Power Systems For a Hot, Flat, and Crowded World

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Innovation You Can Depend On

Energy Source

Fossil

Solar

Geothermal

Water (Gravity)

Wind

Nuclear

Bio-derived

Bio-produced

Renewable HC

Oil

Coal

Gas

Hydrogen (H₂)

* “Not to scale”
ΔP ↝ “motive force”

Heat a gas
- Combustion
- Nuclear
- Geothermal
- Solar
- Gravity - Water
- Dams
- Waves
- Wind

Shaft Work Machine
- Reciprocating engine
  - Spark Ignited (Otto)
  - Compression Ignited (Diesel)
- Stirling
- Turbine

Direct Electric
- Electrochemical
  - Fuel cells
- Photoelectric
- Thermoelectric
- Combined cycle
  - CHP
  - “Hybrids”
  - Waste Heat Recovery
Power Conversion

\[ \Delta P \rightarrow \text{“motive force”} \]

- Heat a gas
- Combustion
- Nuclear
- Geothermal
- Solar
- Gravity
- Dams
- Waves
- Wind

Shaft Work Machines
- Reciprocating
  - Spark Ignited (Otto)
  - Compression Ignited (Diesel)
- Stirling
- Turbine

Direct Electric
- Electrochemical
- Fuel cells
- Hydropower
- Tidal
- Wave
- Shaft Work Machine
- Reciprocating
- Spark Ignited (Otto)
- Compression Ignited (Diesel)
- Stirling
- Turbine

Combined cycle
- CHP
- “Hybrids”
- Waste Heat Recovery

Efficiency
Conservation
The Future of Heavy Duty Diesel Engines and Fuels
Reducing our CO$_2$ Footprint

- Idle Reduction
- Hybrids
- High Efficiency Clean Combustion
- Low Temp Aftertreatment
- Waste Energy Recovery

CO$_2$ ↔ Energy Efficiency

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Energy Efficiency
2007 HD Engine Energy Balance

Fuel Energy
100%

Indicated Power
50%

Heat Transfer
26%

Exhaust
24%

Gas Exchange
4%

Friction
1.5%

Accessories
2.5%

Brake Power
42%
Enabling Technology for Efficiency Improvement

Advanced Combustion (Mixed Mode)
- Stoichiometric
- Early PCCI
- Lifted Flame

Indicated Power 55.5%

Fuel Energy 100%

Heat Transfer 23.5%

Exhaust 21%

Gas Exchange 2%

Friction 1.0%

Accessories 2.5%

Brake Power 50%
Enabling Technology for Efficiency Improvement

Advanced Combustion
• FIE (Higher Inj. Pressure, Multiple Inj)
• CEGR Cooling Systems
• Air Handling (Elec assist turbo)
• High Cylinder Pressure
• Closed Loop Combustion Control

Indicated Power 55.5%

Fuel Energy 100%

Heat Transfer 23.5%

Exhaust 21%

Gas Exchange 2%
Friction 1.0%
Accessories 2.5%
Brake Power 50%
Enabling Technology for Efficiency Improvement

Fuel Energy 100%

Indicated Power 55.5%

Heat Transfer 23.5%

Exhaust 21%

Gas Exchange 2%
Friction 1.0%
Accessories 2.5%
Brake Power 50%

Low Temperature Aftertreatment
- lower soot loading
- low pressure drop
- regen controls/strategy
Enabling Technology for Efficiency Improvement

Fuel Energy
100%

Indicated Power
55.5%

Heat Transfer
23.5%

Exhaust
21%

Gas Exchange
2%

Friction
1.0%

Accessories
2.5%

Brake Power
50%

Gas Exchange
- Electrically assisted turbo
- EGR pump
- Variable valve actuation
Enabling Technology for Efficiency Improvement

- **Fuel Energy**: 100%
- **Indicated Power**: 55.5%
- **Heat Transfer**: 23.5%
- **Exhaust**: 21%
- **Gas Exchange**: 2%
- **Friction**: 1.0%
- **Accessories**: 2.5%
- **Brake Power**: 50%

**Friction Reduction**
- Piston and rings
- Bearings
- Surface treatment
Potential Advanced HD Engine Energy Balance

Fuel Energy 100%

Indicated Power 55.5% (+5.5%)

Heat Transfer 23.5% (-2.5%)

Exhaust 21% (-3%)

Gas Exchange 2% (-2%)

Friction 1.0% (-0.5%)

Accessories 2.5%

Brake Power 50% (+8%)
Waste Energy Recovery

- *Engine* Waste Heat Recovery
- *Vehicle* Kinetic Energy Recovery (Hybrids)
Waste Heat Recovery vs. Hybrid

