Ultra-High-Efficiency Engines: Integration, Optimization, Realization

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High-Efficiency Engines

• Manage the exergy of the resource:
  – minimize exergy destruction within the engine,
  – maximize work extraction by the engine,
  – minimize the exergy transferred to the environment (best engine & least impact).

• Accomplishing this requires:
  – Integration—to maximize extraction
  – Optimization—to minimize destruction
  – Realization—to translate concepts into reality
Energy Distribution for Modern SI and CI Engines

Energy Distribution (LHV, %)

Exhaust Loss
Heat Loss
Mechanical Loss
Work

NA Gasoline
10.6 bar BMEP

23.9
36.7
37.4

NA Diesel
8.8 bar BMEP

20.8
32.8
44.1

TC Diesel
10.6 bar BMEP

20.9
32.3
44.5

NA Gasoline
10.6 bar BMEP

10.6 bar BMEP

8.8 bar BMEP

10.6 bar BMEP
Exergy Distribution for Modern SI and CI Engines

- NA Gasoline (10.8 bar BMEP)
  - Combustion Loss: 19.9%
  - Turbo Loss: 15.8%
  - Exhaust Loss: 27.3%
  - Heat Loss: 35.2%
  - Mechanical Loss: 1.9%
  - Work: 100%

- NA Diesel (8.9 bar BMEP)
  - Combustion Loss: 21.1%
  - Turbo Loss: 11.8%
  - Exhaust Loss: 23.3%
  - Heat Loss: 41.6%
  - Mechanical Loss: 2.2%
  - Work: 100%

- TC Diesel (10.8 bar BMEP)
  - Combustion Loss: 20.8%
  - Turbo Loss: 0.4%
  - Exhaust Loss: 11.9%
  - Heat Loss: 22.8%
  - Mechanical Loss: 2.3%
  - Work: 100%
Observation

- The only approach that minimizes all three losses is the use of *high-temperature combustion* with *low heat rejection* and enhanced *work extraction or regeneration*. (This also increases power density.)

- Use of low-temperature combustion *increases* combustion irreversibility and *reduces* power density. (It cannot be used at full load.)
Integration I

- Exergy efficiencies ~50% possible (~52% LHV).
- Power density more than doubles (~28 bar MEP).
- Surface temperatures about the same as for gas turbine thermal barrier coatings (~1000°C).
- Still more exhaust exergy available!
Exergy efficiencies ~60% possible (~63% LHV).
- Power density more than triples (~38 bar MEP).
- Surface temperatures about the same as for gas turbine thermal barrier coatings (~1000°C).
- Requires method for high-temperature combustion.
High-Temperature Combustion

• Traditional Diesel-style combustion is well suited to high temperatures.
• The problem is emissions: soot and NOx.
• What if you could make a Diesel engine that did not produce soot? (Well below regulatory limits)
• What if you could run a Diesel engine at stoichiometric so that you could use a three-way catalyst for NOx (and CO, HC)?
• Result would be ultra-efficient, powerful, and clean, possibly less expensive, and well suited to use in heavy-duty transportation.
Realization I: A Sootless Diesel?
A Methanol or Ethanol “Diesel”

- Methanol

- Ethanol

- A temperature at injection of at least 1100K is required for good ignition.
- Both methanol and ethanol do produce soot—even reagent grade!
- But is the net soot below legal limits?
Sootless? Alcohols? Let’s ask the engine!

<table>
<thead>
<tr>
<th>Configuration Modeled</th>
<th>TDC Temp. (K)</th>
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</thead>
<tbody>
<tr>
<td>Naturally aspirated, metal surfaces</td>
<td>1077</td>
</tr>
<tr>
<td>Naturally aspirated, LHR surfaces</td>
<td>1131</td>
</tr>
<tr>
<td>Intercooled turbocharger, metal surfaces</td>
<td>1203</td>
</tr>
<tr>
<td>Intercooled turbocharger, LHR surfaces</td>
<td>1223</td>
</tr>
<tr>
<td>Non-intercooled turbocharger, LHR surfaces</td>
<td>1306</td>
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</table>

<table>
<thead>
<tr>
<th>Bore</th>
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<tbody>
<tr>
<td>Stroke</td>
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<tr>
<td>Speed</td>
<td>1800 RPM</td>
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<tr>
<td>Volumetric Efficiency</td>
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<tr>
<td>Injection Timing</td>
<td>MBT</td>
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<tr>
<td>CR</td>
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<tr>
<td>Injection Pressure</td>
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<tr>
<td>Heater Temperature</td>
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</table>

