 0.75 m
- Reconstruction algorithm: Evolutionary Reconstruction Technique (ERT)[2]

Camera arrangements





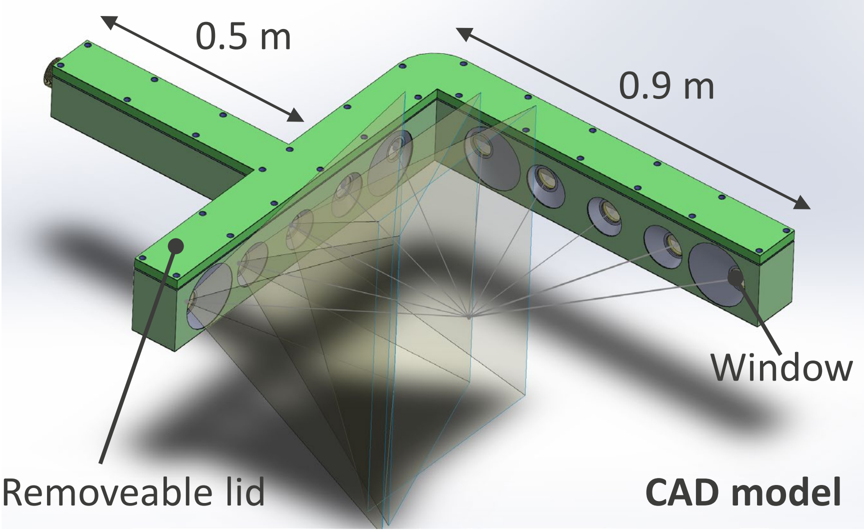


[2]Unterberger, Kempf and Mohri, Energies, 12(11) (2019)

Multi-camera system

Probe design

- Direct implementation into test furnaces
- Water-cooled construction made from stainless steel, 100 kW @ 1.5 m^3/h water flow rate and 20 °C
- Design optimized for 10 cameras in L-arrangement and a minimum heat loss from the surface
- Air flushing of windows to avoid particle deposition and provide active cooling of electronics



Multi-camera system (2)

Optical setup

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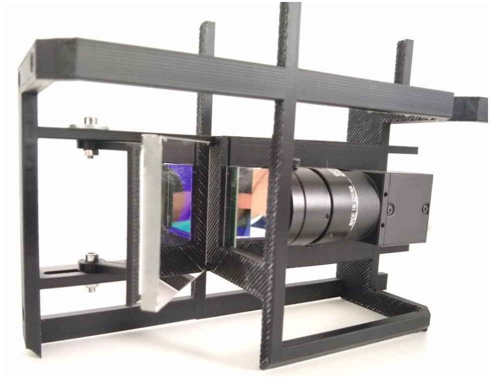
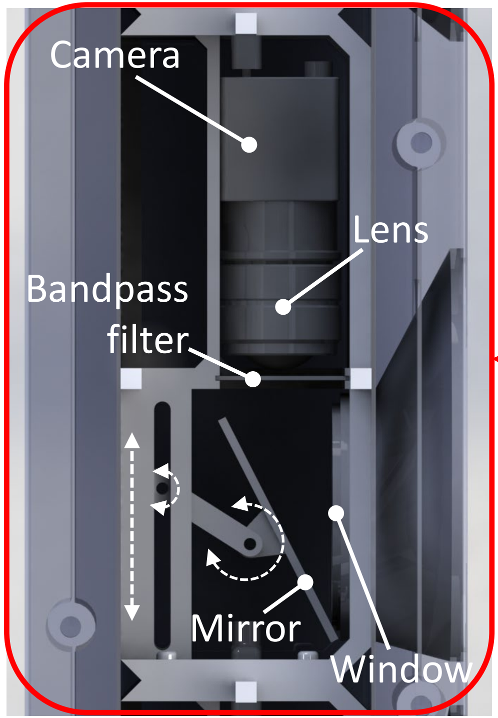
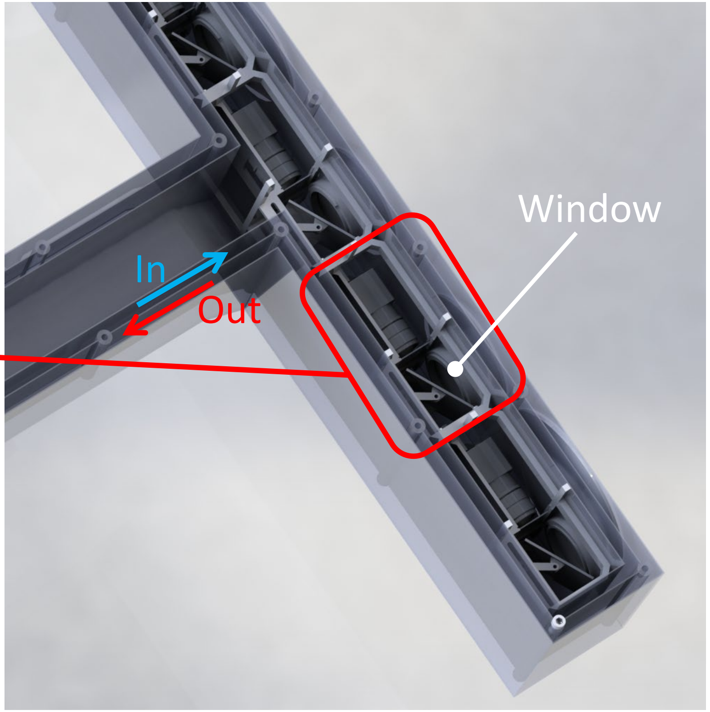
- 10 FLIR Blackfly S cameras, 2/3” monochrome sensor, 2448 × 2048 pixel, 3.45 µm
- 6 mm wide angel lens
- Bandpass filter (CH*), CWL 431 nm, FWHM 28 nm
- Broadband mirror
- Heat protection glass