- **Waste Heat Recovery**
- **Hybrid**

- **Customer Benefit**

- **Frequent Start/Stop**

- **Seldom Start/Stop**
Waste Heat Recovery for Advanced HD Engine

Fuel Energy 100%

Indicated Power 55.5%

Heat Transfer 23.5%

Exhaust 21%

Waste Heat Recovery

Gas Exchange 2%

Friction 1.0%

Accessories 2.5%

Brake Power 50%

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WHR System Schematic

- Ram Airflow
- WHR Condenser/Reserv.
- CAC
- Engine Radiator
- Mechanical Fan
- ISX Engine
- Comp
- Turb
- EGR Valve
- Air In
- Feed pump
- Boiler
- Superheater
- Power Conditioning
- Gen.
- Recuperator
- Turbine
- Power Out
- Bypass valve
- Check valve
- Press. Ctrl. Valve
- Aftertreatment
- Exhaust Out
- Boiler
- Filter/Dryer
- Boost Pump
WHR System Schematic

- Ram Airflow
- WHR Condenser/Reserv.
- CAC
- EGR Valve
- Mechanical Fan
- ISX Engine
- WHR System Schematic
- Boost Pump
- Filter/Dryer
- Power Out
- Feed pump
- Boiler
- Superheater
- Power Conditioning
- Turbine
- Gen.
- Check valve
- Press. Ctrl. Valve
- Bypass valve
- Exhaust Out
- Boiler
- WHR System Schematic
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System uses R245 refrigerant as working fluid to extract energy from EGR system, generate electricity and use it to make power at flywheel.
Energy Balance for Waste Heat Recovery and Electric Accessories

Fuel Energy 100%

Indicated Power 55.5%

Gas Exchange 2%
Friction 1.0%
Accessories 1.0%
Brake Power 57% (+ 15%)

Heat Transfer 19.5%
EGR Source (ORC) 4%
EGR + Exhaust Source 1.5%

Exhaust 19.5%

Electric Accessory Drive
Historical and Projected HD Brake Thermal Efficiency

Advanced Waste Energy Recovery and Vehicle Electrification

Waste Energy Recovery

Brake Thermal Efficiency (%)


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Alternative Diesel Fuels and Hydrogen
Alternative Fuels in general...

- My personal view:
  - Installed base of consumer vehicles
    + sunk investment in delivery infrastructure
    = alternative fuel \(\rightarrow\) like conventional gasoline or diesel fuel

  - Boutique engines for boutique fuels (or vice versa)
    make no business sense (just lab entertainment)

- Why I might be wrong:
  - If a reformulated fuel enables a significant fuel economy improvement at low emissions, it could get more interesting to adapt special engine and fuel technology for each other.
Alternative Diesel Fuels

- “Fossil” source
  - Coal
  - Natural gas

- Renewable -- Derived from biological sources
  - Ethanol (corn, sugar cane, switchgrass / cellulose, …) – usually = “gasoline”
  - Biodiesel (soy, canola, jatropha, sugar cane …)
  - Biomass gasification (cellulose, animal waste, landfill gas)
Alternative Fuels from Coal and Natural Gas

- Synthetic liquids – Fischer-Tropsch
  - Natural gas to liquid (GTL)
  - Coal (to gas) to liquid (CTL)
- Requires lots of water for coal to liquid
- Excellent fuel properties, especially diesel
  - Zero aromatics
  - Zero sulfur
- Lower emissions – but not enough
Other Alternative Fuels from Coal

- Methanol
  - Toxic, soluble in water
  - Poor autoignition quality

- Di-Methyl Ether (DME)
  - Gaseous at normal atmospheric pressure and temperature – requires pressure to liquefy
  - Good for cooking and for potato guns

- Neither is a good diesel fuel
Renewable Diesel Fuels

- Bio-derived diesel
  - Soy, Canola / Rapeseed, Jatropha
  - Fatty Acid Methyl Ester (FAME)
  - Molecule generally heavier than average diesel
  - Quality is crucial -- Glycerin impurity is a filter killer

- Bio-produced diesel
  - Amyris: Genetically engineered yeast produce diesel-range hydrocarbon from sugar
Hydrogen … A complicated story

- Must be separated from other molecules (water, hydrocarbons) – and that takes energy
- Only “zero carbon” if formed from water using energy NOT from carbon or hydrocarbons
- Practical issues with distribution and storage (energy storage density, material compatibility, ventilation)
- Need “mass quantities” to be interesting from a CO$_2$ standpoint
- Really long term … needs work now, but won’t pay off for decades
- Silver lining for the engine guys: Solve the manufacturing and distribution problems, and an internal combustion engine is a good way to burn it (and way cheaper than fuel cells)
Producer-Gas 1 MW Power Generation Plant Coimbatore, India
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- 您可信赖的创新
- L'innovation
- Sur Laquelle Vous Pouvez Compter
- 期待に答える技術革新
- Innovación En La Que Usted Puede Confiar
- 신뢰할 수 있는 혁신
- Inovação Que Você Pode Confiar
- नवगुणि जिस पर आप निर्भर कर सकें