Integrated Systems approach in thermal modeling by using GT-Suite

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Oct. 29, 2014
Outline:

New industry requirements

Challenges in thermal modeling:
- Fast warm-up vs Cooling capability
- Fuel Economy/ Performance

Modeling approaches

Model applications:
- Steady state simulations;
- Warm up studies – evaluation of contributors;
- Engine oil cooler assessment
- Calibration support
- DFSS studies
New industry requirements

CO2 Regulatory Emission requirements
EU vs. US and China (Passenger Vehicles)

- US CAFE/GHG requirements
  - TODAY: 39.5 mpg (~166g)
  - 2016: 39.5 mpg (~166g)

- EU CAFE requirements
  - 2014: 130g (49 mpg)
  - 2018: 95g (67 mpg)

EU vs. China
- CHINA
  - 2016: 95g (67 mpg)

Courtesy of Roger Clark
OUTLOOK FOR GLOBAL FUEL ECONOMY AND GREEN HOUSE GAS REQUIREMENTS

- **China**: • 7.5L/100km in 2015 (37 mpg) • 5.0L/100km by 2020 (56 mpg)

- **U.S. Federal**: • In 2016, at 35.5 mpg • By 2025, at 54.5 mpg • Gasoline up to $3/gallon

- **Canada**: • Green Levy • 6.6L/100km (35.5 mpg) in 2016

- **Japan**: • 29% CO₂ in 2010 → 2015

- **European Union**: • 130g/km in 2015 (43 mpg) • 95g/km in 2020 (58 mpg) • Local CO₂ taxation • Gasoline up to $6/gallon

- **Korea**: • 140g/km (39.5 mpg)

- **Mexico**: • 10.8 km/l by 2015

- **India**: • 150 gCO₂/km by 2015 (43 mpg)

- **California**: • 80% CO₂ reduction by 2050 • ZEV, PZEV rules

- **Courtesy of Roger Clark**
Challenges in thermal modeling

- Fast engine warm up:
  - Fuel energy redistribution – from Energy to Coolant to Energy to Engine thermal masses;
  - Define a proper threshold to avoid boiling;
  - Deliver a min coolant flow to maintain the engine thermal balance

- Cooling capability:
  - Higher coolant capability is needed for a stoichiometric engine operation and for a hotter running engines in general
Challenges in thermal modeling

- All subsystems contributing to the engine thermal balance are to be included
- All physics are to be captured

Design
Performance
Testing

Significant level of complexity
Modeling approaches

- CFD data;
- System isothermal analysis

Controls

Engine performance (GTP)
- Combustion heat

Engine thermal masses
- Heat from IEM
- Heat from friction
- Heat to oil
- Heat to coolant

Components friction

Lube system
- From Dyno test or GTP approach;
- From in-house software

Cooling system

- CFD data;
- System isothermal analysis
Modeling approaches

Oil in head
Head thermal mass
Head coolant
Fuel heat generation
Block coolant
Block thermal mass
Oil in block

Main Model – with modules
FRM-Engine
Coolant
Block

Coolant
Modeling approaches

• **Cooling system:**
  • Engine cooling system that includes engine specific components;
  
  • Coolant pump (s) thru pump performance curves (flow rate as a function of RPM and Pressure);
  
  • Thermostat (s) / Cooling control valve (s)
  
  • Dyno or Vehicle cooling system – depending on project request;
  
  • Heat exchangers require both fluid inputs
• **Lubrication system:**
  • The major components included in the model are:
    • **Oil pump** performance that usually comes from the isolated lube system analysis:
      - pump curves at various RPM and oil temps for two pressure modes of the variable displacement pump (if applicable)
    • **Engine oil cooler** and **turbocharger** (if applicable)
    • **Oil block flow passage** that includes main gallery, main and rod bearings, piston squirters;
    • **Oil head flow passage** with cam bearings, cam phasers and lifters;
    • **Oil pan** (oil sump)

Such a representation supports friction module connections
Modeling approaches

**Air flow/Combustion system:**
- In order to provide the fuel energy coming to the system at a certain engine speed/load condition a stand alone GTP model is integrated into the engine thermal model;
- FRM (Fast Run Model) for both Steady State and Transient Operations
  - **Intake and Exhaust Systems** – Simplified but still capture main tuning effects
  - **Combustion Characteristics** – Contains accurate attributes for specified operating conditions
  - **Controls** – Contains representative algorithms for proper engine controls; ie: throttle, camshafts, waste gate, spark, etc

**Exhaust system:**
- Conventional exhaust system - represented thru the GTP model;
- System with integrated exhaust manifold - an additional heat exchange between the IEM gasses and engine thermal mass is to be included
Modeling approaches

