Designing Efficient Engines: Strategies Based on Thermodynamics

• INTRODUCTION AND BACKGROUND
  ➢ Insights from Thermodynamics

• DESCRIPTION OF THE CYCLE SIMULATION

• ENGINE AND OPERATING CONDITIONS

• RESULTS AND DISCUSSION
  ✓ Overall Results – Efficiencies
  ✓ Parametric Results (extra)
  ✓ Thermodynamics
  ✓ Nitric Oxide Results (extra)
  ✓ Exergy Destruction (extra)

• SUMMARY AND CONCLUSIONS
INTRODUCTION AND BACKGROUND

-- Importance of Thermodynamics --

- Often overlooked in discussions of engines
- Rich and long history related to engine developments
- An IC engine is not a heat engine: not limited by Carnot efficiency
- Combustion devices are subject to exergy destruction
- IC engine design for high efficiency can be guided by understanding the thermodynamics
INTRODUCTION AND BACKGROUND

- The importance of thermodynamics is demonstrated by comparing a conventional and high efficiency engine.
- Efficiency increases due to CR, lean operation and the use of EGR – what is the contribution of each?
- What are the thermodynamic reasons for the increases of efficiency?
- Not all items will be obvious or measureable.
THERMODYNAMIC ENGINE CYCLE SIMULATION

Features/Considerations:
1. One common pressure
2. Three gas temperatures
3. Three volumes and masses
4. Separate heat transfer
PROCEDURES FOR SOLUTIONS

• ORDINARY DIFFERENTIAL EQUATIONS
• NUMERICAL TECHNIQUES: EULERS
• INITIAL CONDITIONS: $T_1$, $p_1$, Residual Fraction
• BOUNDARY CONDITIONS: INLET & EXHAUST
• SPECIFY SUBMODEL PARAMETERS:
  - Thermodynamic properties (Heywood, 1988)
  - Heat transfer coefficient (Hohenberg, 1979; Chang et al., 2004)
  - Friction (Sandoval and Heywood, 2003)
  - Fuel mass rates
  - Flow rate parameters
  - Exergy and second law considerations
  - Nitric oxide kinetics (Dean and Bozzelli, 2000)
  - Other
## SPECIFICATIONS FOR THE ENGINE

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>Automotive, V-8</td>
</tr>
<tr>
<td>Bore/Stroke</td>
<td>102/88 mm (4.0/3.5 in)</td>
</tr>
<tr>
<td>Displacement</td>
<td>5.7 liter (350 in³)</td>
</tr>
<tr>
<td>bmep</td>
<td>900 kPa</td>
</tr>
<tr>
<td>Engine speed</td>
<td>2000 rpm</td>
</tr>
<tr>
<td>Combustion timing</td>
<td>MBT</td>
</tr>
<tr>
<td>Geometric compression ratio</td>
<td>from 8:1 to 16:1</td>
</tr>
<tr>
<td>Valve arrangement</td>
<td>OHV, 2 valves/cylinder</td>
</tr>
</tbody>
</table>
TWO ENGINE OPERATING CONDITIONS:

- CONVENTIONAL
- HIGH EFFICIENCY
### Operating Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conventional</th>
<th>High Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>bmep (kPa)</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>CR</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>$\theta_{\text{burn}}$</td>
<td>60°</td>
<td>30°</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>EGR (%)</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>$p_{\text{inlet}}$ (kPa)</td>
<td>92</td>
<td>170</td>
</tr>
<tr>
<td>$p_{\text{exh}}$ (kPa)</td>
<td>105</td>
<td>180</td>
</tr>
<tr>
<td>Timing</td>
<td>MBT</td>
<td>MBT</td>
</tr>
</tbody>
</table>
RESULTS

- Overall efficiency gains
- Comparison to experiments
- Contributions to efficiency increase
- Thermodynamic insights
DESCRIPTION OF CASES
– STRATEGY –
Add features in a sequential fashion

<table>
<thead>
<tr>
<th>CASE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CR = 8; $\theta_b = 60^\circ$; $\varphi = 1.0$; EGR = 0%</td>
</tr>
<tr>
<td>2</td>
<td>CR = 16; $\theta_b = 60^\circ$; $\varphi = 1.0$; EGR = 0%</td>
</tr>
<tr>
<td>3</td>
<td>CR = 16; $\theta_b = 30^\circ$; $\varphi = 1.0$; EGR = 0%</td>
</tr>
<tr>
<td>4</td>
<td>CR = 16; $\theta_b = 30^\circ$; $\varphi = 0.7$; EGR = 0%</td>
</tr>
<tr>
<td>5</td>
<td>CR = 16; $\theta_b = 30^\circ$; $\varphi = 0.7$; EGR = 45%</td>
</tr>
</tbody>
</table>
Overall Efficiency (1/5)

