Integrated Vehicle Thermal Management – Combining Fluid Loops in Electric Drive Vehicles

U.S. Department of Energy
Annual Merit Review

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## Overview

### Timeline
- Project Start Date: FY11
- Project End Date: FY14
- Percent Complete: 80%

### Budget
- Total Project Funding (to date): $1,575 K *
- Funding for FY13: $575 K *
- Funding for FY14: $250 K
- Partner In-Kind Cost Share: $375 K **

### Barriers
- **Complexity**: integrated multi-valve system for multiple thermal loads
- **Low temperature operation**: cabin heating at very low temperatures
- **Front-end heat exchanger frosting**: heat pumping below 0°C ambient

### Partners
- **Interactions/collaborations:**
  - Delphi
  - Halla Visteon Climate Control
- **Project Lead**: NREL

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* Shared funding between VTO programs: VSST, APEEM, ESS
** Not included in total
Relevance: Project Objectives

• Combine electric drive vehicle (EDV) fluid loops to reduce weight, cost, and energy consumption
• Integrated thermal solution to increase EDV range at national level

• Recent focus: bench testing

ESS = energy storage system
PEEM = power electronics and electric motors
Relevance: Support Broad VTO Efforts

• DOE VTO Multi-Year Program Plan
  o “... development of advanced vehicles and components to maximize vehicle efficiency ...”

• EV Everywhere Grand Challenge
  o A goal of EV Everywhere is to have automobile manufacturers produce a car with sufficient range that meets consumers’ daily transportation needs

• Combined Fluid Loop (CFL) Project
  o Develop CFL system to maximize vehicle efficiency and range by reducing auxiliary loads and improving battery thermal management

VTO = Vehicle Technologies Office
Relevance: VTO Integration

- **Vehicle Systems**
  - Lee Slezak
  - David Anderson

- **Energy Storage**
  - Tien Duong
  - Brian Cunningham
  - Peter Faguy

- **Power Electronics & Electric Motors**
  - Susan Rogers
  - Steven Boyd

- Vehicle electric powertrain model
- Battery thermal and efficiency models
- Power electronics and electric motor thermal models
**Approach/Strategy: Overview**

- Evaluate with 1-D thermal model
- Bench test verification of performance and address technical barriers
- Collaborate with industry on vehicle-level demonstration

### Timeline:

- **Modeling** (FY11 & FY12)
- **Bench Testing** (FY13 & FY14)
- **Vehicle Testing** (Future)
Approach/Strategy: Challenges

- Investigate performance over wide range of conditions
- Enable heat pump operation and waste heat recovery
- Identify efficiency versus complexity trade-offs to develop solutions for cost reduction and EDV range improvement

Impact of Temperature on Range

*ANL climate chamber dynamometer testing of stock 2012 Nissan Leaf

ANL = Argonne National Laboratory
AVTA = Advanced Vehicle Testing Activity
# Milestones

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| **Q3** June 2014 | **Milestone:**  
  • Complete modifications of bench test apparatus for cold weather operation and test the CFL concept in a cold environmental chamber |
| **Q4** Sept. 2014 | **Milestone:**  
  • Submit a summary of the project results in the DOE annual report format |
Technical Accomplishments and Progress: Overview

• March 2013 to March 2014 – Bench testing
  o Constructed bench test apparatus
  o Integrated vehicle, power electronics, electric motor, battery, and cabin models into LabVIEW data acquisition and control system
  o Constructed CFL system using prototype heat exchangers from Delphi and an electric compressor from HVCC
  o Completed hot weather steady-state testing
  o Near completion of hot weather drive-cycle testing
• Designed for hardware-in-the-loop drive cycle testing with vehicle load simulation

HX = heat exchanger
PTC = positive temperature coefficient
WEG = water/ethylene glycol
Technical Accomplishments and Progress: CFL System

- Allows multiple configuration strategies, including waste heat recovery and heat pumping
• Most important technical accomplishment was successful design, construction, and operation of CFL test bench
Technical Accomplishments and Progress: Steady-State Cooling

- Stable system operation, reasonable energy balances and errors, and performance meeting expectations

COP = coefficient of performance
• Cabin pull-down penalty due to experiment thermal mass – real system more compact

UDDS = Urban Dynamometer Driving Schedule
Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary Results

PEEM & ESS Temperatures for HWFET at $T_{amb} = 38^\circ C$

- PEEM temperatures within thermal limits, ESS control strategy needs further investigation

