Where the Heat goes?  
Thermal Analysis of Internal Combustion Engines

Global Star User Conference

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Thermal Analysis of IC Engines

Overview

Introduction

CAE Procedure

Gas-side heat transfer

Coolant-side heat transfer

Validation

Summary
Thermal Analysis of IC Engines

Introduction

• **Downsizing of engines:**
  → Increase of specific engine power output
  → Higher thermal loading
  → Optimized and very effective cooling system is needed

• **Shorter development cycles**
  → Less project time
  → Robust & accurate CAE process

→ **Target for CAE**
  → Predictive results are required.
  → Calculated structural temperatures within +/- 5 K from reality.
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CAE Procedure

- CFD Combustion Simulation
  - ES-ICE + STAR-CD
- CFD Coolant Flow Simulation with solid (CHT)
  - STAR-CCM+
- Averaging over working cycle
  - $\alpha_{\text{gas}}(x,t)$
  - $T_{\text{gas}}(x,t)$
  - $T_{\text{wall}}^*(x)$
- Some Iterations
  - $\alpha_{\text{gas}}^*(x)$
  - $T_{\text{gas}}^*(x)$
- 1D Gas Exchange Simulation
  - GT-Power
- Thermomechanical Analysis (FEM)
  - ABAQUS
- CFD Combustion Simulation
  - ES-ICE + STAR-CD

Symbols:
- $m_{\text{Fuel}}$
- $\lambda$
- $p_{\text{in}}(t)$
- $T_{\text{in}}(t)$
- $p_{\text{exh}}(t)$
- $T_{\text{exh}}(t)$
- $n, P$

Coolant

$d\dot{m}/dt_{\text{Coolant}}$
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Gas-side Heat Transfer

CFD Combustion Simulation
ES-ICE + STAR-CD

Averaging over working cycle

\[ \alpha_{\text{gas}}(x,t) \]
\[ T_{\text{gas}}(x,t) \]

Some Iterations

CFD Coolant Flow Simulation with solid (CHT)
STAR-CCM+

1D Gas Exchange Simulation
GT-Power

Thermomechanical Analysis (FEM)
ABAQUS

\[ \frac{dm}{dt}_{\text{Coolant}} \]

\[ T_{\text{wall}}^*(x) \]
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Gas-side Heat Transfer

Motivation
- Wall heat transfer has influence on thermodynamics, emissions, wall film, etc.
- Thermal loads are an important input for FEA

⇒ Realistic calculation of thermal loads on engine structure is essential

Simulation Approach
- CFD simulation of working cycle / gas-side heat transfer
- Cycle-averaging of heat transfer coefficients and local gas temperatures
- Mapping to CFD-CHT model

Result
- Detailed analysis of thermal loading
- Thermal boundary conditions for FEA
- Pre-calculation of structural temperatures
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Gas-side Heat Transfer

Sensitivity analysis of combustion system parameters (Diesel)

- Nozzle Bore Dia.
- Nozzle Depth
- Start of Injection
- Pre-Injection
- Init. Temperature
- Boost Pressure
- EGR Rate

→ Combustion system specification should be considered as good as possible
→ In real-life project work, these information are often not yet available
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Gas-side Heat Transfer

Sensitivity analysis of basic CFD model parameters

*Turbulence model and wall function have the biggest impact*
*Selection of suitable submodels is required*
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Gas-side Heat Transfer

Sensitivity analysis of turbulence modelling

<table>
<thead>
<tr>
<th>Turbulence model</th>
<th>ΔQ_w [%]</th>
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<tbody>
<tr>
<td>Model A</td>
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<tr>
<td>Model B</td>
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<td>Model C</td>
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<tr>
<td>Model L</td>
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</tr>
</tbody>
</table>

→ Selection of a suitable turbulence model is mandatory
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Sensitivity analysis of wall function

Experiment (Woschni)
Standard Wall Function
Wall Function Model A
Wall Function Model B
Wall Function Model C

Selection of suitable wall function model is mandatory
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Cycle-averaged heat input boundary condition from working-cycle CFD

Combustion chamber  Exhaust ports  Liner

→ 3d effects captured (e.g. non-symmetric heat flux distributions)
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Coolant-side Heat Transfer

CFD Combustion Simulation
ES-ICE + STAR-CD

CFD Coolant Flow Simulation with solid (CHT)
STAR-CCM+

Averaging over working cycle

α_{gas}(x,t)
T_{gas}(x,t)

Average over working cycle

α_{gas}^*(x)
T_{gas}^*(x)

1D Gas Exchange Simulation
GT-Power

n, P

Thermomechanical Analysis (FEM)
ABAQUS

Some Iterations

dm/dt_{Coolant}

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Conjugate Heat Transfer Model

Polyhedral calculation grid with conformal interfaces

→ Sufficient discretisation necessary (approx. 20 mil. cells for R4 engine model)
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Coolant-side Heat Transfer

Coolant properties

• **Chemical composition of cooling fluids affects**
  → Convective heat transfer behaviour as well as
  → More important, phase change behaviour / boiling heat transfer performance

• **Differences of surface temperatures up to 20 K are observed**

→ Detailed boiling behaviour of coolant fluid should be known
Boiling modelling

- **Available models**
  - **Single-phase Rohsenow model**
    - To be parameterised / calibrated
    - But:
      - No transition / film boiling effects captured
      - No boiling suppression at higher velocities captured
  - **Multi-phase transition boiling model**
    - To be parameterised / calibrated
    - But not intended on stationary calculations

- **Developed IAV approach**
  - Transition boiling model equations implemented via field functions in single-phase simulation
  - Boiling suppression considered
  - Calibrated with measurement data
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Coolant-side Heat Transfer

Effects of different Coolant Boiling Performances

Heat transfer performance vs. Cylinder-head temperatures

ΔT approx. 20K

→ Accurate description of coolant boiling behaviour is necessary
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Validation

Differences Simulation to Measurement

This represents a successful simulation, but not yet in target range of +/- 5K
Satisfying predictive simulations are still challenging
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Summary

→ Not only computational power is decisive but accurate submodelling of ALL physics.
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