- Base

- $b_{mep} = 900 \text{kPa}$
- 2000 rpm
- MBT Timing

- Pumping Losses
- Gross Indicated Efficiency
- Mechanical Friction
- Brake Efficiency
- Net Indicated Efficiency

- Case 1: Base
- CR = 16
- $\theta_b = 30^\circ$
- $\phi = 0.7$
- EGR = 45%
Overall Efficiency (2/5)

- Base
- Increase CR to 16

Overall Efficiency (2/5)
Overall Efficiency (3/5)

- Base
- Increase CR to 16
- Short Burn Duration

**Base Case**

- **bmeP** = 900 kPa
- 2000 rpm
- MBT Timing

**Gross Indicated Efficiency**

**Net Indicated Efficiency**

**Brake Efficiency**

**Mechanical Friction**

**Pumping Losses**

**Cases**

1. BASE
2. CR = 16
3. $\theta_b = 30^\circ$
4. $\phi = 0.7$
5. EGR = 45%

Efficiency (%): 50, 55, 45, 40, 35
Overall Efficiency (4/5)

- Base
- Increase CR to 16
- Short Burn Duration
- Lean Mixture

Diagram:
- $b_{mep} = 900$ kPa
- 2000 rpm
- MBT Timing
- Pumping Losses
- Gross Indicated Efficiency
- Net Indicated Efficiency
- Brake Efficiency
- Mechanical Friction

Cases:
1. BASE
2. CR = 16
3. $\theta_b = 30^\circ$
4. $\phi = 0.7$
5. EGR = 45%
Overall Efficiency (5/5)

- **Base**
- **Increase CR to 16**
- **Short Burn Duration**
- **Lean Mixture**
- **Add 45% EGR**

*Graph showing indicated and brake efficiency with various cases.*
**Overall Efficiency**

- Increase of indicated efficiencies: 37% to 53.9% (x 1.46)
- 16.9% increase
- Highest improvements from CR, lean and EGR
- Dilute operation requires higher inlet pressures
- Brake values somewhat mitigated by increases of friction

**Graph Details**

- bmep = 900 kPa
- 2000 rpm
- MBT Timing

**Parameters**

- **CR**: 16
- **\( \theta_b \)**: 30°
- **\( \phi \)**: 0.7
- **EGR**: 45%

**Efficiencies**

- Indicated Efficiency
- Gross Indicated Efficiency
- Pumping Losses
- Mechanical Friction
- Brake Efficiency
- Net Indicated Efficiency

**Changes**

- **\( \Delta \eta = 16.9\% \)**
Comparison to Experimental Results
Table 5. Comparisons to Results from [22]

<table>
<thead>
<tr>
<th>ITEM</th>
<th>REFERENCE (Kokjohn et al. [22])</th>
<th>THIS WORK (High Eff Case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore/Stroke (mm)</td>
<td>137/165</td>
<td>102/88</td>
</tr>
<tr>
<td>Fuels</td>
<td>Gasoline/Diesel</td>
<td>Isooctane</td>
</tr>
<tr>
<td>Inlet Pressure (kPa)</td>
<td>200</td>
<td>170</td>
</tr>
<tr>
<td>Geometric CR</td>
<td>16.1</td>
<td>16</td>
</tr>
<tr>
<td>EGR (%)</td>
<td>45.5</td>
<td>45</td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>0.77</td>
<td>0.7</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>1300</td>
<td>2000</td>
</tr>
</tbody>
</table>

**RESULTS:**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>REFERENCE (Kokjohn et al. [22])</th>
<th>THIS WORK (High Eff Case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMEP&lt;sub&gt;NET&lt;/sub&gt; (kPa)</td>
<td>1100</td>
<td>1015</td>
</tr>
<tr>
<td>Net Ind Efficiency (%)</td>
<td>50</td>
<td>53.9</td>
</tr>
<tr>
<td>Peak Pressure (MPa)</td>
<td>12</td>
<td>12.0</td>
</tr>
<tr>
<td>Nitric Oxide (g/kW-h)</td>
<td>0.01</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Effect of Individual Engine Parameters (extra)
Thermodynamic Reasons for Efficiency Increases
Gains in efficiency only partly due to reduced heat losses – the rest is largely a result of the increases of CR and ???
Heat Transfer Reductions

