“ERC Research on Advanced Fueling Strategies for High Efficiency, Low Emission Engines”

Rolf D. Reitz
Engine Research Center
University of Wisconsin-Madison

Acknowledgements:
- ERC faculty, staff and students

http://www.erc.wisc.edu/
Engine Research Center

- Founded in 1946 ~70 years ago!
- Largest academic research center focusing on internal combustion engines in the U.S.
- ~$3 million annual research budget – 7 active faculty
  - 50-50% Federal-Industry funding,
  - Direct-injection Engine Research Consortium (DERC) - 36 members
- Over 50 graduate students, 10-15 post-docs and visiting scholars, 8-10 research and administrative staff
- Engine research
  - Primary focus is engine performance, combustion, emission control
  - Diesel, spark-ignition and advanced combustion engine research
- Major themes
  - Education of students
  - Use of real engines and diagnostics
  - Emphasis on interaction between experiments and modeling
  - Interaction with practicing engineers
Outline

- Development of today’s fuels (1910-1970)
- “Early” history of ERC research (1946-1995)
- ERC research in advanced fueling strategies
  - Multiple injections (1994)
  - Gasoline compression ignition (2001)
  - Dual fuel RCCI (2009)
  - Dual injector, dual fuel strategies (2014-15)
- Conclusions and future research directions
Ignitability affects engine efficiency - limits compression ratio (CR).

Early Spark Ignition (SI) engines were plagued by “spark knock”, CR ~ 4:1.

Cylinder pressure measurements by Midgley and Kettering at DELCO/GM showed different fuels had different knock tendency

  e.g., kerosene worse than gasoline

Volatility differences were thought to be the explanation.

Guided by the “Mayflower,” they added a red dye (iodine) to kerosene and knock tendency was greatly reduced!

Unfortunately, tests with other red dyes did not inhibit knock, disproving the theory.

But, finding powerful antiknock additives was a major serendipitous discovery!

Research after WW-I was motivated by national security
- Improved fuel efficiency with higher CRs made possible the first non-stop airplane flight from New York to San Diego in the 1920’s.

GM and US Army studied hundreds of additives and found aromatic amines to be effective knock suppressors.

1920 experimental GM car driven on gasoline with toluidine with CR ~7:1
- 40% better fuel consumption than 4:1.

Engine exhaust plagued by unpleasant odors - “the goat”!

Much research was devoted to find acceptable additives,
- finally leading to tetraethyl lead (TEL)

But, TEL caused solid deposits, damaged exhaust valves and spark plugs.
Scavenger additives with bromine and chlorine corrected the problem.
- Partnership with Ethyl-Dow and DuPont to extract compounds from sea water
- 10 tons of sea water needed to provide 1 lb of bromine!

WW-II aviation engines used iso-heptane (triptane: 2,2,3-trimethyl butane)
- allowed CR as high as 16:1.
Lead poisoning was an early concern
- In 1926 US Surgeon General determined that TEL poses no health hazards.
- Use of lead in automotive fuels has been called “The mistake of the 20th century”

1950: Dr. Arie Haagen-Smit - cause of smog in LA to be HC/NO
- Cars were the largest source of UHC/NOx

1950: Eugene Houdry - developed catalytic converter for auto exhaust.
- But, lead was found to poison catalytic converters.

20 years later: US EPA announces gas stations must offer "unleaded" gasoline,
- Based accumulated evidence of negative effects of lead on human health.
- Leaded gasoline was still tolerated in certain applications (e.g., aircraft),
  but was permanently banned in the US in 1996, in Europe since 2000

**World Wars & national security** played a major role to define automotive fuels.

Today’s engines and their fuels would not have been developed without close collaboration between engine OEMs, energy and chemical companies!

A consequence of collaboration between “big” engine and “big” oil is that transformative changes in transportation systems will not occur easily.

A new concept engine must be able to use available fuels,
A new fuel must run in existing engines.
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“Race between compression ratio and octane number”

ERC: diesel focus      Advanced comb.