Camera module



Rendered CAD model

Furnace implementation
Case 1

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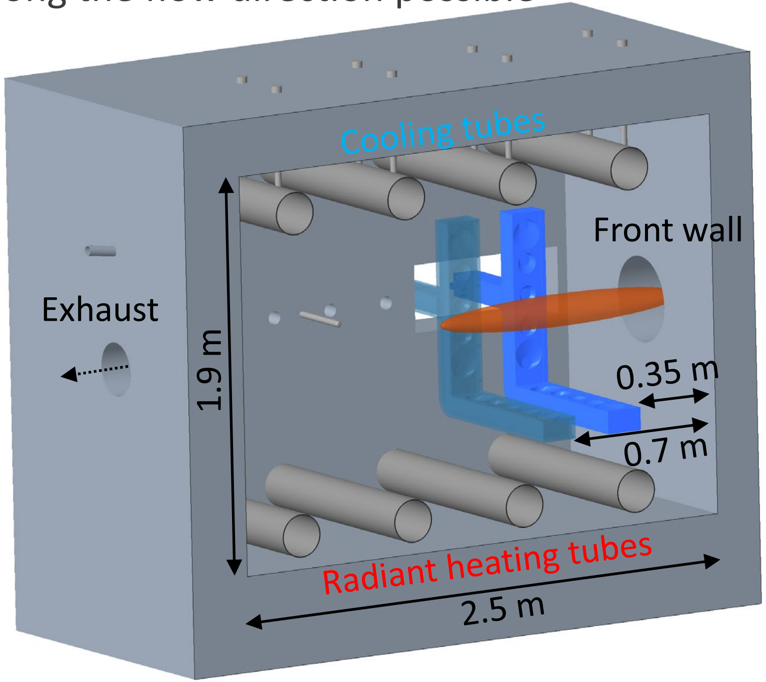
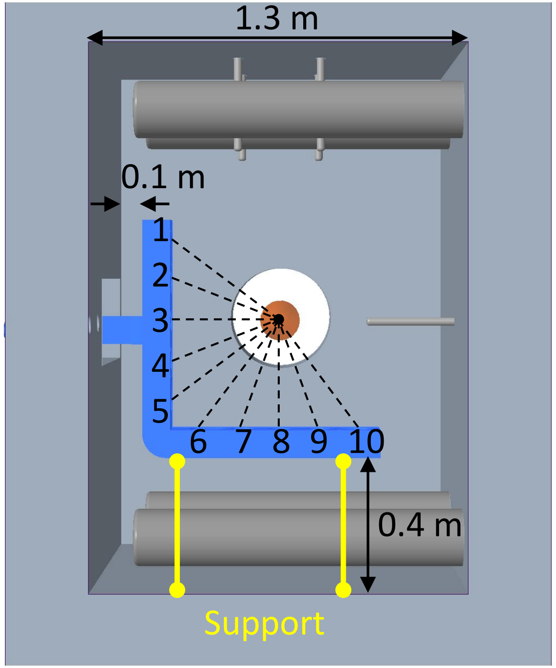
- GWI's 300-kW temperature-controlled "Nassheuer Furnace"
- Probe entry through the window
- Translation along the flow direction possible

