Integrated Vehicle Thermal Management Systems (VTMS) Analysis/Modeling

2009 DOE Vehicle Technologies Annual Merit Review

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Overview

Timeline

- Project Start: FY 2007
- Project End: FY 2010
- Percent Complete: 55%

Budget

- Total Funding (FY07-FY10)
  - DOE: $450K
  - Contract: $0K
- Annual Funding
  - FY08: $150K
  - FY09: $100K

Partners/Collaboration

- Collaboration with Electrical and Electronics Technical Team (EETT) which includes NREL and ORNL.

Barriers

- Commercially viable integrated vehicle thermal management enabling advanced propulsion technologies to reduce oil consumption.

Vehicle Systems Analysis

Technical Tasks

- Modeling and Simulation
- Integration and Validation
- Benchmarking

2007 Oil Consumption by Sector – Million Barrels per Day
Objectives

VTMS Objectives
- Safety
- Reliability
- Performance
- Comfort

Energy Use Pressures
- Consumer demand
- Regulations
- Energy security
- Environment

FY 08 Objectives
1) Investigate current technologies for improved vehicle thermal management, waste heat utilization, and integrated cooling.
2) Propose areas of focus for research into waste heat utilization and integrated cooling that apply to advanced vehicle propulsion systems.
3) Develop initial concepts of new waste heat utilization techniques and integrated cooling.
Objectives: Definition

What is integrated vehicle thermal management?

Look at Total Thermal Management Package Based on Vehicle Type

Not

Add-on Compartmentalized Component Focused Thermal Management
Objectives: Benefits

Integrated Vehicle Thermal Management

Reduce : Remove : Re-use

Safety | Robustness | Comfort | Component Count | Aerodynamics

Alternative Vehicle Propulsion Tech.

Cost & Size | Mass

Energy Diversification | Energy Efficiency

Reduced Reliance on Petroleum Imports for Transportation

Energy : Environment : Economics
Milestones (FY08 & FY09)

**FY08**
- Investigated challenges related to vehicle thermal management.
- Reviewed current and proposed technologies related to improving vehicle thermal management.
- Identified potential areas for future research focus.

**FY09**
Approach (FY08 & FY09)

- Conduct review of thermal management challenges and technologies across multiple vehicle propulsion technologies.

- Identify potential areas for research and development (R&D) specifically related to:
  - Waste heat utilization.
  - Integrated systems.

- Propose R&D concepts that:
  - Maximize benefit with least change.
  - Have wide application to multiple advanced vehicle propulsion technologies.

- Develop analytical analysis capabilities and methodologies to evaluate system feasibility of R&D concepts.
Technical Accomplishments

- As one transitions away from internal combustion engines the quantity (kW) and quality (°C) of the waste heat decreases.
- The impact is significant for PHEVs during engine off operation.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Component</th>
<th>Peak Output Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Vehicle (CV)^+</td>
<td>Engine (ICE)</td>
<td>122</td>
</tr>
<tr>
<td>HEV^+</td>
<td>Engine (ICE) Electric Machine Inverter Battery</td>
<td>82 39 39 50</td>
</tr>
<tr>
<td>PHEV^+</td>
<td>Engine (ICE) Electric Machine Inverter Battery</td>
<td>79 44 44 47</td>
</tr>
<tr>
<td>Fuel Cell Vehicle (FCV) (Battery and DC/DC converter not included)</td>
<td>Fuel Cell Electric Machine Inverter</td>
<td>150 120 120</td>
</tr>
<tr>
<td>Electric Vehicle (EV)</td>
<td>Electric Machine Inverter Battery</td>
<td>120 120 150</td>
</tr>
</tbody>
</table>

*Note: Brake values can be significantly higher. Comparison value based on the kinetic energy of a midsize vehicle at 40 MPH stopping within 7 seconds.

