Gas- und Wärme-
Institut Essen e.V.

I www.gwi-essen.de

A matter of scale? – (Industrial) combustion research from the lab to real-life application

IFRF Event "From lab scale to industrial combustion: challenges for the scale up of experimental and simulation approaches"

Jörg Leicher, Rouen/France, April 25th, 2023

Does size/scale matter?

Spoiler alert: Yes, it does!
At least in combustion…

Scales in stationary combustion applications

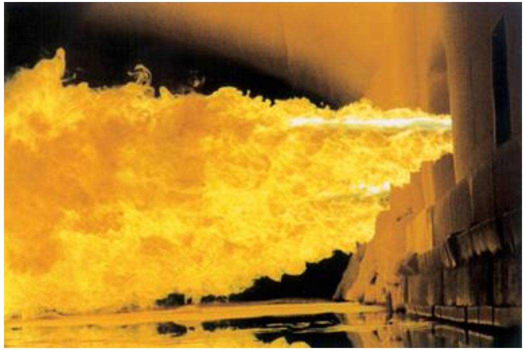
Residential/commercial

Source: Vaillant

- P: < **50 kW,** λ: 1.2 – 1.4
- Length scale: **1 m**
- Low-temperature heat, warm water
- Premixed or partially premixed combustion

Industrial process heating

Source: HVG



- P: up to **200 MW,** λ: 0.9 – 1.2
- Length scale: up to **100 m**
- Process heat
- Usually non-premixed combustion, often with air preheating or oxy-fuel

Power generation

Source: Siemens Energy

- P: up to **1.5 GW,** λ: ≈ 2
- Length scale: about **10 m**
- Power generation
- Lean premixed combustion (pressurized)

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Similarity analysis in fluid dynamics

Similarity analysis and the use of **scaled-down models** have a long tradition in many fields of **applied fluid dynamics**.

Aviation


Image: WikiCommons/NASA

Image: KLM

Shipbuilding

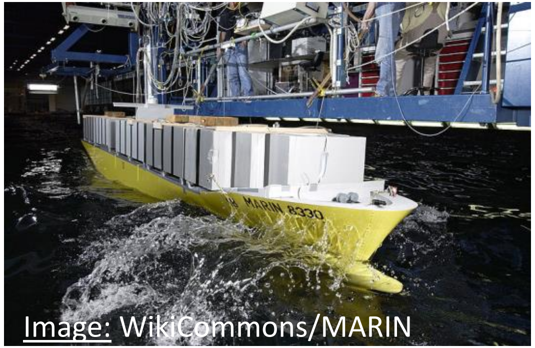


Image: WikiCommons/MARIN


Image: WikiCommons/Niels Johannes

Criteria for similarity

Theoretically, there are three criteria needed to achieve complete similarity between a **reduced-scale model** and the **real-scale system** in a **non-reactive flow**: geometric, kinematic and dynamic similarity.

Geometric similarity: the **geometric model** is of the **same shape** as the application, usually scaled down.

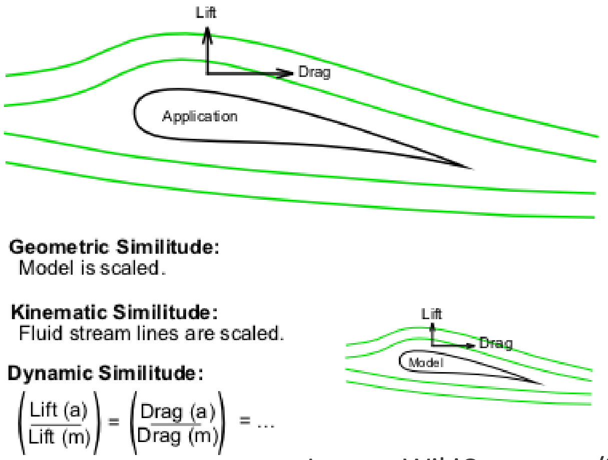


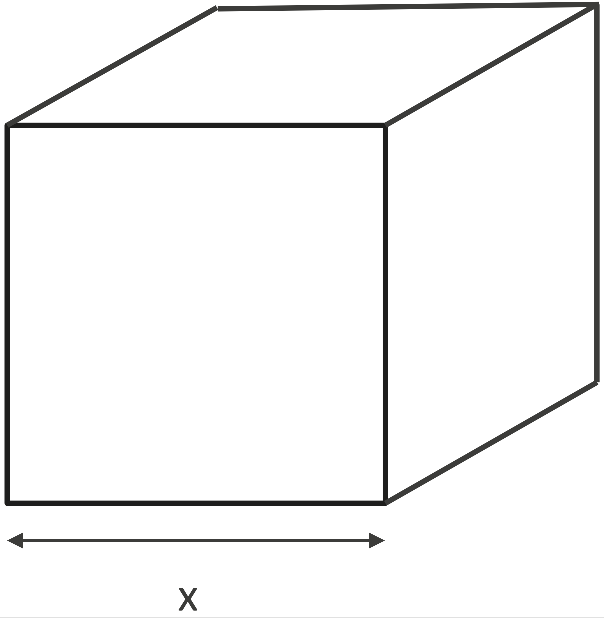
Image: WikiCommons/Duk

Kinematic similarity: the fluid flows in both the model and the real application undergo **similar changes over time**, i.e. the **streamlines** are similar.

Dynamic similarity: the **ratios of all forces** acting on corresponding fluid particles and boundary surfaces in the two systems **are the same**.

Criteria for similarity, cont'd

Theoretically, there are three criteria needed to achieve complete similarity between a **reduced-scale model** and the **real-scale system** in a **non-reactive flow**:
geometric, kinematic and dynamic similarity.



- With **combustion**, things become a bit more difficult, as the fluid itself changes during the process (ρ, T, X_i, ...).
- Some **combustion-related phenomena** and aspects scale with the **volume** ($\sim x^3$) of the combustion space, e. g. heat release, chemical reactions or residence times.
- Others scale with the **surface area** ($\sim x^2$), most importantly wall heat losses.

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Criteria for similarity, cont‘d

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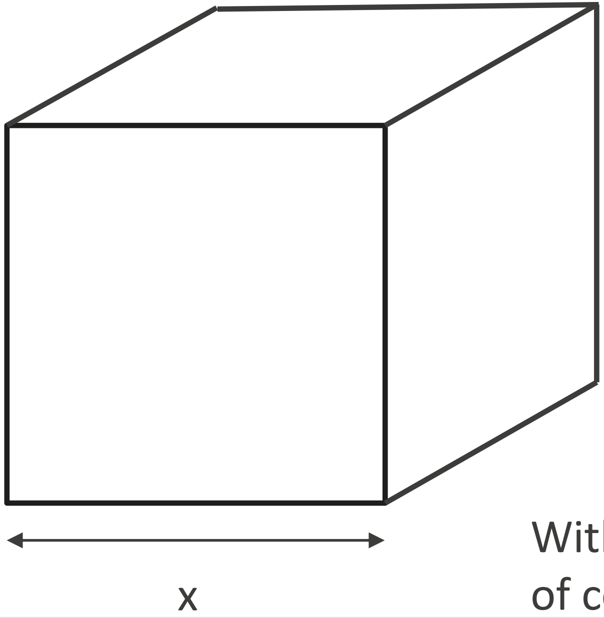
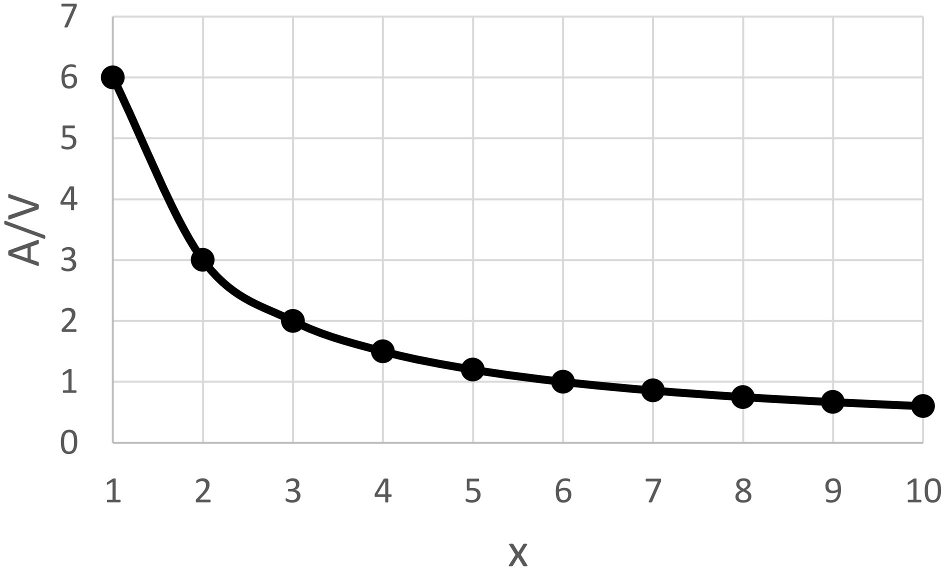
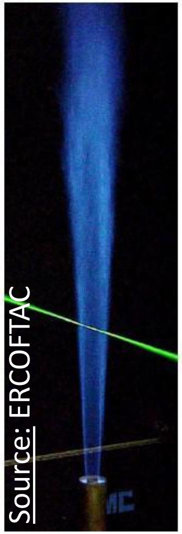