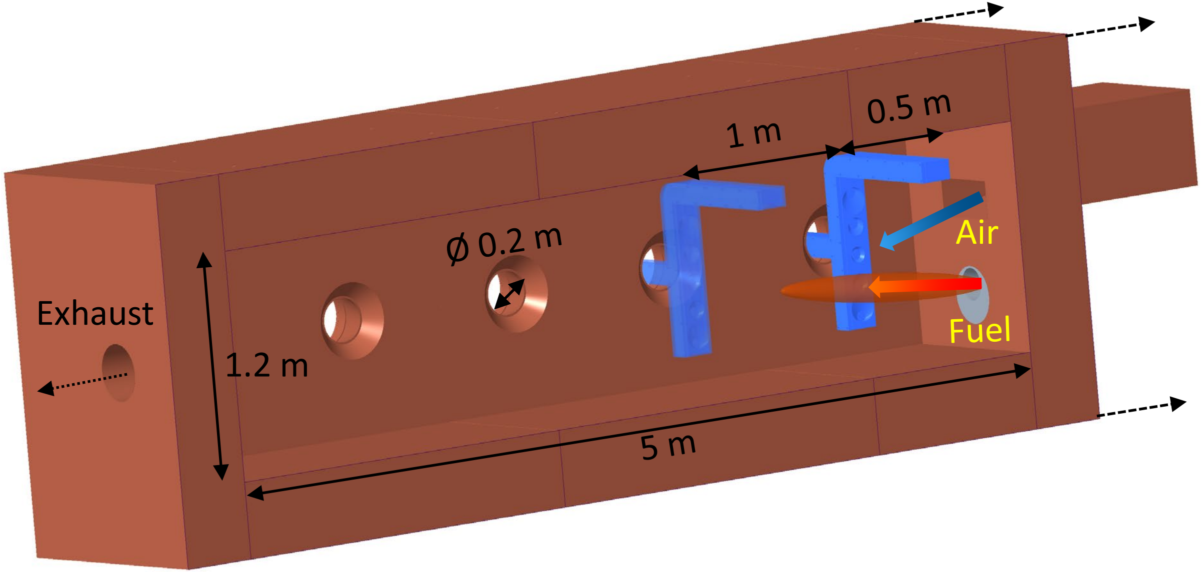


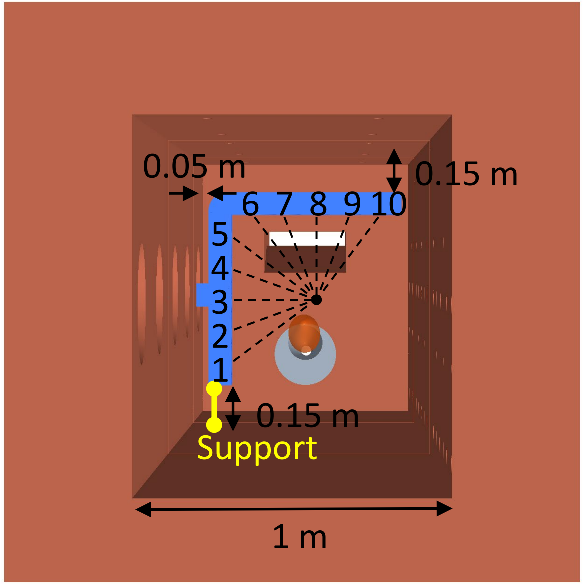


Furnace implementation (2)

Case 2

- GWI's 1.2-MW "Red Furnace"
- Probe entry through the front wall opening, front wall replaceable
- Optical access points (ø 250 mm) can be used to measure in streamwise direction

