Relevance of and Research Challenges in IC Engine Combustion Process

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Outline

- Academic Research > from Fundamentals to Applications and vice-versa
- Industrial Relevance of ICE Reactive Thermofluidics
- Scientific Challenges in ICE Reactive Thermofluidics
- Our Strategy and examples of Research Methods
- Conclusions
PORTFOLIO LOOP OF ACADEMIC RESEARCH

Applicability, Practical Relevance, …

Under application

Fundamental research

University interests limit

Risk, Disruption, Novelty, …
Why Engine Combustion Research?

Cross-cutting engineering science discipline with very large impact to the overall energy system* well beyond mid-of-the-century (today ≈ 85% of world final energy based on chemical energy carriers – IEA prognosis of >> 50% for 2050)

Enormous scientific challenge – coupling of turbulence with detailed reaction kinetics, multiphase, exothermistry, multi-species transport

Swiss industry in the field very important (ABB, WinGD, FPT, KISTLER, Liebherr, DUAP, Wenko, Motorex, CRS, …)

But: Can every transport mode be electrified?
Electrification Potential of the Swiss Heavy-Duty Fleet

When battery energy densities improve

When battery swapping technology is available

Based on detailed technology and demand analysis
Source: E. Çabukoglu, LAV
ICE-CHP as «power on demand» concept to balance intermittent PV

Results from Regional Studies

Response Time: 0 (min) from zero to full load
Future Potential of Synthetic Renewable Fuels

**Origin**: biogenic, excess electricity, solar-chemical sources/processes

**Composition**: H$_2$, CH$_4$, C$_x$H$_y$O$_z$ (gaseous or liquid)

**Research Challenges and Opportunities**
Chemistry (Autoignition, Flame Characteristics, Pollutant formation)
Upstream Processes (LCA)
Optimized combustion modii for zero emissions incl. minimal CO$_2$
### Which Energy Sector should we try to decarbonize first?

CO$_2$ Mitigation effect (g) per kWh electricity

<table>
<thead>
<tr>
<th>Source of Electricity</th>
<th>Buildings HP vs burners</th>
<th>Replacement of coal power plants</th>
<th>Electrify car vs. Hybrid ICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>800-1’100</td>
<td>900-1’200</td>
<td>450-600</td>
</tr>
<tr>
<td>CCGT/EU-Mix (50/50)</td>
<td>400-700</td>
<td>500-800</td>
<td>50-200</td>
</tr>
</tbody>
</table>

Therefore: Target Low-Hanging Fruits First!
Research Challenges in ICE Thermofluidics/(1)

Flow field

- Unsteady hyrdodynamic and thermal boundary layers (B.L.)
- Local/micro-scale vortices in the vicinity of the wall drive transport phenomena
- Flow velocities not parallel to wall but stochastically distributed → Driven by large vortices outside the B.L.
- Unsteady heat transfer

⇒ Tremendous spatial (and temporal) resolution for CFD and optical diagnostics!

Turbulence

- Many generation mechanisms
- Unsteady
- Inhomogeneous and probably non-isotropic
- Low frequency turbulence → Cycle-to-cycle fluctuations
- High frequency → “Real” turbulence
Research Challenges in ICE Thermofluidics/(2)

- Complex flame-turbulence interaction
- Combustion regime (Flamelets, Broken Reaction Zones, etc)?

Turbulent Premixed in Lean (Diluted) Mixtures

Non Premixed (Diffusion) Flames

- Often two- (sprays) or three- (with particle) phase flows
- Convective and strongly radiative heat transfer

Flame torches
Research Challenges in ICE Thermofluidics/(3)

- Pre-Chamber: Flame wall interaction
- Main-Chamber: Ignition mechanism → Flame propagation or Autoignition?
- Low-Temperature, 2-stage autoignition

Turbulent Jet Ignition

HCCI, RCCI, Dual Fuel

Laser/Plasma Induced Ignition

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Research Strategy on Engine Combustion

→ **Objectives:**
  - Maximum energy conversion process efficiency (fuel consumption, CO₂ emissions)
  - Minimization of pollutant emissions (NOₓ, soot, UHC, …)
  - Emerging (reformulated, biogenic) fuels → (closed C-loop and/or Power-to-Fuel)

→ **Methods:**
  - Computer based simulation of combustion and chemically reactive systems
  - Non-intrusive, in-situ diagnostics of turbulence/flame/structure interactions in model and real-world systems
  - Simulation and diagnostics in Microsystems, porous media and on surfaces (emerging)
  - Energy Systems Models for Research Agenda Definitions
A hierarchical research Approach

Description of requirements

Simulations
- Application - Understanding
  - 0-D Models
- Industrial CFD - Design
  - CFD-RANS
    - Application-Oriented Models
    - Model validation under real conditions
- Detailed investigations
  - CFD-LES
    - Detailed Combustion Models
    - Model development/validation
- Fundamental Understanding
  - DNS
    - Fundamental Investigations