- Only a portion of the heat transfer reductions are converted to work.
- For these conditions, a 10.6\% reduction of heat losses increases the indicated thermal efficiency by 3.4\% (abs).
- For different conditions, the factor of improvement changes but is of the same order.
## Contributions to Efficiency Gains

<table>
<thead>
<tr>
<th>Feature</th>
<th>Incremental Gain of Indicated Efficiency (%)</th>
<th>Relative Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Ratio Increase</td>
<td>6.5</td>
<td>39</td>
</tr>
<tr>
<td>Shorter Burn Duration</td>
<td>1.2</td>
<td>7</td>
</tr>
<tr>
<td>Reduced Heat Transfer</td>
<td>3.4</td>
<td>20</td>
</tr>
<tr>
<td>??? (by difference)</td>
<td>5.8</td>
<td>34</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16.9%</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
Increased ratio of specific heats important for conversion of thermal energy to work.

Small increases yield large benefits.

From simple “Otto” cycle, may show that a 5% increase of gamma results in about a 20% relative increase of efficiency (e.g., 30% to 36%).
## Contributions to Efficiency Gains

<table>
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<td>1.2</td>
<td>7</td>
</tr>
<tr>
<td>Reduced Heat Transfer</td>
<td>3.4</td>
<td>20</td>
</tr>
<tr>
<td>Ratio of Specific Heats Increase</td>
<td>5.8</td>
<td>34</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16.9%</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
SUMMARY/CONCLUSIONS

- Completed a thermodynamic assessment of the parametric changes for increased efficiency
- The most important features are increased compression ratio, lean operation and EGR
- Reasons for the gains are CR advantage, reduced heat losses and the increased ratio of specific heats
- The role of increased ratio of specific heats is important and can account for 30% or more of the gains
- Reducing heat losses even further can provide additional gains and is thermodynamically favorable
Extra Information
Brief Discussion of Exergy
These results demonstrate the differences between energy and exergy quantities.
Exergy Comparison

For high efficiency engine, destruction of exergy increases – but trade-offs are favorable for increased thermal efficiencies.
Exergy Destruction

Increases of exergy destruction largely due to dilution which results in lower combustion temperatures.

![Graph showing exergy destruction during combustion for different cases.](image)

- Case 1: BASE
- Case 2: CR = 16
- Case 3: $\theta_b = 30^\circ$
- Case 4: $\phi = 0.7$
- Case 5: EGR = 45%

**Conditions:**
- bmep = 900 kPa
- 2000 rpm
- MBT Timing
- 4th Sequence
Brief Discussion of Emissions
CO₂ and NO Values

Carbon Dioxide Estimates

- Conventional Case: 1.2
- High Efficiency Case: ~0.4
- 29.2% reduction

Nitric Oxide Estimates

- Conventional Case: ~100%
- High Efficiency Case: ~0%
- ~100% reduction
Effect of Engine Parameters
Lean operation provides efficiency gains.

Gains are largely a result of reduced heat losses and higher gamma values.

Requires higher inlet pressures.

Brake values subject to higher friction.

Friction increases largely due to piston/rings/cylinder friction.
Exhaust Gas Recirculation

- EGR provides efficiency gains
- Gains are largely a result of reduced heat losses and higher gamma values
- Requires higher inlet pressures
- Brake values subject to higher friction
- Friction increases largely due to piston/rings/cylinder friction

bmep = 900 kPa
\( \phi = 0.7, \theta_b = 30^\circ \)
2000 rpm, cr = 16
MBT Timing
Increased CR is a significant factor

A consequence of the mechanical advantage and the greater expansion ratio

Due to high dilution, spark knock not expected to be an issue
- Decreasing burn duration has a modest impact.
- The improvement diminishes for shorter durations.
- The difference between 60° and 30° burn duration is about a factor of 3.5 higher pressure rise rate.
Combustion Timing