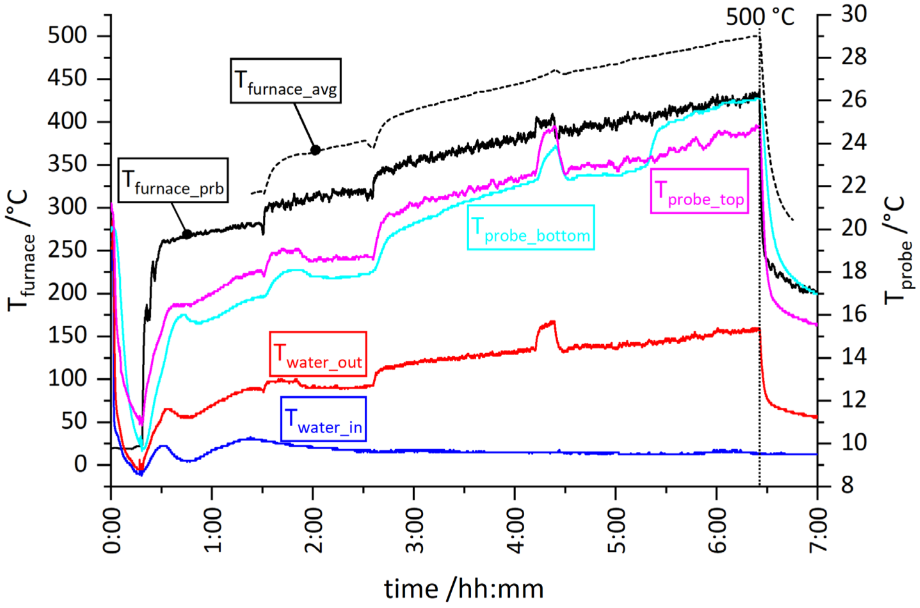


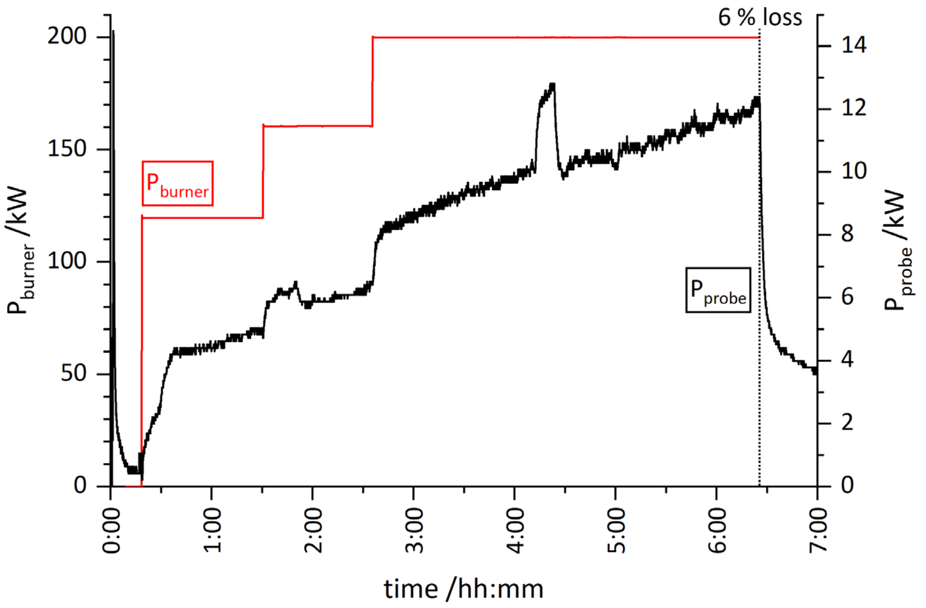


Cooling performance

Operation parameters

- Water flow rate: 30 l/min
- Water pressure: 0,7 bar
- Flushing air flow rate: 30 m³/h





Proof of concept experiments

Case 1

Investigated Conditions

- $T_{furnace\_max}$ = 400 °C
- P_{burner} = 80 – 160 kW
- λ = 1.1 – 1.4
- Re_D = 37,140 – 92,964

[3]Unterberger, Menser, Kempf, Mohri, IEEE International Conference on Image Processing (ICIP) (2019)