HWFET = Highway Fuel Economy Driving Schedule
Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary Results

Combined Cycle (45% UDDS/55% HWFET) - Range

- A/C Penalty: -11%
- PEEM/ESS Penalty: -0.3%
- Soak Penalty: -2.6%

Range [Mi]

Ambient Temperature [°C]
Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary Results

Combined Cycle (45% UDDS/55% HWFET) - Range

- A/C Penalty
- PEEM/ESS Penalty
- Soak Penalty

Range [Mi]

Ambient Temperature [°C]

-11% - 26% - 16% - 0.3% - 2.6% - 0.5% - 5.5% - 0.4% - 4.2%
Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary Results

**Combined Cycle (45% UDDS/55% HWFET) - Range**

- PEEM cooling <1% penalty to range, ESS cooling penalty significant at higher ambient temperatures
## Responses to FY13 AMR Reviewers’ Comments

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| Consider defog and defrost       | • Without vehicle cabin, direct testing is not possible, but heating capacity matches conventional vehicle  
• If vehicle test is pursued, direct evaluation is possible |
| Collaborate with vehicle OEM     | • Bench testing in close collaboration with Delphi  
• Interest from Delphi and a vehicle OEM to develop technology for vehicle demonstration |
| Characterize baseline for “extreme” environments | • Bench testing at ambient temperatures from -30°C to 43°C |

OEM = original equipment manufacturer
Collaboration: Delphi

• Delphi provided prototype refrigerant-to-coolant, and coolant-to-air heat exchangers

[Diagram with labels: Flow Meter, Suction, Sub-cooler, TEV, Receiver/Dryer, Condenser, Chiller, Discharge.]

TEV = thermostatic expansion valve
Collaboration: Halla Visteon Climate Control

- Halla Visteon Climate Control provided high-voltage DC electric compressor capable of heat pump operation
Collaboration: Summary

• **Industry**
  - Delphi
  - Halla Visteon Climate Control

• **VTO Tasks**
  - Advanced Power Electronics and Electric Motors
    - PEEM thermal models
  - Vehicle Systems
    - FASTSim vehicle powertrain model
  - Energy Storage Systems
    - Battery thermal and efficiency (voltage vs. temperature) models
Remaining Challenges and Barriers

• **Complexity**
  - Must define trade-offs between complexity and efficiency for industry buy-in

• **Low temperature operation**
  - Cold weather testing must demonstrate sufficient heat pump performance when supplemented with waste heat

• **Front-end heat exchanger frosting**
  - Testing must measure impact of hot coolant defrost cycling
Proposed Future Work

• **Remainder of FY14**
  - Complete hot weather drive cycle testing
  - Conduct cold weather drive cycle testing
  - Identify best practices for system design and control
  - Analyze technology impact on EDV range and thermal management

• **FY15 and beyond**
  - Work with industry partners (suppliers and an OEM) to demonstrate technology at vehicle level
Summary

• Designed and built test apparatus to validate potential of CFL to reduce cost, weight, and volume of thermal system while increasing vehicle range

• Hot weather testing almost complete, cold weather testing to begin soon

• Looking to work with industry partners on a vehicle-level demonstration to develop the technology and reduce national energy consumption
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Technical Back-Up Slides
Cooling Mode (Active ESS Cooling)
Cooling Mode (Passive ESS Cooling)
“Free” Cooling Mode

- Liquid
- PEEM
- Vehicle Cabin
- Refrigerant
- WEG
- Air
- ESS
- WEG-to-air HX
- Var.
Mild Heating Mode (Only Heat Recovery)

- Liquid
- PEEM
- Vehicle Cabin
- Cabin Heater
- ESS
- Front-end WEG-to-air HX

Legend:
- Refrigerant
- WEG
- Air
Heating Mode

- Condenser
- Evaporator
- PEEM
- PTC Heater
- Cabin Heater
- Cabin Cooler
- Vehicle Cabin
- Front-end WEG-to-air HX
- ESS

Flow of Refrigerant:
- Condenser to PEEM
- PEEM to PTC Heater
- PTC Heater to Cabin Heater
- Cabin Heater to Cabin Cooler
- Cabin Cooler to Vehicle Cabin
- Vehicle Cabin to Front-end

Flow of WEG:
- Condenser to Evaporator
- Evaporator to PTC Heater
- PTC Heater to ESS

Flow of Air:
- WEG-to-air HX to ESS
- ESS to Front-end