WW-II

clean air act

opec

muscle car: miles/$
1930s Profs. G.C. Wilson and R.A. Rose
- Pioneered work on pressure pickups and reduction of diesel ignition delay via use of fuel additives.

1942, post-WW-II Profs. P.S. Myers ME*47 and O. Uyehara ChE*45
- studied under Profs. L.A. Wilson and K.M. Watson
- 2-color pyrometry in a Fairbanks Morse engine equipped with a window


- Led to a $50K WARF grant plus housing in T-25 "war surplus" building and CRC contract to measure end-gas temperatures in SI engines with iodine spectra absorption


“Phil Anotto” retired ~1986 and produced 48 PhDs and 80 MS graduates

http://www.erc.wisc.edu/theses.php

2015: ERC has produced over 500 graduates
Major Technologies:
Engine diagnostics, drop and spray vaporization, combustion, emissions, chemical kinetics, cycle and CFD modeling, fuels, heat transfer

1949-52 Ignition improvers – Army fuels
1949 Emissions - Diesel smoke
1951 Drop vaporization
1959-63 Heat flux-radiation measurements
1962 Super-critical environments
1964 Pressure → heat release rate
1966 End gas knock
1977 Total cylinder contents dumping (NOx)
1981 Compression-Ignited Homogeneous Charge Combustion
1982 UHC sampling probe measurements correlated with model predictions
1986 ERC named ARO Center of Excellence for Advanced Propulsion
1991 3-D CFD modeling for engine development
1991-94 Diesel multiple injection

Krieger & Borman ASME 1966
Johnson, Myers & Uyehara, SAE 1966
Najt & Foster SAE 830264
Reitz & Rutland SAE 911789
Nehmer & Reitz SAE 940668

Outline

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- Conclusions and future research directions
ERC: Advanced fueling strategies – multiple injections

1994: Nehmer, D.A., MS
Measurement of the Effect of Injection Rate and Split Injections On Diesel Engine Soot and NOx Emissions

1994: Tow, T., MS
The Effect of Multiple Pulse Injection, Injection Rate and Injection Pressure on Particulate and NOx Emissions from a D.I. Diesel Engine

1994: Pierpont, D.A., MS
An Experimental Study of the Effect of Injection Parameters and EGR on D.I. Diesel Emissions and Performance

Single injections

![Graph showing particulate vs. NOx for single injections]

Common-rail injector
90MPa injection pressure
125 degree spray angle
1600 rev/min, 75% load

Split injections

![Graph showing particulate vs. NOx for split injections]

Han et al. SAE 960633

Nehmer & Reitz SAE 940668
Tow, Pierpont & Reitz SAE 940897
Pierpont, Montgomery & Reitz SAE 950217
**ERC: Advanced fueling strategies – fuels and split injection**

**2001: Marriott, Craig D. MS**
An Experimental Investigation of Direct Injection for Homogeneous and Fuel-Stratified Charge Compression Ignited Combustion Timing Control

**Gasoline-fueled HD diesel engine**
- Low pressure common rail, hollow cone injector
- GCI, PFS, PPC, ….

**Engine Emissions vs Start of Injection Timing**
700 RPM PHI=0.22

**NOx Emission and Combustion Efficiency Comparison:**
Single vs Split Injections
Intake Air Temp = 119°C PHI = 0.21


Marriott & Reitz SAE 2002-01-0418
Canakci & Reitz IJER 2003
Hanson et al. SAE 2009-01-1442
Dempsey & Reitz SAE 2011-01-0356
Ra et al. SAE 2011-01-1182