The 2012 heavy duty soot limit is 0.01 g/hp-hr
With a little better resolution…

- In the normal Diesel region, methanol and ethanol are below the regulatory soot limits by a factor of 10.
- At stoichiometric, methanol is below by a factor of 10, ethanol a factor of 2.
- At stoichiometric, a TWC can be used for NOx control.
- These are initial tests in an unoptimized system, a properly engineered system is likely to be even better (to hedge against even lower soot limits).
At 96% measured combustion efficiency, we expect that a “sootless” Diesel engine with high power density, 59% exergy efficiency (62% LHV), and NOx control by inexpensive TWC is possible using either M100 or E100.
Optimization

- Mitsubishi SOFC/GT/ST triple cycle power plant
- >70% efficiency (LHV)

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Component</th>
<th>Model Power (MW)</th>
<th>MHI Power (MW)</th>
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<tbody>
<tr>
<td>SOFC</td>
<td>Fuel Cell</td>
<td>-21.6</td>
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</tr>
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<td></td>
<td>Inverter</td>
<td></td>
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<tr>
<td>Gas Turbine</td>
<td>Compressors</td>
<td>-351</td>
<td></td>
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<td></td>
<td>Turbine</td>
<td>855</td>
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<td></td>
<td>Generator</td>
<td>-5.04</td>
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<td>Steam Turbine</td>
<td>Pumps</td>
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<td></td>
<td>Turbines</td>
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<td></td>
<td>Generator</td>
<td>-2.59</td>
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<td>Overall</td>
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<td>1162</td>
<td>1160</td>
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<tr>
<td>Efficiency</td>
<td></td>
<td>70.2%</td>
<td>70+%</td>
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</tbody>
</table>
Attractor-Based Architecture Optimization

- Joint optimization of both cycle and parameters.
- Cycle evolves by addition of transducers (devices).
- Parameters and figures of merit can affect the cycle!
It really wants to be recuperative…
And it wants to be intercooled…

If you do all that, a power plant with ~78% efficiency (LHV) to electricity is possible, in a double-cycle (regenerative) configuration.
Realization II: A piston-based, mixed fuel-cell, combustion engine system

The stream, which now contains a large amount of H₂, goes through the fuel cell, but not all of the H₂ is utilized.

Cylinders 2 and 4 act as afterburners and combust any species that have not been fully oxidized by either the fuel cell or cylinders 1 and 3.

Cylinders 1 and 3 act as fuel reformers and run rich, resulting in a product stream of approximately 5-10% H₂ and 10-15% CO.

Rich combustion products undergo the water gas shift (WGS) reaction, resulting in a product stream of 20-25% H₂ and 0.25-3% CO.

Depleted Reactants → Fuel Cell → Depleted Air → Exhaust
Rich Combustion Products → Shift Reactor → Fuel/Air Mixture → Piston Engine
Two combustion variants…

SI Engine

HCCI Engine

www.caranddriver.com
Several candidate fuels…
A couple of FC possibilities…

We are really just getting started, but our objective is a laboratory demonstration with combined efficiency of 70% based on LHV. (Which is not possible for conventional ICE.)
Thanks for listening!

Please visit our posters and meet the students who do all the work!
Exergy Management

- Heat Loss
  - About one-quarter of the overall exergy destruction is due to heat transfer.
  - Of that, about half of the destruction occurs across the in-cylinder thermal boundary layer.
  - To reduce exergy destruction, we must reduce the heat transfer. (Not recoverable.)
  - To do that, we must either lower the temperature of the in-cylinder gases (LTC), or raise the temperature of the wall surfaces (LHR).
Exergy Management

• Combustion Loss
  – About one-fifth of the overall exergy destruction is due to combustion irreversibility.
  – Only two possible ways to reduce this: combustion at extreme states or use of restrained reaction.
  – Reduced irreversibility at extreme states requires high-temperature combustion (HTC).
  – The possibility exists to used mixed restrained and unrestrained reaction (FC+ICE).
Exergy Management

• Exhaust Loss
  – About one-seventh of the overall exergy destruction is due to exhaust exergy.
  – Only one way to reduce this: extract more exergy before exhausting the gas.
  – Can be accomplished by use of combined (bottoming) cycles.
  – Can be accomplished by use of regenerative (intertwined) cycles.
Packaging a Bottoming Cycle

ISX Engine with WHR

Preserve EGR Control System

Boiler Replaces EGR Cooler and Integrates with EGR system

WHR Power Turbine

Courtesy John Wall – Cummins

SAE International
Paper 2013-01-0278