EFC Topic 4.1
Measurements for Simulation benchmarking

Presented by Brian Peterson (TU Darmstadt)

Objectives of 4.1

Contents:

• Engine participants to EFC
• Summarize available data
• Scope and uniqueness of data
• EFC subtopics addressed by data
## Contributions

1. **Transparent Combustion Chamber Engine**, David Reuss, [dreuss@umich.edu](mailto:dreuss@umich.edu)  
   
   **TCC** (GM/UM)

2. **Spark-Ignited Direct-Injection Engine**, Brian Peterson, [peterson@csi.tu-darmstadt.de](mailto:peterson@csi.tu-darmstadt.de)  
   
   **SIDI** (TU Darmstadt)

3. **SGEmac Experimental Database**, Cecile Pera, [cecile.pera@ifpen.fr](mailto:cecile.pera@ifpen.fr)  
   
   **SGEmac** (IFP)

4. **Sandia H\(_2\)** Direct-Injection Engine, S. Kaiser, [sebastian.kaiser@uni-due.de](mailto:sebastian.kaiser@uni-due.de)  
   
   **H2ICE** (SNL/U DuE)
1. TCC (GM/UM)
TCC Engine Measurements and LES Working Group

Simulations:
Tang-Wei Kuo, Xiaofeng Yang, General Motors Company, Sponsor
Chris Rutland, University of Wisconsin
Daniel Haworth, Pennsylvania State University

Measurements:
Volker Sick, Dave Reuss, University of Michigan

Scope:
• Provide accurate and repeatable data base for RANS and LES model validation.
• Identify sources and mitigate CCV.
Design Intent:

- Transition from Imperial College analogue for simulation benchmarking circa 1990.
- Platform for fundamental, empirical studies of CCV.
- Simulation Grid Friendly
  - Geometrically simple
  - Efficient multi-cycle simulation*
- Optically accessible for measurements.

- Features to exaggerate fluid mechanics
  - “Pancake” chamber & Undirected port → high CCV
  - Small $D_{\text{valve}}/D_{\text{bore}}$ → high shear @ low rpm

* Haworth, OGST, 1999
History of experimental installations

**TCC - 0**  GM R&D,  1995 – 2002 publications
- GM Intake and Exhaust systems, single-angle valve seat
- PIV, RANS, LES development in reciprocating ICE
- Motored and fired data

**TCC – II**  University of Michigan,  2010 – 2014 publications & posted data
- UM intake and exhaust systems
- Full quartz cylinder, improved piston ring, two-angle valve seats
- Motored data

**TCC – III**  University of Michigan  2013 -
- Added: fuel (C$_3$H$_8$), N$_2$ dilution, flame arrestors → new GT Power model
- Refurbish valve train, (four-angle seats)
- Motored and fired data
**TCC-II Engine**

5 Measured Pressures

92mm x 86mm BxS, 10:1 CR

"Closed" & heated intake-air metering system
GT Power model available
**Engine Operation**

- Motored at 400, 800 & 1600 rpm
- each 5 ca deg, 70 continuous cycles
- 3000 cycles at 100 & 300 ca aTDCexh
- 2 and 3 component PIV measurements
- 1.6 & 2.9 mm resolution, recorded simultaneously
Data Integrity

- Dynamic measurement of Instrumentation timing:
  - encoder–piston TDC timing
  - valve lift & open/close ramps.

- Optical-engine compression-ring design → blowby < 1% at 95 kPa

- Pressure & Velocity Measurement range, noise, & uncertainty documented.