**SOI 300 → 100°: SOI1 ~ 180° (60%); SOI2 ~ 90°**
**ERC: Advanced fueling strategies - diesel vs. gasoline**

**Kalghatgi et al. SAE 2007-01-0006**


<table>
<thead>
<tr>
<th>Engine</th>
<th>heavy-duty, flat cylinder head, shallow bowl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore x Stroke [mm]</td>
<td>127 x 154</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>14.0</td>
</tr>
<tr>
<td>Injector hole, dia [µm]</td>
<td>8, 200</td>
</tr>
<tr>
<td>Engine speed [rpm]</td>
<td>1200</td>
</tr>
<tr>
<td>Swirl ratio</td>
<td>2.4</td>
</tr>
<tr>
<td>Intake temp [C], Pressure [bar]</td>
<td>40, 2.0</td>
</tr>
<tr>
<td>Oxygen @ IVC/EGR [%]</td>
<td>15.8/25</td>
</tr>
<tr>
<td>Pilot split ratio [%]</td>
<td>30</td>
</tr>
</tbody>
</table>

**Diesel SOI = -2**
- CA = tdc
- CA = +4
- CA = +6
- CA = +12

**Gasoline SOI = -11**
- CA = -8
- CA = tdc
- CA = +10
- CA = +12

**Engine Research Center**
Diesel vs. gasoline - emissions

Additional time for mixing with gasoline offers significant benefit for soot reduction in CIDI engines

Vishwanathan & Reitz CST 2010
Combustion optimization - fuel and EGR selection

HCCI simulations used to choose optimal EGR rate and PRF (isooctane/n-heptane) blend

Predicted contours agree well with HCCI experiments

Fuel reactivity must change with EGR rate for optimum ISFC

As load is increased the minimum ISFC **cannot** be achieved with either neat diesel fuel or neat gasoline

Gasoline-diesel “cocktail”

ERC PRF mechanism
Ra & Reitz, CNF 2008
Optimized Reactivity Controlled Compression Ignition

- Port injected gasoline
- Direct injected diesel

Crank = -64.9 °ATDC

Injection Signal

- Squish Conditioning
- Ignition Source

-80 to -50
-45 to -3
Crank Angle (deg. ATDC)

CFD with Genetic Algorithms used to optimize multiple injection strategy

GA: Senecal & Reitz SAE 2000-01-1890

Kokjohn et al. SAE 2009-01-2647
<table>
<thead>
<tr>
<th>Engine</th>
<th>Heavy Duty</th>
<th>Light Duty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>CAT SCOTE</td>
<td>GM 1.9 L</td>
</tr>
<tr>
<td>Displ. (L/cyl)</td>
<td>2.44</td>
<td>0.477</td>
</tr>
<tr>
<td>Bore (cm)</td>
<td>13.72</td>
<td>8.2</td>
</tr>
<tr>
<td>Stroke (cm)</td>
<td>16.51</td>
<td>9.04</td>
</tr>
<tr>
<td>Squish (cm)</td>
<td>0.157</td>
<td>0.133</td>
</tr>
<tr>
<td>CR</td>
<td>16.1:1</td>
<td>15.2:1</td>
</tr>
<tr>
<td>Swirl ratio</td>
<td>0.7</td>
<td>2.2</td>
</tr>
<tr>
<td>IVC (° ATDC)</td>
<td>-85 and -143</td>
<td>-132</td>
</tr>
<tr>
<td>EVO(° ATDC)</td>
<td>130</td>
<td>112</td>
</tr>
<tr>
<td>Injector type</td>
<td>Common rail</td>
<td></td>
</tr>
<tr>
<td>Nozzle holes</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Hole size (µm)</td>
<td>250</td>
<td>128</td>
</tr>
</tbody>
</table>

Engine size scaling
Staples, SAE 2009-01-1124
### Experimental validation - HD Caterpillar SCOTE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMEP (bar)</td>
<td>9</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>1300</td>
</tr>
<tr>
<td>EGR (%)</td>
<td>43</td>
</tr>
<tr>
<td>Equivalence ratio (-)</td>
<td>0.5</td>
</tr>
<tr>
<td>Intake Temp. (°C)</td>
<td>32</td>
</tr>
<tr>
<td>Intake pressure (bar)</td>
<td>1.74</td>
</tr>
<tr>
<td>Gasoline (% mass)</td>
<td>76, 82, 89</td>
</tr>
<tr>
<td>Diesel inject press. (bar)</td>
<td>800</td>
</tr>
<tr>
<td>SOI1 (° ATDC)</td>
<td>-58</td>
</tr>
<tr>
<td>SOI2 (° ATDC)</td>
<td>-37</td>
</tr>
<tr>
<td>Fract. diesel in 1st pulse</td>
<td>0.62</td>
</tr>
<tr>
<td>IVC (°BTDC)/Comp ratio</td>
<td>143/16</td>
</tr>
</tbody>
</table>