With **combustion processes**, there is an additional layer of complexity.

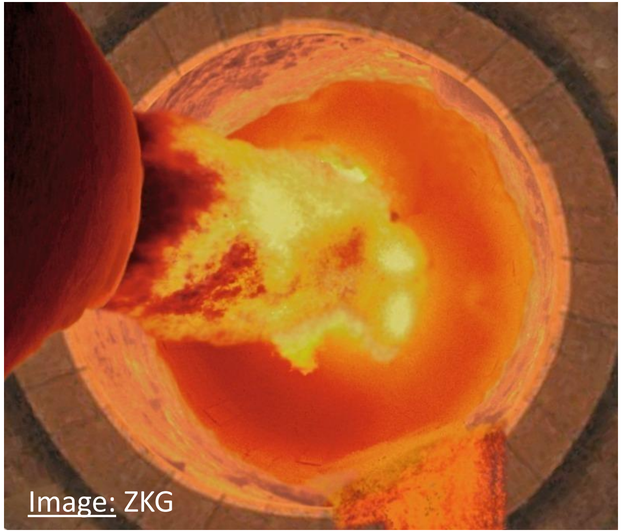
Lab scale vs. full-industrial scale

Sandia Flame D



- Size and complexity
- Control of boundary conditions
- (Un)certainties
- Reproducibility /representability
- Interaction with the product, e.g. heat transfer, process emissions, …
- Accessability for (advanced) measurement techniques
- Cost, risk, time and logistics
- Documentation

Rotary furnace



Lab-scale experiments are specifically designed to investigate certain phenomena, and simplified accordingly. With industrial systems, you take what you get…

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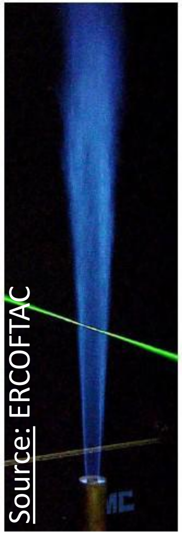
Lab scale vs. full-industrial scale

complexity, uncertainty, cost, risk, …



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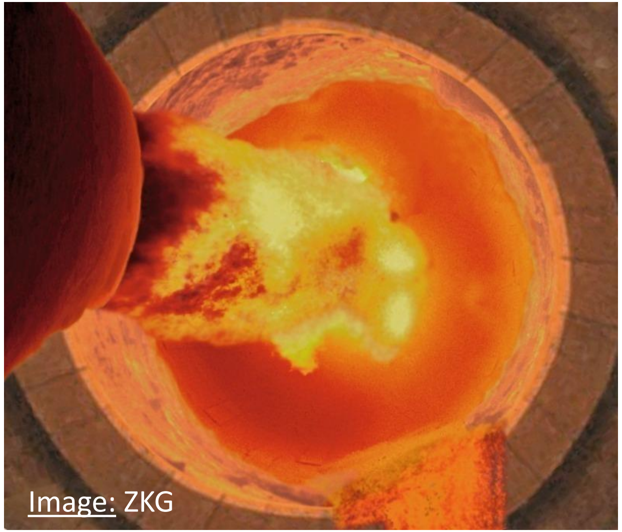


control of boundary conditions, data resolution (time & space), reproducibility, accessability, …

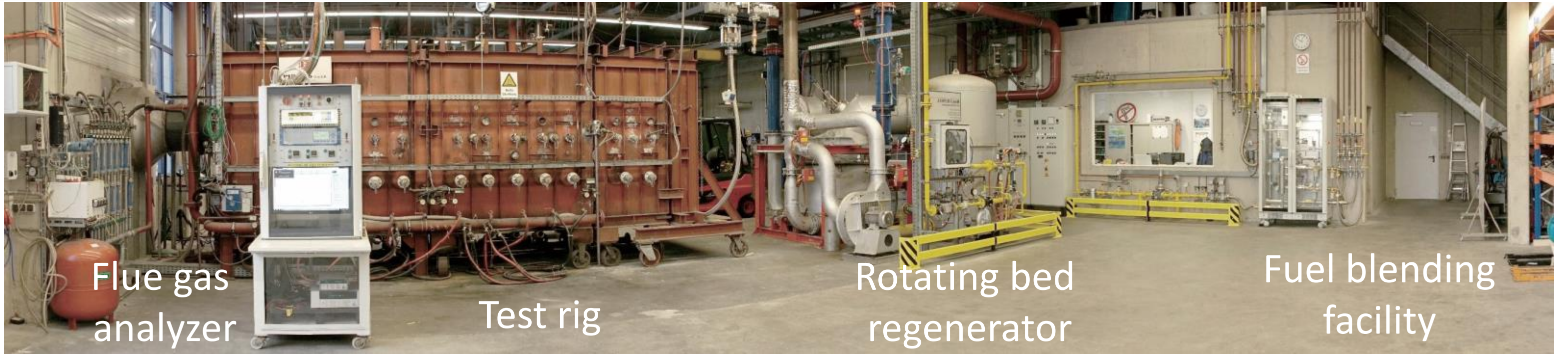
Definitions – a proposal for applied combustion research

- **Lab scale:** experiments **designed specifically** to investigate **well-defined** physical/chemical **phenomena**. Focus on good control over the boundary conditions, reproducibility and accessibility with (advanced) measurement techniques.

- **Industrial scale:** The actual application**, as it is found in industry**. Focus on fitness for purpose, safety, product quality (where applicable), efficiency, pollutant emissions, CAPEX/OPEX, …

- **Semi-industrial scale:** experiments designed to **recreate the crucial features** of an industrial process on a **smaller scale**, with some **simplifications**. Focus on reasonable **accessibility** for measurement techniques, good control over **boundary conditions** and **reduced cost** and **risk**.

