Engine System Approach to Exhaust Energy Recovery

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Program Objectives

Establishing the Baseline

Technical ‘Recipe’ for Improved WHR

Summary and Conclusions
Program Objective

- Develop components, technologies, and methods to recover energy normally *exhausted as waste heat* from the engine.
- Improve engine efficiency with:
  - No increase in emissions
  - No reduction in power density
  - Compatible with anticipated aftertreatment
- TARGET – Demonstrate 10% improvement in overall thermal efficiency (OTE).

*Focus on technologies that have a strong chance of being brought to production for 2010 and/or TierIV*
Refine recipe, final component and system design. Analytical demo of 10% improvement.

We are here
Peak Torque Conditions

Engine C15

Baseline '07 C15 Engine Configuration

Stack Energy 22.2%
Precocler HR
ATAAC HR
CGI Cooler HR
Engine Heat Rej
Pumping = 1.5kw
Brake Power

Ambient

ATAAC
PC
HP Comp
LP Comp

Stack

DPF

CGI Cooler
CGI

Baseline Fuel Energy (kW)
Brake Power
Engine
Heat Rej
ATAAC HR
CGI Cooler HR
Stack Energy 22.2%
Precocler HR

Baseline

U.S. Department of Energy
CATERPILLAR
Exhaust Energy and Availability

Would need ~50% recovery of stack availability to achieve +10% OTE.

Need system level attack to achieve +10%

- ~34% exits stack
- ~16% (throttling, turbines, DPF)
- ~8% (primarily ports)
- ~8% CGI flow (dumped)
- ~34% of Exhaust availability used
Path to +10% Overall Thermal Efficiency

- Port Insul. (0.5%)
- Piping (0.5%)
- Intercooling (1.3%)
- High Eff. HP Turbine (2.0%)
- High Eff. LP Turbine (1.0%)
- Compressors (0.7%)
- Supplemental* (4.0%)

* Turbocompound or Bottoming Cycle

Can this be achieved?

Demo’d on HTCD Program

Baseline is ’07 C15 On-Highway
Target: +0.5% overall thermal efficiency

- Focus on interstage ducts
- Lower losses
- Improved flow distribution
- Turbines - low exit Mach #

System Integration and optimization of turbocharger component selection
Target: +2.0% overall thermal efficiency
- Translates to ~ +10% turbine stage efficiency improvement

HTCD 50% OTE HP Turbo
- High-efficiency radial wheel – Caterpillar design
- Divided housing for blowdown pulse utilization, engine breathing
- Nozzled inlet for incidence control – same OD as production HP
- Parts procured, ready for G.S. test
- +5% T-S vs production predicted

Need more!
EWHR Program

Component Analysis – HP Turbine

Target: +2.0% overall thermal efficiency
• Translates to ~ +10% turbine stage efficiency improvement

Mixed-Flow Turbine
• High Efficiency at high specific speeds
• Aero design and structural analysis complete
• same OD as production HP
• + 3-5% efficiency relative to radial

From Baines, Fundamentals of Turbocharging
Target: +1.0% overall thermal efficiency
  • Translates to ~ +6.5% turbine stage efficiency improvement

HTCD 50% OTE LP Turbine
  • High Efficiency radial wheel – Caterpillar design
  • Nozzled inlet for incidence control - same OD as production LP
  • +5% T-S vs production LP

Need more!
Target: +1.0% overall thermal efficiency
  • Translates to ~ +6.5% turbine stage efficiency improvement

Axial Turbine
  • High Efficiencies
    • 84-86% T-S efficiencies demo’d on Caterpillar prototypes
  • Potential for reducing interstage duct losses
  • Combination of radial HP feeding axial LP
Target: +0.7% overall thermal efficiency
  • Translates to ~ +2.5% compressor efficiency improvement

High Efficiency Compressor Design
  • Caterpillar design
  • High blade backsweep
  • Low solidity vaned diffuser
  • Same OD as today’s production
  • +2-3% efficiency predicted
  • Design/analysis complete, procurement underway
Target: +4.0% overall thermal efficiency

Caterpillar Experience

Mechanical
2006 HTCD Program

Turbocompound Engine Configuration
Component Analysis - Turbocompound

Target: +4.0% overall thermal efficiency

- 83% efficient compound turbine
- 93% mechanical efficiency

**Component Analysis - Turbocompound**

**Fuel Energy (kW)**

- Stack Energy
- Precooler HR
- ATAAC HR
- CGI Cooler HR
- Engine Heat Rej
- Brake Power (cyl)

**Brake Power (cyl)**

- Baseline
- Port Insulation
- Intercooler
- Turbos
- Turbo Compound

**Energy**

- +0.5% OTE
- +1.3% OTE
- +3.7% OTE
- +3.9% OTE

**Overall Thermal Efficiency**

- +9.1% OTE overall
- +0.5% Piping
- +9.6% OTE overall

**BUT………**
Target: +4.0% overall thermal efficiency

- Turbocompound benefit highly sensitive to backpressure
- Additional 30KPa backpressure cuts benefit by half
Target: +4.0% overall thermal efficiency

EWHR Program

Component Analysis – Bottoming Cycle

Brayton Engine Configuration

Brayton Cycle
Target: +4.0% overall thermal efficiency

Brayton Cycle
• Difficult to achieve high cycle efficiencies at ‘low’ heat source temps
• Highly sensitive to turbo efficiencies, heat exchanger effectiveness, operating conditions
• Extensive sensitivity conducted to optimize system
**Component Analysis – Brayton Cycle**

**Target:** +4.0% overall thermal efficiency

- **Assume 83% efficient Brayton turbo components**
- **Assume 90% heat exchanger effectiveness**

In event of +30kPa back pressure, incremental benefit increases to +4.6%
Goal of +10% OTE via improved WHR can be achieved
- Line of sight to 9-10% improvement via analysis
- Additional system optimization investigations ongoing

Multiple paths to reach goal
- Brayton cycle offers most potential
  - Highly sensitive to component performance
  - Must be combined with other technologies (port insulation)
- Turbocompound similar efficiency benefit as Brayton
  - Highly sensitive to backpressure
  - Offers additional benefit of response improvement, especially ETC
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