**Effect of gasoline percentage**

- **Experiment**
- **Simulation**

- Neat Diesel Fuel
- 76%
- 82%
- 89%

- Neat Gasoline

**Computer modeling predictions confirmed**

Combustion timing and Pressure Rise Rate control with diesel/gasoline ratio

**Dual-fuel can be used to extend load limits of either pure diesel or gasoline**
RCCI – high efficiency, low emissions, fuel flexibility

Indicated efficiency of $58\pm1\%$ achieved with E85/diesel

Emissions met in-cylinder, without need for after-treatment

Considerable fuel flexibility, including ‘single’ fuel operation

Diesel can be replaced with $<0.5\%$ total cetane improver (2-EHN/DTBP) in gasoline - less additive than SCR DEF

Splitter, SAE 2010-01-2167; Hanson, SAE 2011-01-0361, Kokjohn IJER 2011
Heat release occurs in 3 stages

Cool flame reactions from diesel (n-heptane) injection

First energy release where both fuels are mixed

Final energy release where lower reactivity fuel is located

Changing fuel ratios changes relative magnitudes of stages

Fueling ratio provides “next cycle” CA50 transient control
Multi-cylinder RCCI - transient operation

GM 1.9L Engine Specifications

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>EURO IV Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>82 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>90.4 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>1.9 liters</td>
</tr>
<tr>
<td>Cylinder Configuration</td>
<td>Inline 4</td>
</tr>
<tr>
<td></td>
<td>4 valves per cylinder</td>
</tr>
<tr>
<td>Swirl Ratio</td>
<td>Variable (2.2-5.6)</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>17.5</td>
</tr>
<tr>
<td>EGR System</td>
<td>Hybrid High/Low Pressure, Cooled</td>
</tr>
<tr>
<td>ECU (OEM)</td>
<td>Bosch EDC16</td>
</tr>
<tr>
<td>ECU (new)</td>
<td>Drivven</td>
</tr>
<tr>
<td>Common Rail Injectors</td>
<td>Bosch CRIP2-ML</td>
</tr>
<tr>
<td></td>
<td>148° Included Angle</td>
</tr>
<tr>
<td></td>
<td>7 holes, 440 flow number.</td>
</tr>
<tr>
<td>Port Fuel Injectors</td>
<td>Delphi</td>
</tr>
<tr>
<td></td>
<td>2.27 g/s steady flow</td>
</tr>
<tr>
<td></td>
<td>400 kPa fuel pressure</td>
</tr>
</tbody>
</table>

UW RCCI Hybrid Vehicle

SAE Paper 2015-01-0837
Highway Fuel Economy Testing of an RCCI Series Hybrid Vehicle
Reed Hanson, Shawn Spannbauer, Christopher Gross, Rolf D. Reitz, University of Wisconsin; Scott Curran, John Storey, Shean Huff, ORNL
RCCI operating range – ORNL & ERC

RCCI offers diesel-like or better BTE across speed-load range

- UDDS/FTP cycle

ORNL simulations indicate RCCI offers >20% fuel economy c.f. 2009 PFI engines

Load expansion via alternative fuels, VVA, dual direct injection, …..
ERC: Advanced fueling strategies – RCCI load expansion

**2015:** Lim, J., PhD
High Power Output Operation of RCCI Combustion

Direct injection of both diesel and gasoline

Stock piston geometry has 2 zones:
- Squish with high surface/volume ratio,
- Bowl with low S:V ratio

HD RCCI engine:
21 bar IMEP gasoline/diesel
IVC conditions: 3.42 bar, 90°C, 46%EGR