2D imaging results

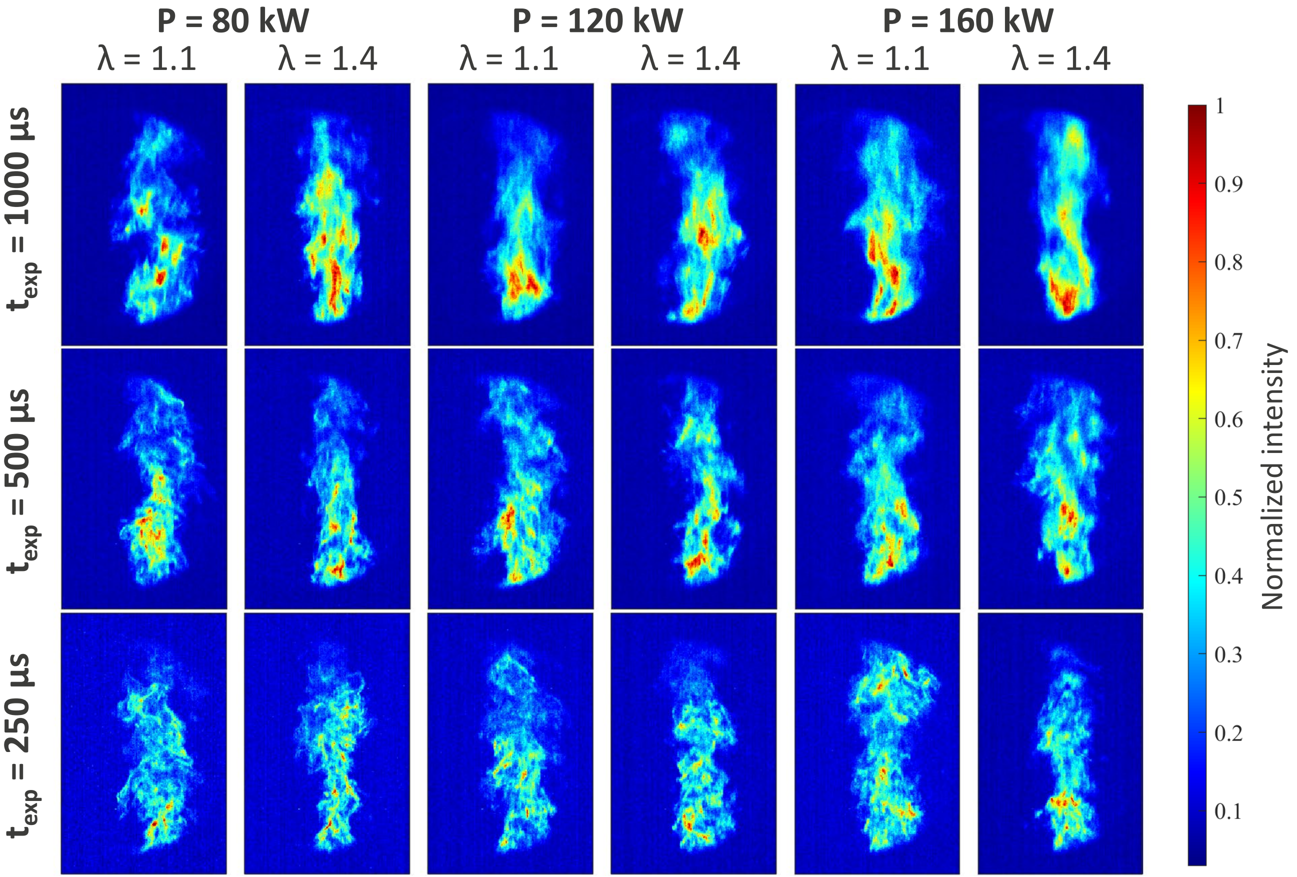
in cooperation with

Image acquisition

- Simultaneous imaging with 10 cameras
- Variation of exposure time at constant gain