In engine performance - FRM model transient/steady state

Original GTP model
FRM model

Model conversion

Original FRM

Computational time gain

Run time:
Original GTP model – 80 X RT;
FRM with component reduction – 40 X RT;
FRM with GTP model recalibration – 3 X RT
Modeling approaches

• **Engine thermal structure:**
  - Thermal mass partitioning:
    - Each cylinder is represented separately – cylinder to cylinder temp gradient
    - Traditional block and head masses;
    - More detailed cylinder head masses split – if refined temp distribution is needed;
    - Each cylinder Block mass split between a liner+ block mass attached to a liner and the rest of the block mass
  - Crankshaft and crankcase are represented as separated masses – due to high contribution in an overall engine mass;
  - Oil pan – to account for heat lost thru the pan to ambient
Modeling approaches

• **Engine thermal structure:**

Additional GT tools are to be used for a model build simplification

![Diagram showing the process of model building using GT tools](image)
Modeling approaches

- **Friction**
  
  - Several levels of simplifications:
    - As defined in GTP module;
    - Split between major contributors:
      - Piston;
      - Main and rod bearings;
      - Cam bearings;
    - Others
  
  - Additional friction heat is a function of temperature
Model applications:

- Steady state cases;
- Transient warm up;
- Maximum cooling modes;
- Oil cooler determination;
- Calibrations
- DFSS studies
Model applications - Steady state cases:

- Serve primarily as model validation

### Engine Coolant out temps - Fixed RPM

![Graph of Engine Coolant out temps](image1)

### Oil sump temps - Fixed RPM

![Graph of Oil sump temps](image2)

**Heat transfer, fixed RPM, at 245 sec.**

- 917.8, 6%
- 4587.9, 29%
- 1512.1, 10%
- 1361.5, 9%
- 7268, 46%

**Redistribute**

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Model applications – Transient warm-up:

- Standard and non-standard driving cycles;
- Evaluation of fluids, metal, surfaces temps over time;
- **Inputs:**
  - RPM vs. time;
  - Load vs. time;
  - With open cooling circuit loop or with an electric pump (coolant on demand) – flow vs. time
- **Outputs:**
  - Energy split;
  - Bulk Metal, fluid temps vs. time;
  - Combustion, waterjacket surface temps
Warm-up analytical results:

- Warm up rate;
- Fuel consumption

Baseline
IEM+Reduced flow
IEM+Higher flow;
IEM, no flow

<table>
<thead>
<tr>
<th>Model</th>
<th>Fuel Consumption</th>
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<tbody>
<tr>
<td>Baseline</td>
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<tr>
<td>Mod.1</td>
<td>0.99%</td>
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<tr>
<td>Mod.2</td>
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<tr>
<td>Mod.3</td>
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Model applications – Oil cooler determination:

• Steady state analysis at various coolant inlet temps and RPM;
• Open cooling circuit (vehicle components are not included);
• The simulations are performed for two cases:
  • System without cooler;
  • System with cooler.
Analysis vs. test: oil sump temp vs. RPM @ fixed coolant °C

Oil sump temperature vs. RPM: with EOC and w/o EOC

Sump temperature difference due to EOC

Test, with EOC
Repeat test, with EOC
Analysis, with TOC
Test, no EOC
Analysis, no EOC

Oil cooler impact evaluation;
Oil cooler sizing
Model applications – Calibration

• Analytical calibration;

• Steady state analysis to cover the entire range of the engine operating conditions:
  • Idle to max speed;
  • Light to WOT loads
Model applications – DFSS studies

• Design for six sigma methodology

• Use the GTS DOE functions to:
  • Create a new DOE;
  • Input control parameters;
  • Run a complete DOE study;
  • Analyze the results or post-process them in the other DFSS tools
Model applications – DFSS studies

One of the examples - **Impact of key parameters on Oil sump temperature**

- Create L12 orthogonal array
- Evaluate L12 array at several levels of noise
- Define the responses

[Graphs showing mean response, signal to noise variation, and factors and levels]

Design robustness
Summary

The GTS software has shown to be a useful tool to resolve the current industry needs in the design and analysis of thermal management systems, it enables one to:

• Combine both modules – heat generation and heat management.
• Study various scenarios and design alternatives.
• Provide the thermal parameters that cannot be directly measured in tests, but needed for engine calibration.

• The simulation results have proven to be reliable when obtained from validated models.

• The base engine thermal model serves as a template for an engine models family that address various design needs.
Acknowledgements

GM colleagues:

GTP:
- Andrew Kosanka;
- Ramakrishna Tatavarthi;

CFD:
- Colin Bosman;
- Shriram Reguraman;
- Subash Janarthanam

Gamma Technology:
- Matt Warner;
- Brad Holcomb