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**High load/speed simulations**
ERC KIVA3V-R2, GA optimization
Discrete Multi-Component fuel evaporation
ERC PRF mechanism
  - 46 species, 142 reactions
Gasjet model for reduced grid dependency
Both injectors at cylinder axis
ERC: Advanced fueling strategies – DDFS strategy

2015: Wissink, M.L., PhD
Direct Injection for Dual Fuel Stratification (DDFS):
Improving the Control of Heat Release in Advanced IC Engine Combustion Strategies

<table>
<thead>
<tr>
<th>EGR [%]</th>
<th>50</th>
<th>40</th>
<th>50</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{EGR}}$ [(^{\circ}\text{C})]</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>$T_{\text{in}}$ [(^{\circ}\text{C})]</td>
<td>51</td>
<td>50</td>
<td>54</td>
<td>50</td>
</tr>
<tr>
<td>$P_{\text{in}}$ [kPa]</td>
<td>186</td>
<td>186</td>
<td>214</td>
<td>186</td>
</tr>
<tr>
<td>$\phi$ [-]</td>
<td>0.66</td>
<td>0.60</td>
<td>0.67</td>
<td>0.57</td>
</tr>
<tr>
<td>$\phi'$ [-]</td>
<td>0.34</td>
<td>0.36</td>
<td>0.34</td>
<td>0.35</td>
</tr>
<tr>
<td>IMEPg [bar]</td>
<td>9.3</td>
<td>8.2</td>
<td>8.7</td>
<td>9.4</td>
</tr>
<tr>
<td>$Q_{\text{fuel}}$ [kJ/cyc]</td>
<td>4.82</td>
<td>4.72</td>
<td>4.92</td>
<td>4.71</td>
</tr>
</tbody>
</table>
More final late-injected fuel

- $\Phi_{\text{premix}} = 0.4$
- $\Phi_{\text{premix}} = 0.37$
- $\Phi_{\text{premix}} = 0.31$

**Engine Research Center**
DDFS provides high efficiency, lower noise/COV, lower heat loss/increased exhaust loss – reducing turbo requirements.
Conclusions and future research directions

Advanced combustion strategies (e.g., GCI, RCCI and its variants) offer practical low-cost pathways to >15% improved internal combustion engine fuel efficiency (lower CO₂)

Made possible by advances in fuel injectors and computer control

RCCI GTEs in the 58-60% range achieved – within ~94% of theoretical cycle.

Inconvenience of two fuels already accepted by diesel industry (diesel/DEF)

RCCI is cost effective and offers fuel flexibility:
- low cost port-injected less reactive fuel (e.g., gasoline, E85, “wet” EtOH, C/LNG) with optimized low pressure DI of more-reactive fuel (e.g., diesel/additized gas)
- reduced after-treatment needed - meet NOx and PM emission mandates in-cylinder
- diesel or SI (w/spark plug) operation can be retained (e.g., mixed mode, limp home).

Improved transient control:
- proportions of low and high reactivity fuels can be changed dynamically, with same/next-cycle combustion feedback control

Direct injection of both fuels allows more control of heat release:
- reduced noise, reduced cyclic variability, no efficiency penalty, move waste heat to exhaust

Future directions:
- transient engine feedback control, load extension (e.g., via: multiple injection, CR, VVA),
- optimized pistons – reduced crevice volumes, insulated pistons.
- optimized boost, EGR, charge-air cooling, alternative fuels……

.. and vehicle testing!
2025 and beyond….
Voyage to new concepts in engine combustion

California ARB:
90% reduction in NOx emissions by 2031 (0.02 g/bhp·hr)
80% reduction in GHG emissions (below 1990 levels) by 2050
Governor’s 50% petroleum reduction target by 2030 (renewable fuels),
and continued reductions in air toxics & diesel PM (PN $6 \times 10^{11}$ 1/km).
Backup
High load GA optimization – 21 bar IMEP