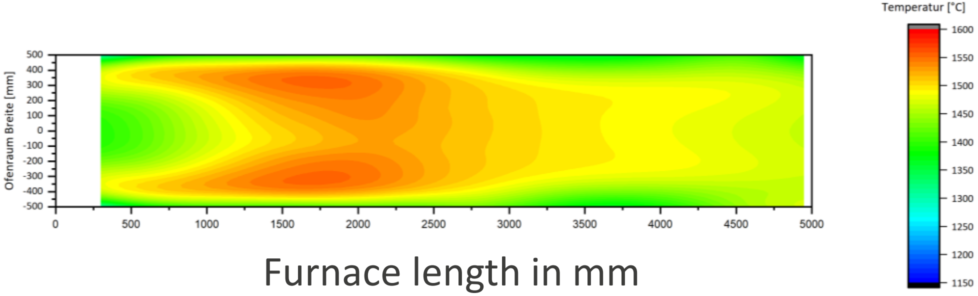
An example of a semi-industrial combustion test rig (GWI Test Rig No. 1)

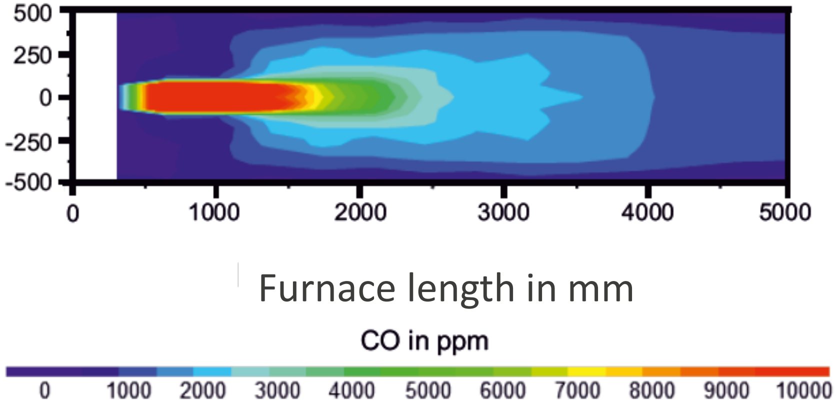


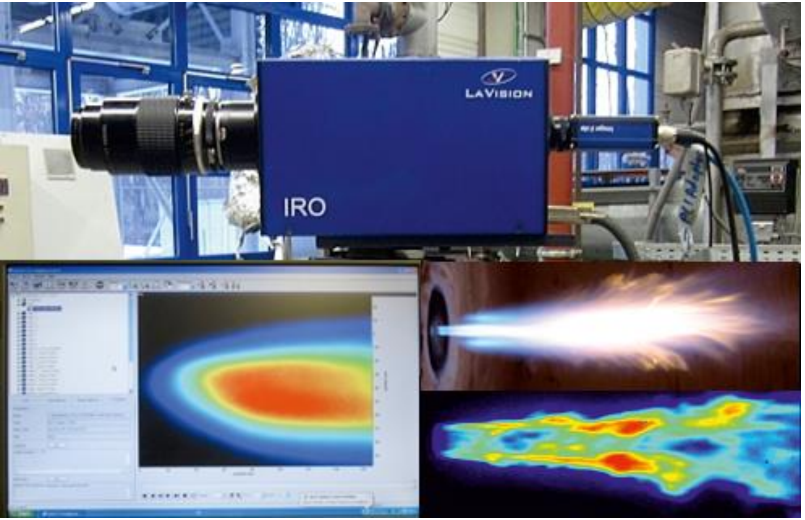
Key features:

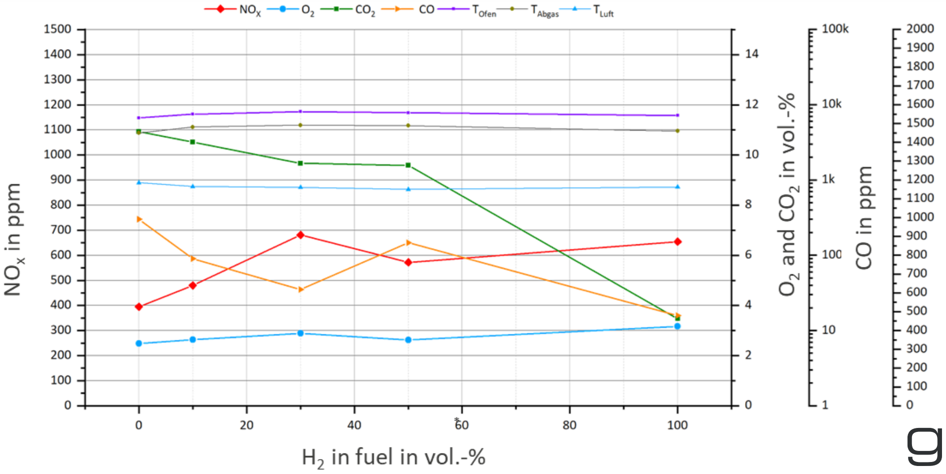
- Maximum firing rate: 1.3 MW
- Maximum wall temp.: 1,600 °C
- Maximum air preheating: 1,250 °C
- Oxy-fuel capable up to 400 kW
- Fuel flexibility (gases), H_2 supply up to 1 MW
- Flexible geometry
- Good accessibility for measurements
- Heat-up time: about 12 h

Experimental data from semi-industrial test rigs









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Do we still need semi-industrial testing anyway?

What about Computational Fluid Dynamics?

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CFD… or why bother with semi-industrial experiments anymore?

- In recent years**, CFD modeling** has become a powerful tool, both for **fundamental research** and **industrial application**, across many fields.

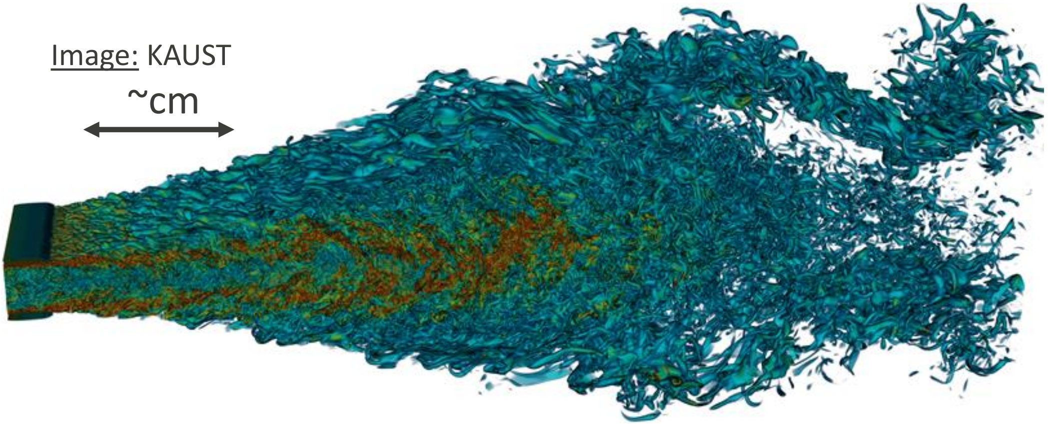
- In principle, CFD could be the ideal tool to **bridge the gap** between lab-scale experiments and full-scale application, offering **high data resolution** at **full scale, without interfering** in the actual process.

- But some challenges and constraints remain, such as:
  - **Boundary conditions** in industrial CFD can often be quite uncertain or „best guesses“.
  - **Trust?** It‘s just numbers in a computer, after all…
  - Scales are **still an issue**: turbulent scales (e. g. Kolmogorov vs. integral turbulent scales), chemical time scales, ….
    Scale-resolving simulations can lead to **extreme hardware requirements**.