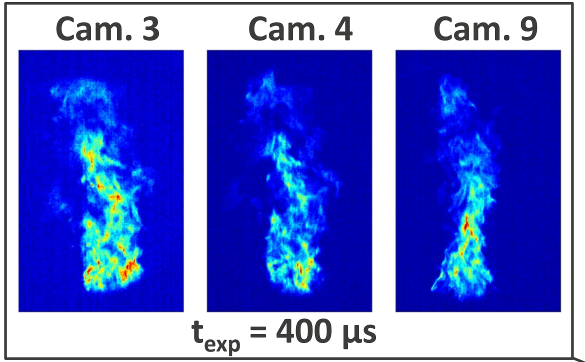
Pre-processing

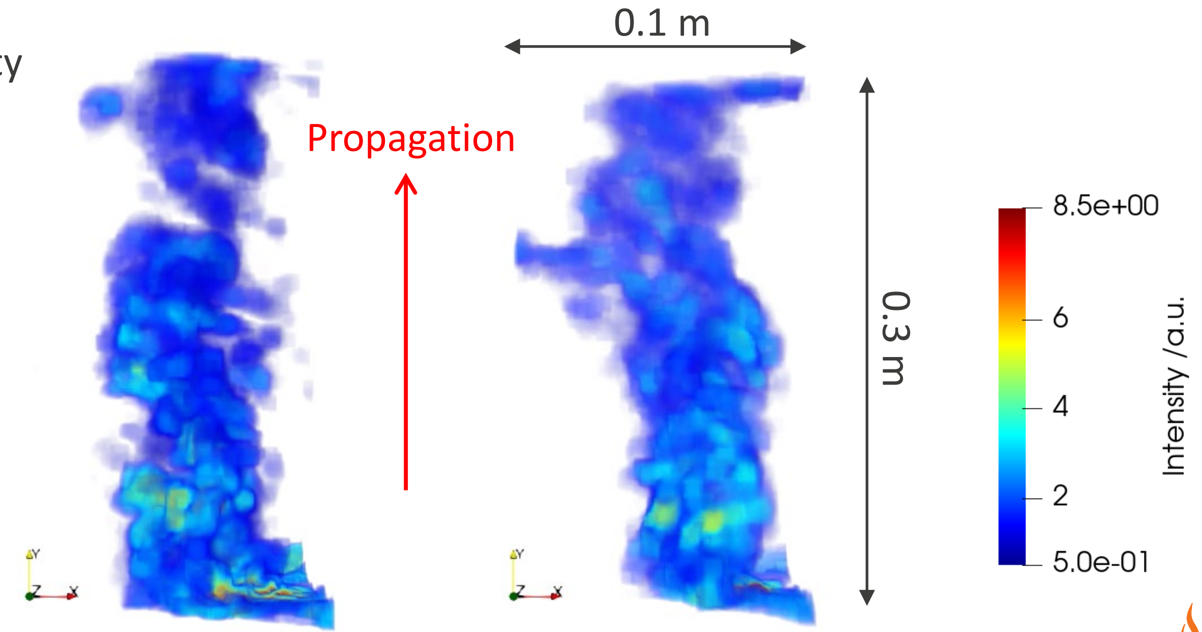
- Binning 5 × 5 pixel
- Empty image region masked out
- Images cropped to 180 × 285 pixel



3D reconstruction results

- Reconstruction algorithm: Evolutionary Reconstruction Technique (ERT)[2]
- Domain discretized to 80 × 150 × 85 voxels (x, y, z)
- Resolution: 2 mm/voxel
- **Result:** instantaneous 3D intensity field of CH* chemiluminescence





80 kW, λ = 1.4

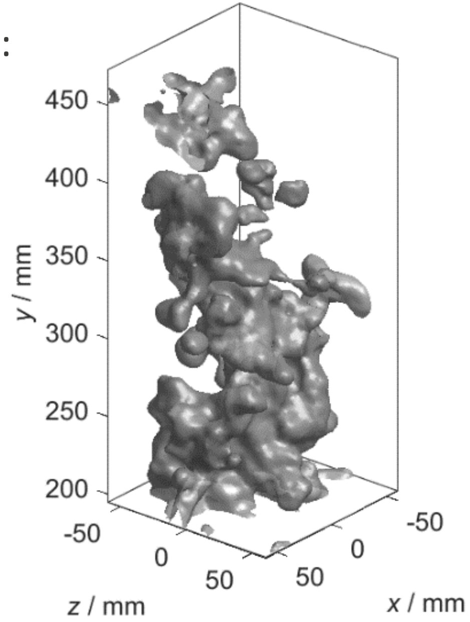
100 kW, λ = 1.1

[2]Unterberger, Kempf and Mohri, Energies, 12(11) (2019)

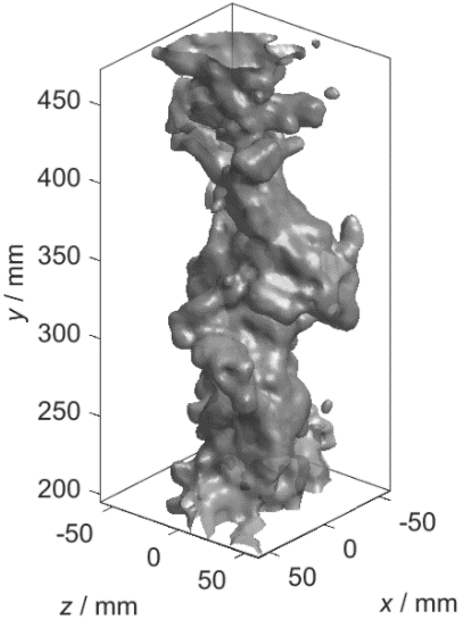
3D reconstruction results (2)

in cooperation with DBI GTI Gastechnologisches Institut, Universität Duisburg Essen – Offen im Denken

- Iso-surface representing the instantaneous flame front
- Fields reveal 3D structural details hidden in the 2D images
- From spatially-integrated to spatially resolved information: flame morphology, heat release, flow characteristics etc.