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<tr>
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</thead>
<tbody>
<tr>
<td>Iso-octane 1</td>
<td>149.8 @</td>
<td>-115.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[mg, °ATDC]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iso-octane 2</td>
<td>87.8 @</td>
<td>-21.0</td>
<td></td>
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</tr>
<tr>
<td>[mg, °ATDC]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-heptane</td>
<td>7.4 @</td>
<td>-3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[mg, °ATDC]</td>
<td></td>
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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>NOx</td>
<td>0.026</td>
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<tr>
<td>[g/kW-hr]</td>
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<tr>
<td>Soot</td>
<td>0.078</td>
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<tr>
<td>[g/kW-hr]</td>
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<td></td>
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<tr>
<td>CO</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>[g/kW-hr]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UHC</td>
<td>2.7</td>
<td></td>
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<tr>
<td>[g/kW-hr]</td>
<td></td>
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<tr>
<td>Gross ITE [%]</td>
<td>46.0</td>
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<tr>
<td>[%], IVC-EVO</td>
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<tr>
<td>Gross ITE [%]</td>
<td>48.2</td>
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<tr>
<td>[%], BDC-BDC</td>
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<tr>
<td>CAD @ 10% HR</td>
<td>7.0</td>
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<td>[ATDC]</td>
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<td>16.0</td>
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<tr>
<td>[ATDC]</td>
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<tr>
<td>CAD 10-90% HR</td>
<td>13.0</td>
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<tr>
<td>Max Pressure</td>
<td>169.7</td>
<td></td>
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<tr>
<td>[bar]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPRR</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>[bar/deg]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dual fuel, direct injection offers high load, high efficiency operation potential

Dual fuel RCCI offers high power with medium load high speed operation

Lim and Reitz ASME GTP, 136, 2014
Lim and Reitz SAE 2014-01-1320
Calibrate 0-D code with experimental data
Use to determine:
- initial conditions
- geometry

Results:
60% GTE possible with:
High Cr
Lean operation ($\Phi < 0.3$)
50% reduction in heat transfer & combustion losses

- Deactivate under-piston oil jet cooling

<table>
<thead>
<tr>
<th></th>
<th>Exp.</th>
<th>GT POWER</th>
<th>GT POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression ratio</td>
<td>14.88</td>
<td>14.88</td>
<td>18.6</td>
</tr>
<tr>
<td>IMEPn (bar)</td>
<td>8.00</td>
<td>7.86</td>
<td>8.69</td>
</tr>
<tr>
<td>Fueling (mg/cyc)</td>
<td>87.13</td>
<td>87.13</td>
<td>87.13</td>
</tr>
<tr>
<td>Gross Therm Eff. (%)</td>
<td>54.3</td>
<td>54.5</td>
<td>59.7</td>
</tr>
<tr>
<td>Net Therm Eff. (%)</td>
<td>52.0</td>
<td>52.1</td>
<td>57.5</td>
</tr>
<tr>
<td>BTE (%)</td>
<td>45.3</td>
<td>45.1</td>
<td>49.1</td>
</tr>
<tr>
<td>FMEP (bar)</td>
<td>1.03</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Convection HX</td>
<td>N/A</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Comb. Eff. (%)</td>
<td>98</td>
<td>98</td>
<td>99</td>
</tr>
<tr>
<td>Intake Pressure (bar)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.68</td>
</tr>
<tr>
<td>Exhaust Pressure (bar)</td>
<td>1.625</td>
<td>1.625</td>
<td>1.75</td>
</tr>
<tr>
<td>Turbo eff. (air filter + DOC)</td>
<td>67.5</td>
<td>62.3</td>
<td>72.8</td>
</tr>
</tbody>
</table>

Splitter et al. SAE 2013-01-0279
Ultra high efficiency, dual fuel RCCI combustion

High efficiency demonstrated
Simulation heat transfer tuned to match data
- 14.88:1 Piston required HX = 0.4
- 18.7:1 required HX = 0.3
Pancake design ~1.2 less surface area
18.7:1 without oil cooling required HX = 0.2

<table>
<thead>
<tr>
<th></th>
<th>GTE (%)</th>
<th>IMEPg (bar)</th>
<th>NTE (%)</th>
<th>IMEPn (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP (pt. 83)</td>
<td>59.1</td>
<td>6.82</td>
<td>55.0</td>
<td>6.27</td>
</tr>
<tr>
<td>GT Power HX =0.2</td>
<td>58.8</td>
<td>6.79</td>
<td>54.8</td>
<td>6.25</td>
</tr>
<tr>
<td>GT Power HX =0.4</td>
<td>56.7</td>
<td>6.55</td>
<td>52.8</td>
<td>6.02</td>
</tr>
</tbody>
</table>

94% of maximum theoretical cycle efficiency achieved!