- Test-to-test engine operation repeatability
  - Operation protocols
  - Redundant transducers & daily calibration
  - Operation control-charting & post-test evaluation
Data Integrity (continued)

- Extensive intake, exhaust, and cylinder-pressure comparative analysis

![Graphs showing data integrity analysis]
Data and Analysis Focus

Intake Jet, 100 CAD aTDC

Undirected TCC Intake Flow Exhibits:
- Large CCV of intake jet
- CCV yields averaging-sample dependency

Details in Topic 4.4
Posted Data*, TCC-II

- Test averages and StdDev
- Per-cycle parameter averages & StdDev: measured values, cycle-integrated parameters
- Per-crankangle measurements: in-cylinder, runners, & plenum pressures; rpm

- Velocity: - 2-component velocity, 2-D grid
  - PIV measurement plane through valve centers
  - 1.6 & 2.9 mm resolution, simultaneously
  - each 5 ca deg, 70 continuous cycles

- Geometry: GT Power model, geometry (.STL)


Data located on UM server. Contact Volker Sick: vsick@umich.edu
2. SIDI (TU Darmstadt)
TU Darmstadt Measurement-Simulation Efforts

• Scope of Investigations
  – Sub-processes of turbulent-combustion in engines
  – Provide established database for model validation

• Experiment Group
  – TU Darmstadt (A. Dreizler)
  – Data available upon request:
    • Brian Peterson (peterson@csi.tu-darmstadt.de), Benjamin Böhm (bboehm@ekt.tu-darmstadt.de)

• Modeling Groups
  – TU Darmstadt (J. Janicka, S. Jarkirlic)
  – TU Freiberg (C. Hasse)
  – U. Duisburg-Essen (A. Kempf)
  – RWTH Aachen (H. Pitsch)
  – Cambridge (N. Swaminathan)
• **Single-cylinder SIDI engine**
  – 4-valve, pentroof head
  – Bore, Stroke: 86 mm

• **Designed for model validation**

• **Engine Test Bench**
  – Well-characterized BCs
    • Flow, T, P, rel. humidity, EGR, fuel (DI, PFI), $\lambda$, spark (V,I)
  – Repeatable, reliable operation and BCs
Optical Engine: Available Cylinder Heads

Wall-guided

- Side mounted injector
- Valves
  - Intake: 33 mm dia.
  - Exhaust: 31 mm dia.
- Clearance Volume: 66.5 cm$^3$
- CR: 8.5

Experimental Setup: Example

8) Peterson et al. 11th Int. Congress Engine Combust. Processes, Ludwigsburg (2013)
9) Baum et al. 16th Int. Symp. Laser Techniques to Fluid Mechanics, Lisbon (2012)
Non-Reacting Flow

• Fundamentals of engine flows
  – Multiple diagnostic approaches
• Comprehensive flow database

High-speed PIV

• Evolution of flow
• Intra-cycle & cyclic flow dynamics

Tomo-, stereo-PIV

• 3D flow
• *All* gradient tensor components
  – Reynolds Stress
  – Anisotropic invariants

High-statistic PIV (up to 2700 cycles)
• Statistical moments of flow
• Convergence
• Conditioned statistics

High Res. PIV (0.4 mm)
• Spatial scales
• Gradients
• Energy spectra

[Image of velocity data and flow dynamics]
Coherence of Measurements

**Velocimetry methods (PIV)**
- Tomographic, stereoscopic, high-speed, low-speed, high resolution

**Data integrity**
- Validated, reliable, repeatable

**Experimental Comparisons**

Ensemble Average Velocity field in Central Axis
Steady-State Flow Bench

• Magnetic Resonance Velocimetry*
  – Water with Gadolinium-based agent
  – Conducted in MRI machine

*Collaboration with Sven Grundmann, Aeronautical Engin. TU Darmstadt

Exp. Fluids (2014) awaiting proofs

Polyamide engine model (1:1 scale)

- Radial flow past valve curtain
- Entire valve periphery
- Velocity recirculation zones
- Charge filling, variations

- 3D intake flow entire domain
- Provides ensemble average

water in
Combustion Characterization

- Flame Propagation
- Mie scattering
  - PDF of enflamed region

- Chemiluminescence
  - Spherical flame growth approximation

- Simultaneous dual-plane OH-LIF & stereoscopic PIV
  - 3D reconstruction of flame surface
  - $u, v, w$ convection velocity
  - 3D local flame speed

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2D probability of enflamed region, spark timing 16° bTDC