- All previous results for MBT timing

bmep = 900 kPa
\( \phi = 0.7, \theta_b = 30^\circ \)
2000 rpm, cr = 16

Net Indicated Efficiency

High Efficiency Case

Brake Efficiency

Relative Combustion Timing (°CA)
<table>
<thead>
<tr>
<th>Item</th>
<th>Value Used</th>
<th>How Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bmep = 900 \text{kPa}, \text{CR} = 8, \text{EGR} = 0%, \text{MBT timing}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>1.0</td>
<td>input</td>
</tr>
<tr>
<td>Engine Speed (rpm)</td>
<td>2000</td>
<td>input</td>
</tr>
<tr>
<td>Mech Frictional mep (kPa)</td>
<td>81.3</td>
<td>from algorithm [19]</td>
</tr>
<tr>
<td>Inlet Pressure (kPa)</td>
<td>92.1</td>
<td>input</td>
</tr>
<tr>
<td>Exhaust Pressure (kPa)</td>
<td>105.0</td>
<td>input</td>
</tr>
<tr>
<td>Start of Combustion ($^\circ \text{bTDC}$)</td>
<td>26.0</td>
<td>determined for MBT</td>
</tr>
<tr>
<td>Combustion Duration ($^\circ \text{CA}$)</td>
<td>60</td>
<td>input</td>
</tr>
<tr>
<td>Cylinder Wall Temp (K)</td>
<td>450</td>
<td>input</td>
</tr>
<tr>
<td>Heat transfer correlation</td>
<td></td>
<td>Hohenberg [20]</td>
</tr>
<tr>
<td>Gross Ind thermal eff (%)</td>
<td>37.63</td>
<td>output</td>
</tr>
<tr>
<td>Net Ind thermal eff (%)</td>
<td>36.98</td>
<td>output</td>
</tr>
<tr>
<td>Brake thermal eff (%)</td>
<td>33.92</td>
<td>output</td>
</tr>
<tr>
<td>Exergy destruction comb (%)</td>
<td>20.37</td>
<td>output</td>
</tr>
<tr>
<td>Max press rise rate (kPa/CA)</td>
<td>152</td>
<td>output</td>
</tr>
</tbody>
</table>
### Table 4. High Efficiency Engine

<table>
<thead>
<tr>
<th>Item</th>
<th>Value Used</th>
<th>How Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bmep = 900 \text{ kPa}$, $CR = 16$, $EGR = 45%$, MBT timing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>0.7</td>
<td>input</td>
</tr>
<tr>
<td>Engine Speed (rpm)</td>
<td>2000</td>
<td>input</td>
</tr>
<tr>
<td>Mech Frictional mep (kPa)</td>
<td>115.9</td>
<td>from algorithm [19]</td>
</tr>
<tr>
<td>Inlet Pressure (kPa)</td>
<td>169.5</td>
<td>input</td>
</tr>
<tr>
<td>Exhaust Pressure (kPa)</td>
<td>179.5</td>
<td>input</td>
</tr>
<tr>
<td>Start of Combustion ($^\circ$ bTDC)</td>
<td>13.5</td>
<td>determined for MBT</td>
</tr>
<tr>
<td>Combustion Duration ($^\circ$ CA)</td>
<td>30</td>
<td>input</td>
</tr>
<tr>
<td>Cylinder Wall Temp (K)</td>
<td>450</td>
<td>input</td>
</tr>
<tr>
<td>Heat transfer correlation</td>
<td></td>
<td>Chang et al. [21]</td>
</tr>
<tr>
<td>Gross Ind thermal eff (%)</td>
<td>54.95</td>
<td>output</td>
</tr>
<tr>
<td>Net Ind thermal eff (%)</td>
<td>53.92</td>
<td>output</td>
</tr>
<tr>
<td>Brake thermal eff (%)</td>
<td>47.79</td>
<td>output</td>
</tr>
<tr>
<td>Exergy destruction comb (%)</td>
<td>24.01</td>
<td>output</td>
</tr>
<tr>
<td>Max press rise rate (kPa/CA)</td>
<td>536</td>
<td>output</td>
</tr>
</tbody>
</table>
Heat Transfer Reductions

- Only a portion of the heat transfer reductions are converted to work.
- For these conditions, a 50% reduction of heat losses increases the indicated thermal efficiency by a factor of about 1.05.
- For different conditions, the factor of improvement changes but is of the same order.

Graph:
- Net Ind Eff
- CR = 16, $\theta_b = 30^\circ$
- CR = 8, $\theta_b = 60^\circ$
- bmep = 900 kPa
- 2000 rpm
- MBT Timing

- Actual/Base
- Relative Heat Transfer (compared to base)