Splitter et al. “RCCI Engine Operation Towards 60% Thermal Efficiency”, SAE 2013-01-0279
### RCCI Fuel flexibility – Alternative fuels

**Natural gas/diesel RCCI**

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>Low-Load</th>
<th>Mid-Load</th>
<th>High-Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross IMEP [bar]</td>
<td>4</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Engine Speed [rpm]</td>
<td>800</td>
<td>1300</td>
<td>1370</td>
</tr>
<tr>
<td>Intake Press. [bar abs.]</td>
<td>1.00</td>
<td>1.45</td>
<td>1.94</td>
</tr>
<tr>
<td>Intake Temp. [°C]</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

**Caterpillar 3401E SCOTE**

- Displacement [L] 2.44
- Bore x Stroke [mm] 137.2 x 165.1
- Con. Rod Length [mm] 261.6
- Compression Ratio 16.1:1
- Swirl Ratio 0.7
- IVC [deg ATDC] -143
- EVO [deg ATDC] 130

**Common Rail Diesel Fuel Injector**

- Number of Holes 6
- Hole Diameter [μm] 250
- Included Spray Angle 145°

**Design Parameter**

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premixed Methane [%]</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>DI Diesel SOI 1 [deg ATDC]</td>
<td>-100</td>
<td>-50</td>
</tr>
<tr>
<td>DI Diesel SOI 2 [deg ATDC]</td>
<td>-40</td>
<td>20</td>
</tr>
<tr>
<td>Diesel Fraction in First Inj. [%]</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Diesel Injection Pressure [bar]</td>
<td>300</td>
<td>1500</td>
</tr>
<tr>
<td>EGR [%]</td>
<td>0%</td>
<td>60%</td>
</tr>
</tbody>
</table>

ERC KIVA PRF kinetics
NSGA-II MOGA
32 Citizens per generation
~9500 Cells @ BDC
UW Condor - Convergence after ~40 genrtns

Nieman, 2012
RCCI Fuel flexibility – Alternative fuels

Double vs. triple injection

Double vs. triple injection

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>23 bar IMEP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 bar IMEP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results

- Soot [g/kW-hr]
- NOx [g/kW-hr]
- CO [g/kW-hr]
- UHC [g/kW-hr]
- $\eta_{\text{gross}}$ [%]

<table>
<thead>
<tr>
<th></th>
<th>2 Inj. Optimum</th>
<th>3 Inj. Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soot [g/kW-hr]</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>NOx [g/kW-hr]</td>
<td>0.24</td>
<td>0.10</td>
</tr>
<tr>
<td>CO [g/kW-hr]</td>
<td>10.8</td>
<td>7.3</td>
</tr>
<tr>
<td>UHC [g/kW-hr]</td>
<td>10.5</td>
<td>3.8</td>
</tr>
<tr>
<td>$\eta_{\text{gross}}$ [%]</td>
<td>45.1%</td>
<td>47.1%</td>
</tr>
</tbody>
</table>

Gross Work vs. Exhaust Loss vs. Heat Transfer vs. Combustion Loss

% of Fuel Energy In

- Gross Work
- Exhaust Loss
- Heat Transfer
- Combustion Loss

Engine Research Center

Nieman MS 2012
RCCI Fuel flexibility – Alternative fuels

23 bar IMEP, triple Injection

• Achieve low soot, despite late 3$^{rd}$ injection
  o Combustion starts in squish region, so diesel #3 injects into a relatively cool environment
  o Fairly small amount injected