80 kW, λ = 1.4



100 kW, λ = 1.1

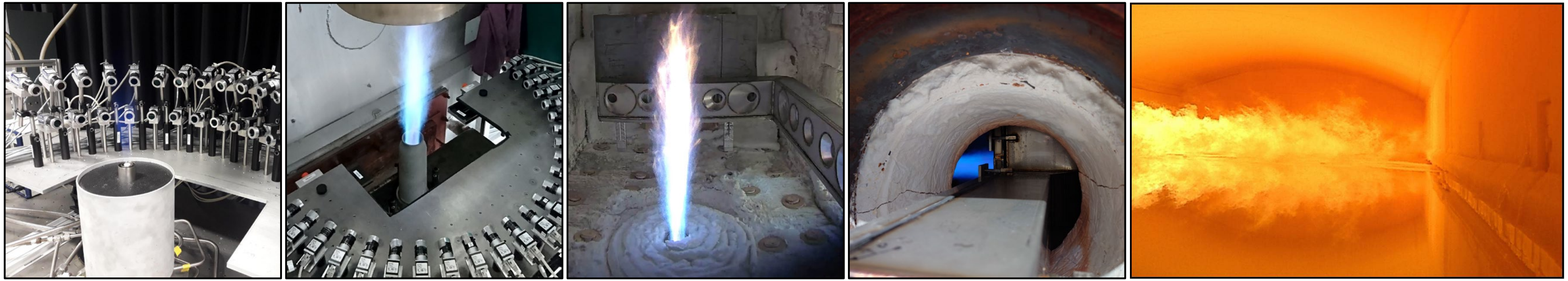
Conclusions and future work

in cooperation with DBI GTI Gastechnologisches Institut, Universität Duisburg Essen – Offen im Denken

- Multi-camera system: 10-camera tomographic imaging setup optimized based on phantom studies
- Water-cooled probe designed for direct implementation into high temperature environments
- Proof of concept experiments: application of CTC to industrial-scale combustion processes

- Test at higher temperatures > 500°C and other combustion types (under-port firing)
- Improvement of the optical setup and post-processing (field-of-view, noise reduction etc.)
- UV-sensitivity (hydrogen combustion)

- Further tomographic techniques: BOST, TIMes etc.
- Close-to-application conditions



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Portable multi-camera tomographic probe for 3D emission measurements in industrial-scale high-temperature combustion processes

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ABSTRACT

A tomographic probe is proposed for 3D imaging in demanding industrial settings comprising high-temperature environments under atmospheric pressure. The probe has an L-shape for multi-angular measurements with a large fan angle and features a water-cooling system for direct placement inside industrial furnaces, overcoming the limited optical accessibility of such devices. The tomographic probe was designed considering quality reconstructions with sufficient resolution using an optimal camera arrangement deduced from phantom studies, optimal heat loss, manufacturing process and portability. A variety of turbulent 3D fields can be reconstructed using simultaneous multi-directional imaging depending on the measurement modality employed. In this work, the probe was fitted with an array of 10 low-cost commodity cameras equipped with wide-angle lenses and 431/28 nm bandpass filters, and used for attainment of chemiluminescence signals to estimate the 3D shape of different industrial flames for the first time. Validation of the probe design was conducted in a laboratory experiment by comparing single-shot fields reconstructed based on images acquired concurrently by cameras in the probe and by our well-established generic tomography setup. The mobility of the probe was demonstrated by achievement of measurements in two different furnaces containing high-speed natural gas/air flames with power outputs ranging from 80 to 280 kW. The test furnaces are representative of gas firing systems that are used in thermal processes like metallurgical applications. The reconstructed fields provide information on the flame position and 3D structures, allowing better characterization of the processes involved and serving as validation data for computational fluid dynamics simulations.

Thank you for your attention

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