Simulations have scale issues too, …

DNS of a combustion process in a gas turbine combustion chamber

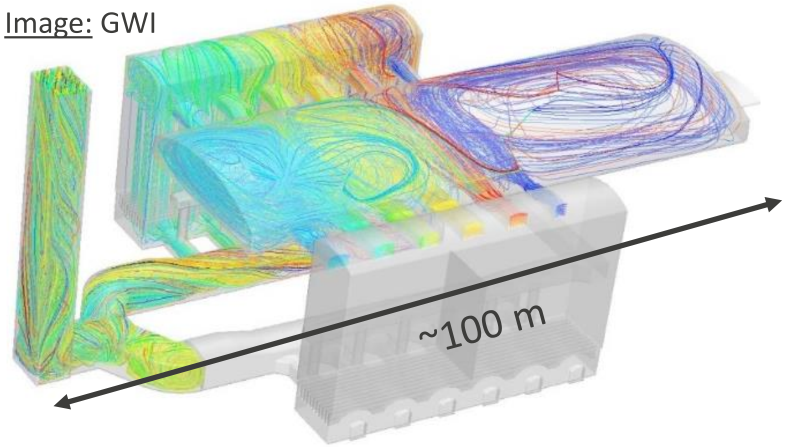
Image: KAUST



- Premixed CH_4/air combustion, gas turbine conditions
- **22 billion cells**, transient, 4 **TB** per time step

CFD simulation (RANS) of a regenerative glass melting furnace (100 MW)

Image: GWI



- Non-premixed natural gas/air combustion, air preheating: 1,200 °C
- About **10 million cells**, steady-state file size: a few **GB** in total

Validating CFD modeling

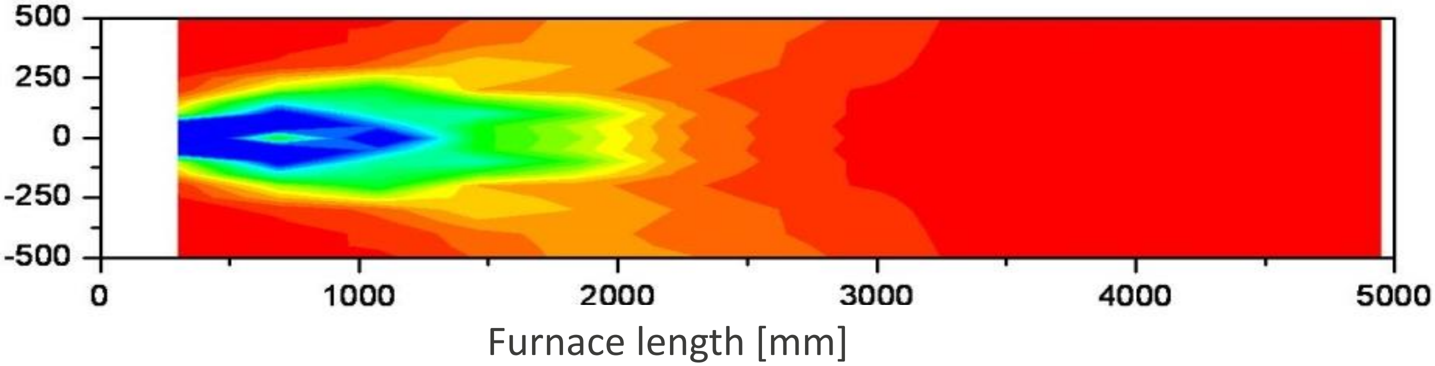
- CFD methods suited to describe combustion phenomena in great detail (e.g. DNS, LES, DES) may be **too computationally expensive** to describe full-scale applications.
  Simplified, less expensive approaches, e. g. **steady-state RANS**, may be necessary.

- Also, the **purpose** of the simulations may vary: **design**/optimization vs. **fundamental analysis.**

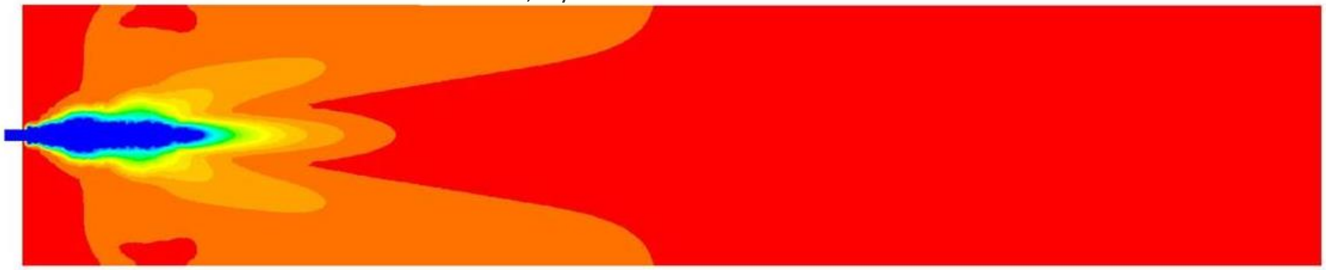
- Any CFD simulation is only as good as the **numerical mesh** it is based on, the **models** and the **solver** that it uses and the **boundary conditions** that are provided.
  Each of these aspects introduces **errors** and **uncertainties**.

- **Validation** using data from **semi-industrial test rigs** is useful to check whether a chosen CFD modelling approach is suitable to describe a full-scale industrial process at all, and to **assess** the **uncertainties** involved.

Measurement vs. simulation: oxy-fuel combustion of natural gas (400 kW)



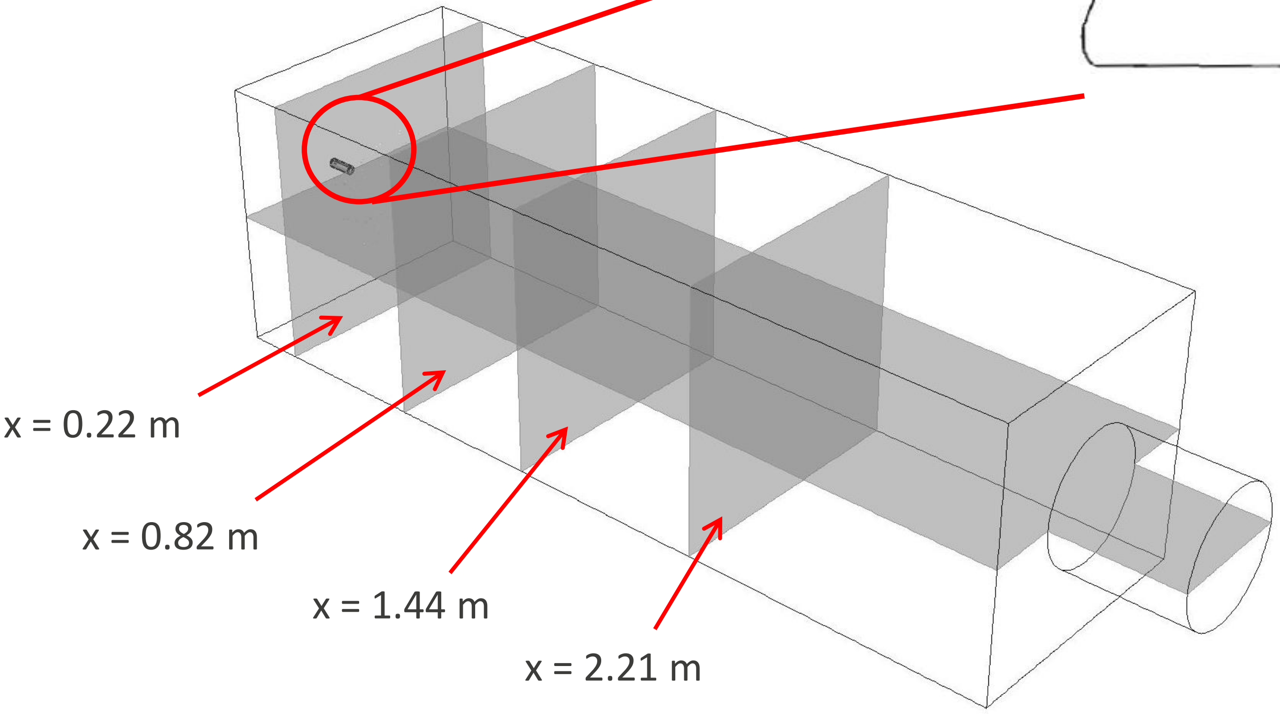
GWI measurement

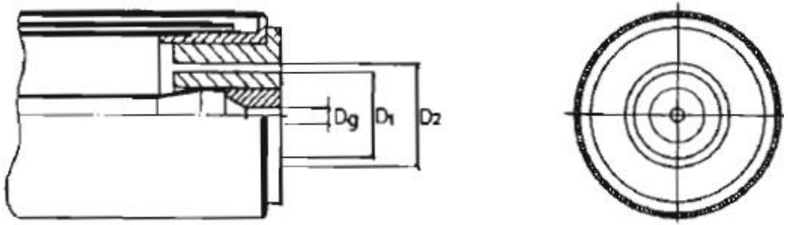


CFD simulation (EDM with 2-step reaction mechanism)