3D reconstructed flame surface and 3C turbulent flow field

PDF of local 3D flame speed

Peterson et al. ProCI (2014)
3. SGEmac (IFP)
Introduction

• Experimental database for validation and development of LES modeling

• **Objective**: study of cycle-to-cycle variations using LES supported by experiments

• **Uniqueness:**
  • Modern engine geometry
  • Experiments with LES
  • 1D Simulations
Complete geometry available
- 4-valve, pentroof
- Based on Renault F7P

Well characterized BCs
- CA° resolved
- Cycle resolved

Operation
- Homogeneous C₃H₈ / air
- Direct-injection (iso-octane)
- Low CCV operating points
- Large CCV operating points
  - Lean, diluted

System Simulation Support
In-cylinder PIV (100 cycles)
Combustion characterisation

**OH-LIF and OH*: Flame kernel structure and location**

-12 CAD  
-8 CAD  
-4 CAD

**Chemiluminescence**
Reactive zone characterization

**1D Analysis**

\( P_{\text{cyl}} \) for low and large CCVs

**Simultaneous PIF and OH-LIF:**
Turbulent flame propagation models

Statistics on combustion (BMF, CA\(_{xx}\), ...)

April 4 & 5, 2014
4. H2ICE (SNL/U DuE)
Sandia H2ICE on the ECN – data and simulation

Acetone PLIF + PIV

Unique measurements
- full bore & stroke
- almost to walls
- quantitative

Laser 532/266 nm

Injector

Exhaust

Intake

Piston

Optical liner

Tumble plate

Intake
Hydrogen DI: a single-phase, fully gaseous, highly underexpanded jet

Experiment
PIV underestimates centerline mean velocity during injection

Simulations:
Shock structure necessitates fine grid near nozzle

\[ c_s (H_2, 300 \text{ K}) = 1270 \text{ m/s} \]
Green: On the ECN web page  Red: Measured but not on ECN page

- Geometry, boundary conditions, intake, cyl., exhaust pressures
  *(valve lifts unintentionally missing on the web)*
- Tumble-plane velocity during compression
  - With and without injection
  - For neutral and tumble-enhanced intake
  - In complete cylinder and pent-roof
- Tumble-plane fuel mole-fraction during compression
  - Angled single-hole nozzle, Inj. at IVC
  - Other injectors and injection timings
- Ensemble-means available, single shots missing
- Flame propagation
  - High-speed Schlieren movies in pent-roof
  - Single-cycle correlated pressure traces and AHRR
- Schlieren movies of early jet penetration
Measured, but currently not on the ECN web page

Multiple-cross-plane imaging (in the mean)

Velocity in the pent roof

Early flame propagation
Collaboration between Sandia and Argonne (2009 – 2011)

Turbulence models and tuning

Grid convergence

Multi-hole nozzles
Simulation helped the experiment in fixing mistakes

**Numerical**

**Experimental (N₂)**

Fluorescence (ns) + phosphorescence (μs - ms)

(at 300 m/s: 100 μs = 30 mm)

Fluorescence (ns) phosphorescence quenched by O₂

More accurate calibration (corrected for fuel lost into intake in flat-field calibration)
Comparisons of/with different RANS-simulations

Argonne Nat’l lab (R. Scarcelli)
- FLUENT
- All k-ε models found to perform similarly well
  
SAE 2011-24-0096
SAE 2011-01-0675
SAE 2009-24-0083

Poli. Milano (T. Lucchini)
- OpenFOAM
- Standard and RNG k-ε found to perform best
  
SAE 2011-24-0036

Convergent Science (J. LeMoine)
- CONVERGE
- RNG k-ε
  
ASME ICEF2014-5610 (submitted)
Status DI-H2ICE

• Engine and lab still usable but unused at Sandia
• No dedicated support for any further experimental activities
• More of the existing data, e.g., velocity in pent-roof and flame-propagation movies could be put online
• Data may be moved to Duisburg server for better site maintenance

• Victor and Sebastian receive and support 2 - 3 requests / year from researchers starting simulations of this engine
Fuel dispersion in different simulations

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<th>Experiment</th>
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<td>Low-tumble case</td>
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H$_2$ICE

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