Technical Accomplishments

CV Selected Component Temperature Ranges

- Exhaust
- Ambient Air
- Transmission Oil
- Engine Oil
- Engine Coolant
- Refrigerant
- Charge Air Cooler
- Alternator
- Power Steering
- Battery - 12V Lead Acid
- Heated Washer Fluid
- Heater Core
- AC Condenser
- AC Evaporator
- Vehicle Cabin
- NOx Trap
- Thermal Reactors
- Particulate Trap Diesel
- Catalyst
- Engine Combustion Wall
- Wheel Mounted Components (Brakes)

Temperature [°C]

CV Peak Heat Load (kW)

- Condenser (HVAC)
- Driveline
- Brakes*
- Engine Coolant
- Engine Exhaust

* Note: Brake estimate can be significantly higher
Technical Accomplishments

PHEV Selected Component Temperature Ranges

- Exhaust
- Ambient Air
- Transmission Oil
- Engine Oil
- Engine Coolant
- Secondary Coolant Loop (PEEM)
- Refrigerant
- Power Electronics
- Electric Machine Winding
- Electric Machine Magnets NdFeB
- Battery - HEV/PHEV/EV
- Charge Air Cooler
- Alternator
- Power Steering
- Battery - 12V Lead Acid
- Catalyst
- Engine Combustion Wall
- Heated Washer Fluid
- Heater Core
- AC Condenser
- AC Evaporator
- Vehicle Cabin
- Wheel Mounted Components (Brakes)

Temperature [°C]

-200 -100 0 100 200 300 400 500 600 700 800 900 1000

PHEV20- Peak Heat Load (kW)

- Engine Coolant
- Difference from CV
- Engine Exhaust
- Condenser (HVAC)
- Brakes*
- Battery
- Inverter
- Motor
- Driveline

*Note: Brake estimate can be significantly higher
Technical Accomplishments

Waste Heat Recovery
• Large heavy-duty diesel applications would see the most benefit.
• Lower heat source temperatures and intermittent heat source operation decrease performance.
• Includes:
  • Turbo-Compounding.
  • Thermoelectrics.
  • Rankine Cycle (shown below).
  • etc.

(Thermal Efficiency)
\[ \eta_{th} = \frac{W_{net}}{Q_{in}} \]
Technical Accomplishments

Heat Pump
- Transfers heat from low temperature environment to a higher temperature environment.
- Performance degrades as temperature delta increases.
- Cabin heating uses: Reverse AC system to aid cabin heating.
  - Air source heat pumps can freeze.
  - Coolant source heat pumps increase coolant warm-up time.
  - Window fogging safety concern.

(Coefficient of performance)

\[ COP_{HP} = \frac{Q_H}{W_{in}} \]
Technical Accomplishments

- Developing methodology and analysis capabilities to evaluate options for integrated thermal management.
- Example shows integration of AC condenser and PE coolant loops.
Technical Accomplishments

- Preliminary heat exchanger sizing shows potential to integrate PE and AC condenser cooling into an integrated system within a vehicle package.

Assumptions:
- Fixed width 711 mm or 28 in.
- Air mass flux 5.42 kg/s-m² based on minimum free-flow cross-sectional area.
- Water ethylene glycol mass flow 0.35 kg/s (~20L/min).
- Aluminum construction (k=170W/m-K).
- Air inlet temperature 40°C.
- Water ethylene glycol outlet temperature 50°C.

Future Work

• Refine heat exchanger and integrated cooling analytical analysis methods (FY09).
  • Integrate pressure drop analysis.
  • Explore alternative heat exchanger designs.
  • Develop analytical models for alternative integrated packages.

• Peak vs. continuous component heat loads and variation over drive cycles across multiple vehicle propulsion configurations (FY09-FY10).

• Investigation of thermal energy storage technologies and other waste heat utilization technologies (FY09-FY10).

• Hardware validation with industry partner (FY10).
Summary

• Advanced energy efficient vehicles face multiple challenges related to thermal management, such as PHEVs.
  • Low waste heat availability with engine off.
  • Cabin heating.
  • Thermal management of additional subsystems.

• Power electronics waste heat recovery is limited due to the lower quantity (kW) and quality (°C) energy in the liquid coolant loop.

• Integrated or combined cooling loops could potentially include opportunities for power electronics.

• Initial analytical capabilities and methodologies to evaluate integrated thermal management options and heat exchanger impacts have been developed.