OXYFLAM experiments at IFRF research station, Ijmuiden (NL)

L x W x H:
3440 mm x 1050 mm x 1050 mm





D_g: 4 mm
D_1: 28 mm
D_2: 36 mm

Source: Lallemant, N, Dugué, J., Weber, R., "Analysis of the Experimental Data Collected during the OXYFLAM-1 and OXYFLAM-2 Experiments - Part One", IFRF Report F85/Y/4, Ijmuiden, NL, 1997

Models and boundary conditions

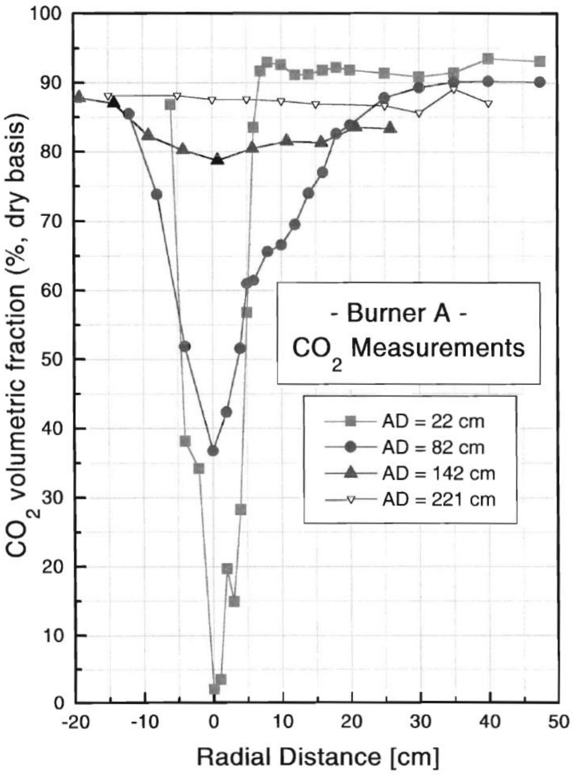
- CFD code: ANSYS Fluent, steady-state RANS
- Mesh: 1.7 Mio. cells, hybrid, full-3D
- Turbulence model: Realizable k-ε
- Combustion model: non-adiabatic PDF-Equilibrium-Model
- Radiation model: Discrete-Ordinates-Model
- Thermal boundary condition at furnace walls (based on measurements):

$$\dot{q} = 35 \frac{kW}{m^2}$$

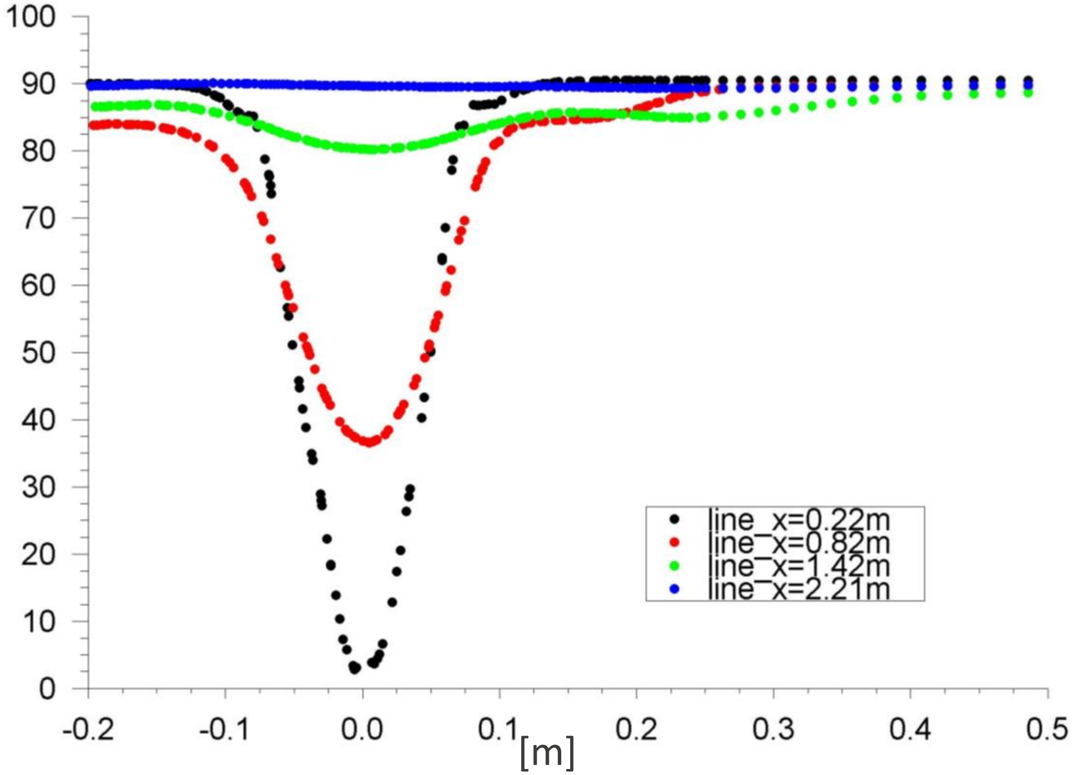
Firing rate	780 kW
λ (100 % O_2)	1.03

Natural gas composition:	
CH_4 [vol.-%]	86.0
C_2H_6 [vol.-%]	5.4
C_3H_8 [vol.-%]	1.87
C_4H_{10} [vol.-%]	0.58
C_5H_{12} [vol.-%]	0.14
N_2 [vol.-%]	4.01
CO_2 [vol.-%]	1.79
O_2 [vol.-%]	0.21

Measurement vs. simulation: CO_2 profiles (Oxy-fuel)