Experiments
- Near-Production Engine
  - 1-cyl Engine
- Near Engine Optical Investigations
  - Optical Meas.
    - RCEM - Real PC Geometry
  - Fundamental Investigations
- Optical Meas.
  - Generic Geometry, Optical PC

Understanding/data flow

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New Flexible Rapid Compression/Expansion Machine (OeCoS)

Space for a single hole fuel injector (optionally with cooling-adaptor)

Engine exhaust valves

Pneumatic valves (four per exhaust valve, two per intake valve)

Two secondary windows (access for laser sheets etc.)

Valve position sensor (One for each valve)

Engine intake valves (one of two shown)

Two large round windows - or -

One window and one holder for multi-hole fuel-injectors / spark plugs / pre-chambers etc.

Optical access

Engine piston
Flex-OeCoS Characteristics

- Block based on a Heavy-Duty Diesel engine
- Max 1800 rpm
- Up to 240bar peak pressure

→ Advantages:
  - Realistic peak pressure
  - Variable effective compression ratio
  - Very good optical access
  - Adjustable turbulence level/field
  - Various temperature and pressure combinations possible
  - Various cylinder head geometries possible
  - Possible to reproduce Medium-speed DF engine Conditions:
    - >100bar at SOI, ~700rpm, different flow field turbulence levels
Variety of Combustion Modes in Our Transparent Test Rigs

→ Optical results

Otto Combustion ($H_2$)  Diesel Combustion  HCCI-Combustion  dual fuel combustion

→ Dual fuel investigations for ignition of lean methane with Diesel pilot
- Ignition of lean homogeneous methane charge with autoigniting Diesel pilot spray
  - Understand influence of methane on autoignition delay and early flame development
  - Develop/validate models for Diesel pilot auto-ignition and the turbulent premixed flame propagation

→ Fuel Indices for Homogenous Combustion Project
- Definition of fuel’s properties related to HCCI combustion
  - Running single combustion stroke under well defined homogenous conditions for different synthetic fuels
  - Observe the behavior and process evolution of different fuels under HCCI combustion
Direct Numerical Simulation (DNS)
DNS for Engines? – Motivation

RANS → Main approach for industrial applications → Calculation of averaged quantities

LES → Research tool => emerging in industry → Able to predict cyclic fluctuations

Results depend on resolution and models (turbulence, heat transfer, flame speed, etc…) => Validation necessary

1) Experiments

2) Reactive DNS
- Not attempted so far
- Numerical Experiment
- All fields are fully resolved available

M. Schmitt*, C.E. Frouzakis, Y.M. Wright, K. Boulouchos; Physics of Fluids, 11/2013
DNS Code: Nek5000 + LAV plugin

- **Nek5000**: scalable, open source, spectral element incompressible flow solver
- General purpose high-order code for CFD
  - Accurate and fast: few degrees of freedom for given accuracy
  - Complex geometries (open and confined)
  - High scalability to over a million processors (exascale computing)

- **Physics**
  - Low-Mach-No-Flows (Direct & Large Eddy Simulation, RANS)
  - Passive scalar transport
  - Conjugate heat transfer
  - Detailed chemical kinetics and species transport
  - Moving mesh / free surface flows

- Open source: [https://nek5000.mcs.anl.gov](https://nek5000.mcs.anl.gov)
Local Wall Heat Flux in IC Engines (DNS!)

Heat flux [W/m²]
(cylinder head)

270°CA

Source: M. Schmitt, PhD, 2014

Heat flux [W/m²]
(cylinder head)

346°CA

1.0 e4

1.3 e5
Flame Propagation in Engine (DNS)

\[
\frac{u'}{S_L^0} \quad 1.41
\]

\[
\frac{l_t}{\delta_f^0} \quad 1
\]

\[
T = 0.500
\]

Low-Engine-Speed / Stoechiometric Operation

\[
T = 0.042
\]

High-Engine-Speed / Lean-Burn Operation

Source: M. Jafargholi, C. Frouzakis
Flame propagation and Wall Heat Transfer
(2-DNS in an engine combustion chamber)

\[ l_t = 2 \delta_f \]
\[ u' = 8.6 S_L^0 \]

Source: M. Jafargholi, C. Frouzakis
Summary

- IC Engine coombustion is a fascinating research field where scientific challenges abandon.
- Chemical Energy Carriers, in particular synthetic renewable fuels will be indispensable in the Global Transportation Market for several decades.
- Relevance of ICE research is high for Swiss export Industry > focus on heavy-duty long range transport.

Therefore: We look forward to several «Combustion Research Days» in Switzerland!
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