

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

- 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



- 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



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

Source: Vaillant

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**.





kiCommons/MARIN





Aviation

Shipbuilding

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.

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



Geometric Similitude: Model is scaled.

Kinematic Similitude: Fluid stream lines are scaled.

Dynamic Similitude:

 $\begin{pmatrix} \text{Lift (a)} \\ \text{Lift (m)} \end{pmatrix} = \begin{pmatrix} \text{Drag (a)} \\ \text{Drag (m)} \end{pmatrix} = \dots$



Image: WikiCommons/Duk

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, Τ, X_i, ...).
- Some combustion-related phenomena and aspects scale with the volume (~x³) of the combustion space, e. g. heat release, chemical reactions or residence times.
- Others scale with the surface area (~x²), most importantly wall heat losses.

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Criteria for similarity, cont'd

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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...

Lab scale vs. full-industrial scale

complexity, uncertainty, cost, risk, ...

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

Source: ERCOFTA

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), H₂ supply up to 1 MW
- Flexible geometry
- Good accessibility for measurements
- Heat-up time: about 12 h



Experimental data from semi-industrial test rigs



Do we still need semi-industrial testing anyway?

What about Computational Fluid Dynamics?



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



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



- Premixed CH₄/air combustion, gas turbine conditions
- 22 billion cells, transient,
 4 TB per time step

- 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)



OXYFLAM experiments at IFRF research station, Ijmuiden (NL)



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 ₂ H ₆ [vol%]		5.4
C ₃ H ₈ [vol%]		1.87
C ₄ H ₁₀ [vol%]		0.58
C ₅ H ₁₂ [vol%]		0.14
N ₂ [vol%]		4.01
CO ₂ [vol%]		1.79
O ₂ [vol%]		0.21

Measurement vs. simulation: CO₂ profiles (Oxy-fuel)



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



Measurement vs. simulation: oxy-fuel combustion



Measurements and simulations in industrial-scale applications



Higher CO₂ 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 :



NH₃/H₂ combustion:
P: 8 kW
λ: 1.05
Various Swirl Numbers:
0< S < 1.1
Further info:</pre>

Poster # 436074, Room 4,

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Wednesday morning

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ECM 2023

(Session #1)

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Further info: ECM 2023 Poster # 436074, Room 4, Wednesday morning (Session #1) Contact: M. Biebl marcel.biebl@gwi-essen.de

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

...semi-industrial test rigs, ...

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

Underport configuration

GWI HT burner test rig

H₂ supply by trailer



.... CFD simulations, ...

Simulation of the impact of H₂ admixture on an industrial burner (100 kW) in a test rig Natural gas





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

- 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 % H₂. 5-day-long test run at 15 % H₂ on all ports.
- Logistics is a challenge: at 100 % H₂, 1 trailer had to be replaced every 40 min. Sufficient H₂ (and trailers!) have to be available for full-scale tests.
- **Safety-compliant handling** of large amounts of H₂ for testing purposes in an industrial plant is not easy.
- *Keeley, A., Hydrogen Combustion on a Float Glass Furnace, ICG 2022, Berlin, Germany



Hazard study



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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)

Thank you for your attention

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