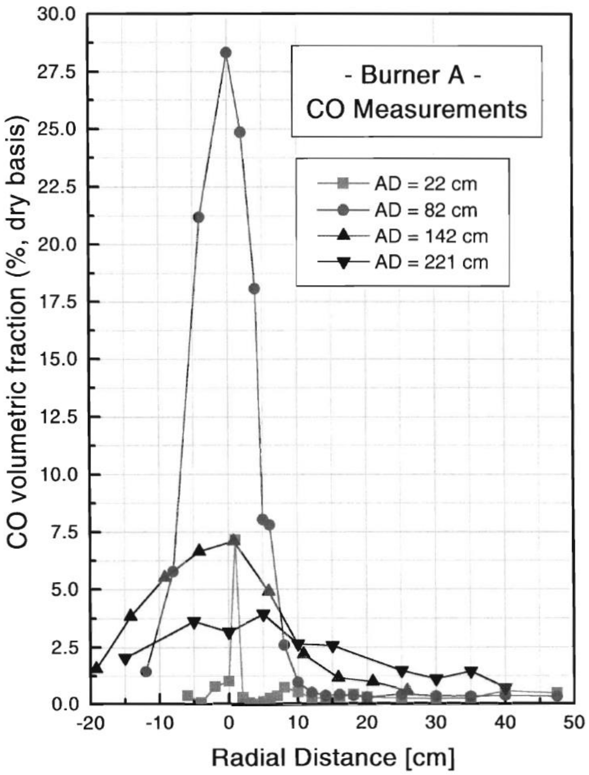


IFRF measurements

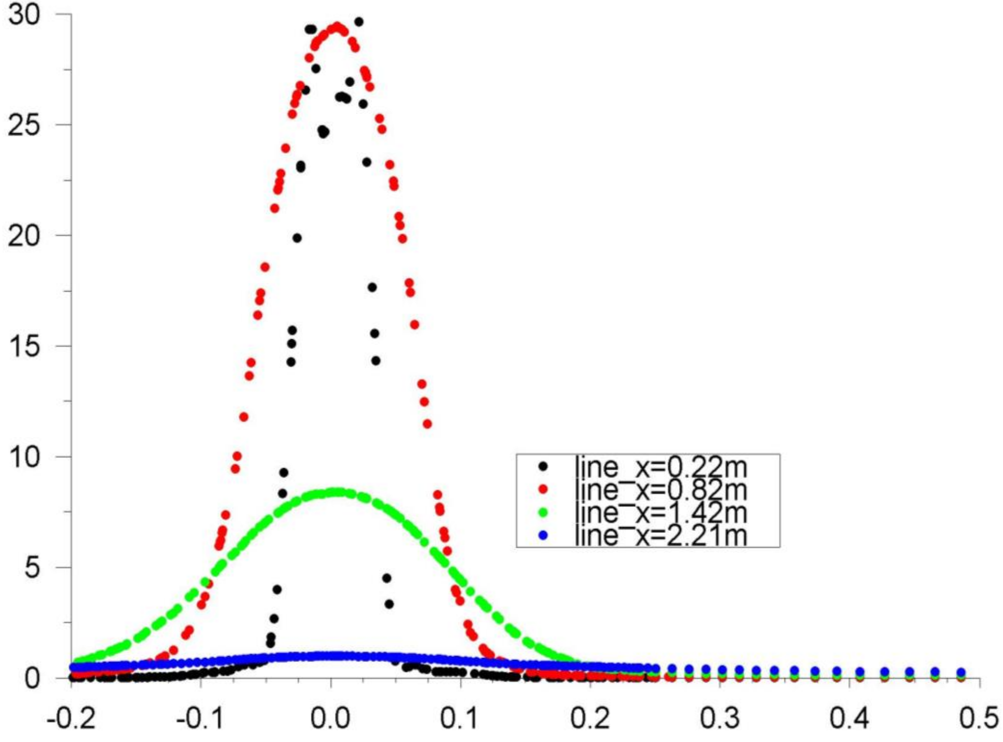


CFD simulation (GWI)

Measurement vs. simulation: CO profiles (Oxy-fuel)



IFRF measurements



CFD simulation (GWI)

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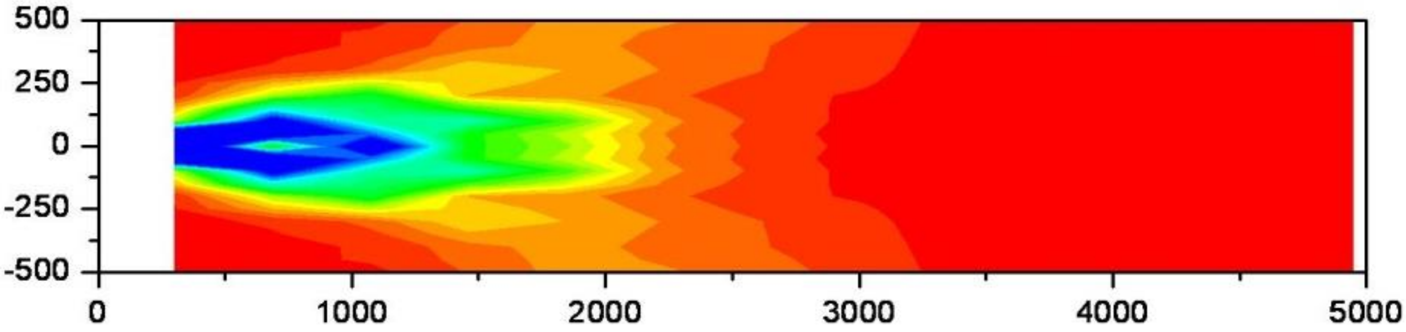
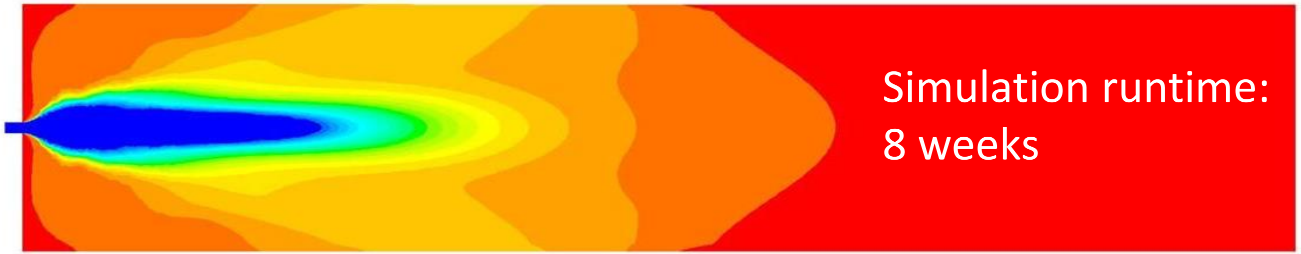
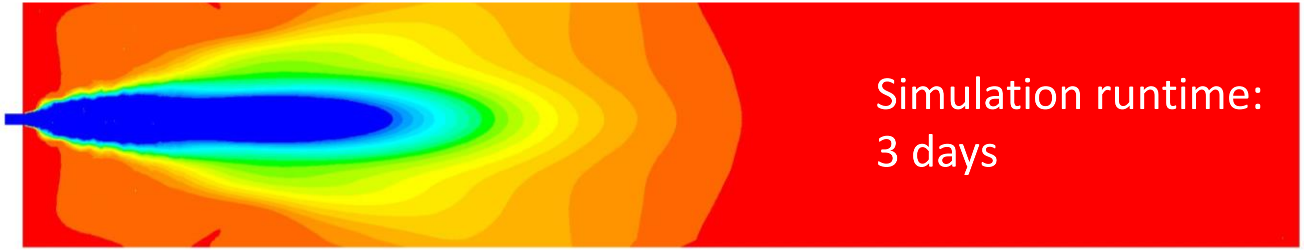
Measurement vs. simulation: oxy-fuel combustion



GWI measurement

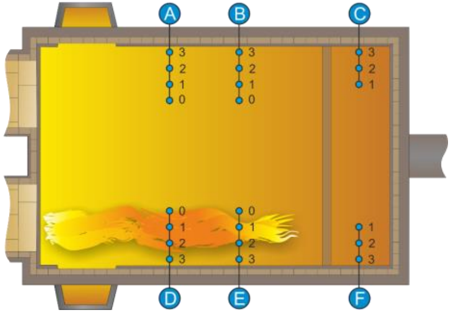


CFD simulation
(EDC
17 species)



CFD simulation
(non-adiabatic
PDF equilibrium)

Measurements and simulations in industrial-scale applications



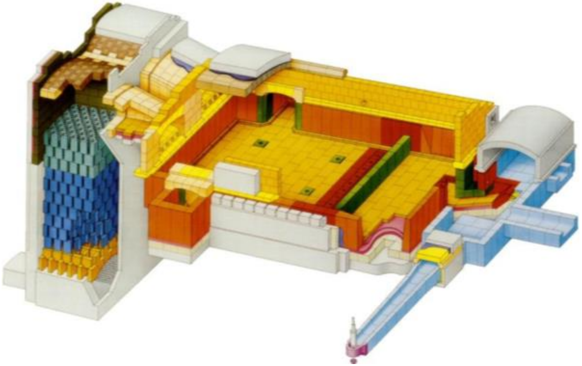
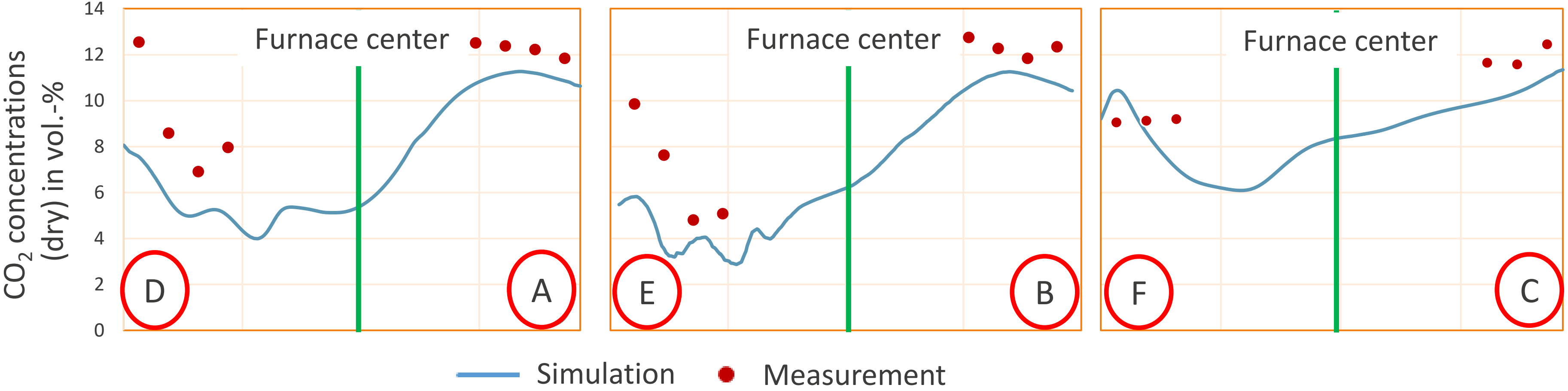


Image: GMIC



Higher CO_2 concentrations in measurements due to process emissions!

The future…
New topics and new methods?

Future developments

- Many energy-intensive industries are faced with **new challenges**, such as:
  - Decarbonization (=> new fuels, electrification and/or hybrid systems)
  - Energy (in)security
  - Digitalization

- At the same time, new tools and methods are becoming available to the industrial sectors, often driven by „**Big Data**“ methods: Artificial Intelligence, Artificial Neural Networks (ANN), Digital Twins, Machine Learning, …

- Many of these new approaches more or less **forego physical modelling** and rely instead on **statistical analysis techniques** and **huge data sets** for **specific plants**. This may limit their usefulness for **extrapolation** to „new“ operational conditions, e. g. using hydrogen instead of natural gas.

New topics require lab-scale experiments, …

Some things are better tried on a small scale first :

NH_3/H_2 combustion:

P: 8 kW

λ: 1.05

Various Swirl Numbers:

0< S < 1.1

Further info:

ECM 2023

Poster # 436074, Room 4, Wednesday morning (Session #1)

Contact: M. Biebl

marcel.biebl@gwi-essen.de

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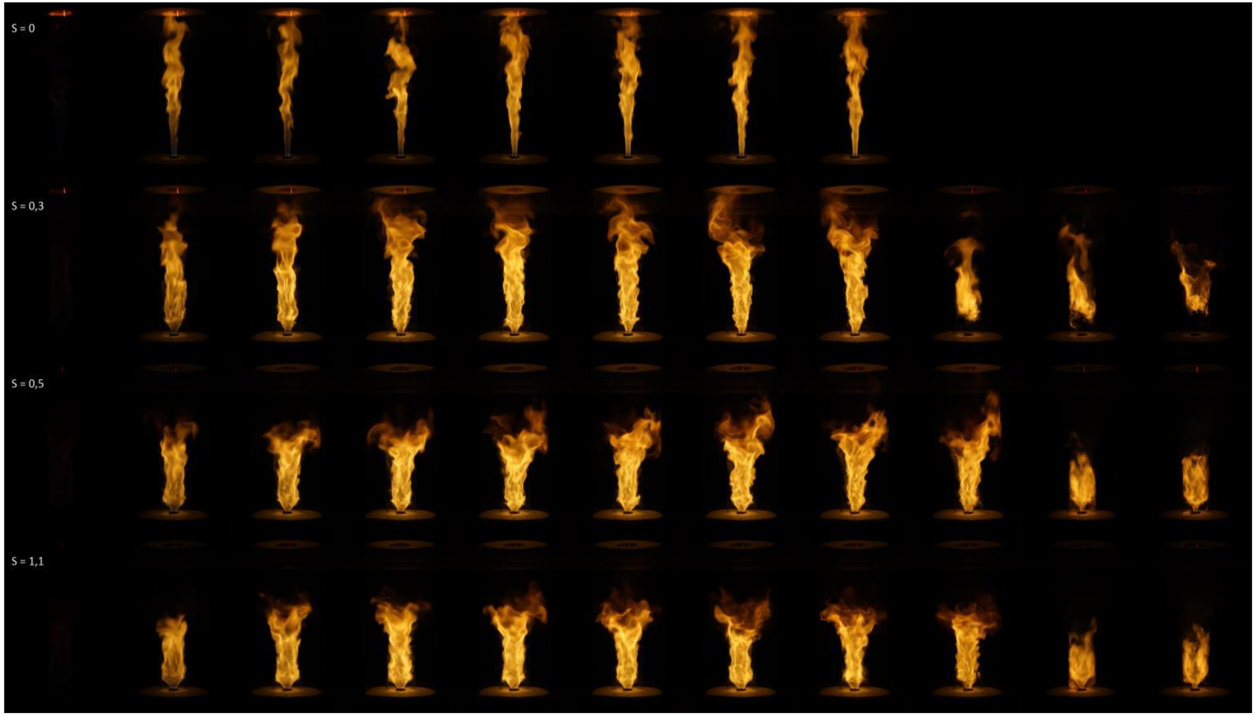

0 % 10 % 20 % 30 % 40 % 50 % 60 % 70 % 80 % 90 % 100 % NH_3

NH_3/H_2 combustion:

P: 8 kW

λ: 1.05

Various Swirl Numbers:

0< S < 1.1

Further info:

ECM 2023

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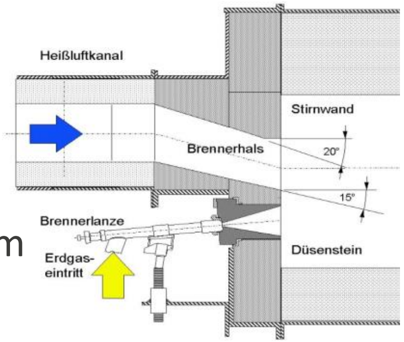
…semi-industrial test rigs, …

Project **HyGlass**: Investigating hydrogen-fired glass melting on a semi-industrial scale

Underport configuration

Preheated air
(1,150 °C)

Variable momentum
fuel lance

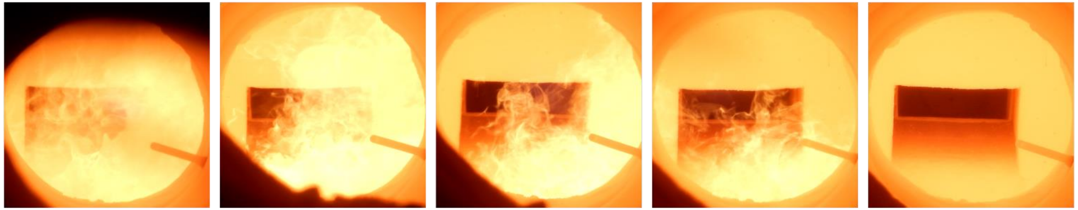


P = 500 kW; λ = 1.1
(constant in all experiments)

GWI HT burner test rig

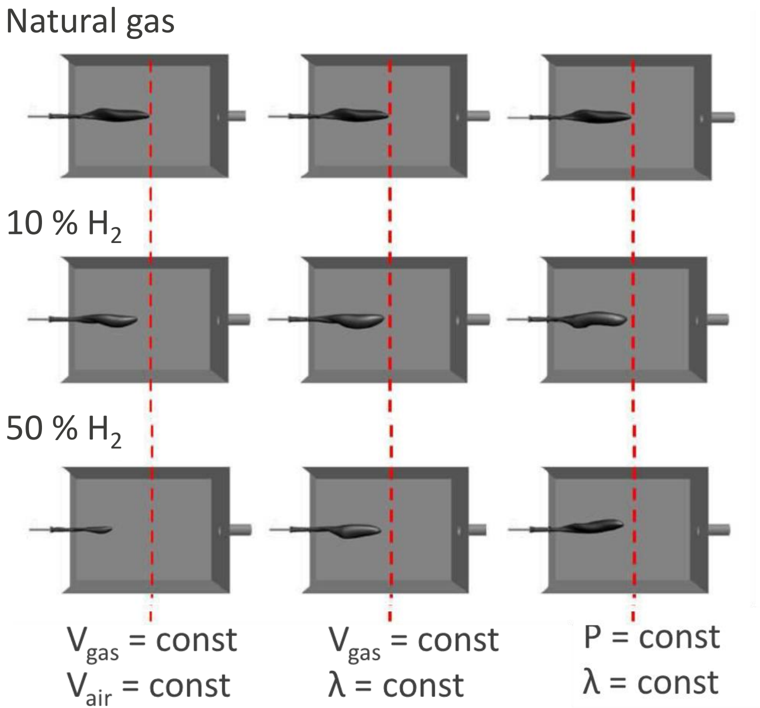
H_2 supply by trailer

NG | 10 % H_2 | 30 % H_2 | 50 % H_2 | 100 % H_2 (by volume)

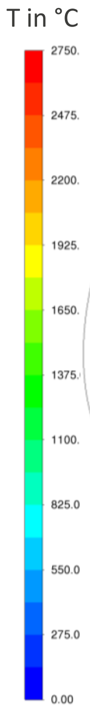


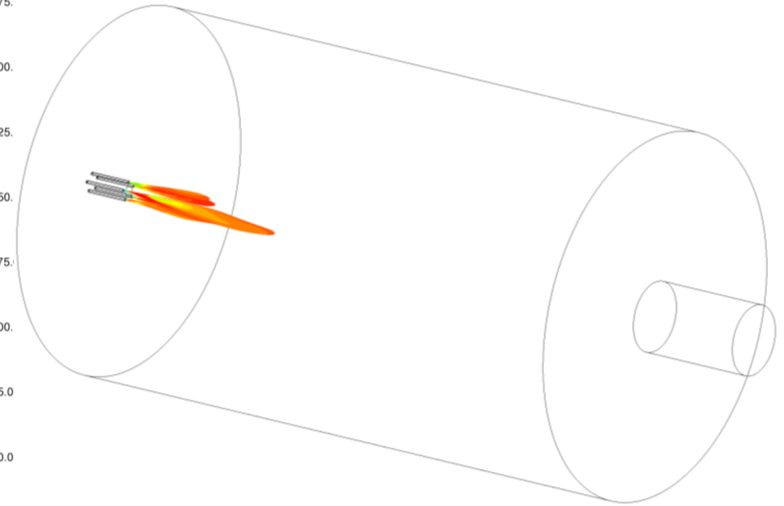
…. CFD simulations, …

Simulation of the impact of H_2 admixture on an industrial burner (100 kW) in a test rig



Oxy-fuel combustion of hydrogen in an 3.5 MW aluminum scrap recycling furnace





Flame shape visualized with iso-surface of the stoichiometric mixture fraction

Images: GWI

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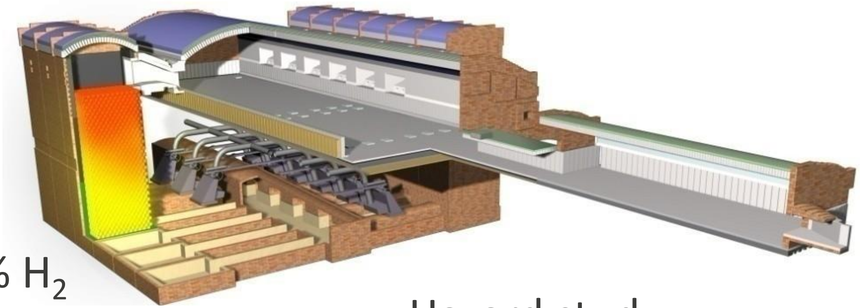
… and full-scale industrial trials (HyNet/HyDeploy, NSG, 2022)*

Image: CGE Glass



- Investigations on the impact of hydrogen on an industrial float glass plant (50 MW) in UK.
- 3 weeks of testing (6 h each) on **1 port**, from 20 % **to 100 % H_2**. 5-day-long test run at 15 % H_2 on **all ports**.
- **Logistics** is a challenge: at 100 % H_2, 1 trailer had to be replaced every 40 min. Sufficient H_2 (and trailers!) have to be available for full-scale tests.
- **Safety-compliant handling** of large amounts of H_2 for testing purposes in an industrial plant is not easy.

Hazard study

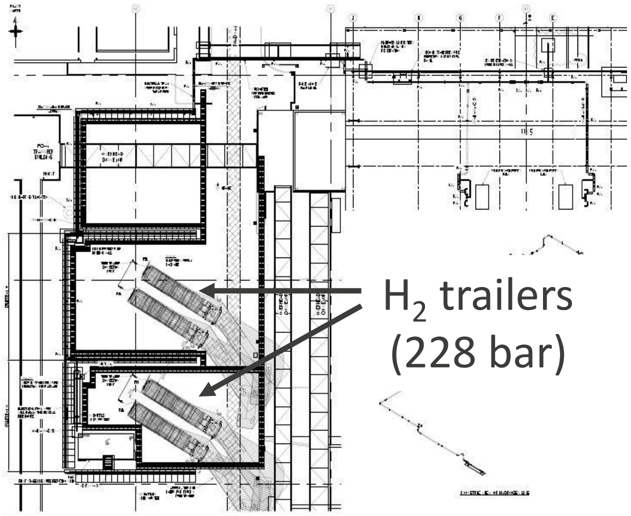


Image: NSG

*Keeley, A., Hydrogen Combustion on a Float Glass Furnace, ICG 2022, Berlin, Germany

Conclusion

- **Scales matter** in combustion research, both because of the **significant differences** in various end-use applications, but also because the **physical and chemical phenomena** themselves.

- Semi-industrial experiments serve to **bridge the gap** between fundamental combustion investigations and full-scale industrial applications, minimizing cost and risk for R & D.

- CFD modeling will likely **not completely replace** semi-industrial testing, but rather **complement** it, as both approaches have their **respective benefits** and **drawbacks**.

- A **combined approach** using lab scale experiments, semi-industrial tests and CFD can help **reduce the risks** and provide **valuable information** when implementing new technologies on an industrial scale.

Finally…

"Nobody trusts a computer simulation except the guy who did it, and everybody trusts experimental data except the guy who did it.

Why not combine the two and get results everybody can mistrust a little."

T. Kordyban

„In theory, there is no difference between theory and practice.

But in practice, there is."

Walter J. Savitch (1923 - 2021)

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Thank you for your attention

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