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

U.S. Department of Energy
Annual Merit Review

National Renewable Energy Laboratory

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APE038

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Overview – Integrated Vehicle Thermal Management (IVTM)

**Timeline**
- Project start date: FY11
- Project end date: FY13
- Percent complete: 10%

**Barriers**
- Cost – *cooling loop components*
- Life – *thermal effects on energy storage system (ESS) and advanced power electronics and electric motors (APEEM)*
- Weight – *additional cooling loops in electric drive vehicles (EDVs)*

**Budget**
- Total project funding
  - DOE share: $375k
  - Contractor share: $0
- FY11 Funding: $375k

**Partners**
- Interactions
  - Visteon
  - EE Tech Team
- Project lead: NREL
IVTM – FY11 Funding Overview, $375k

Collaboration Between 3 Vehicle Technology Activities

Hybrid Electric Systems
Dave Howell – Team Lead

Vehicle Systems
Lee Slezak
David Anderson

Energy Storage
Steve Goguen
Tien Duong
Brian Cunningham
Peter Faguy

Power Electronics & Electric Motors
Susan Rogers
Stephen Boyd

33% 33% 33%
Relevance – The PHEV/EV Thermal Challenge

• Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) have increased vehicle thermal management complexity
  – Separate coolant loop for APEEM (advanced power electronics and electric motors)
  – Thermal requirements for ESS

• Multiple cooling loops may lead to reduced effectiveness of fuel-saving control strategies
  – Increased, weight, volume, aerodynamic drag, and fan/pump powers
  – Reduced electric range

• Cross-cutting system designs are challenging, involving separate teams at OEMs and suppliers

Photo Credit: Mike Simpson, NREL
Relevance – Passenger Compartment A/C and Heating Significantly Impact EV Range

- Vehicle: Mitsubishi iMEV
- Drive Cycle: 10-15
- Impact on range
  - A/C: -34 % to -46%
  - Heating: -46% to -68%

Data Credit: Kohei Umezu and Hideto Noyama, Mitsubishi, Presented at the 2010 SAE Automotive Refrigerant and System Efficiency Symposium
Photo Credit: Mike Simpson, NREL
Relevance – Multiple Cooling Loops Result in Complicated Front-End Airflow

Top View

Air Flow

- Electronics Cooling
- A/C Condenser
- Transaxle Cooling
- Engine Radiator

Fan 1
Fan 2

Side View

Air Flow

- Engine
- Transaxle Cooling
- A/C Condenser
- Electronics Cooling

Fan 1

Data Credit: www.gm-volt.com
Relevance – VTM Objectives

• Overall Objectives
  – Work with industry partners to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains
    o Improve PHEV and EV performance (reduced weight, aero drag, and parasitic loads)
    o Reduce cost and volume
    o Improve battery life

• FY11 Objectives
  – Develop a 1-D (lumped mass, uniform flow) thermal model using commercial software to assess the benefits of integrated vehicle thermal management and identify research opportunities
Approach

• Build a 1-D model (using KULI software) of the APEEM, energy storage, engine, transmission, and passenger compartment thermal management systems
• Combine with vehicle performance/cost and battery life models
• Identify the synergistic benefits from combining cooling systems
• Select the most promising combined thermal management system concepts and perform a detailed performance assessment with production-feasible component data
• Assess technical feasibility
  – Vehicle performance impact
  – Battery life impact
• Acquire additional OEM and supplier partners
FAST = Future Automotive Systems Tool

- Leverage existing DOE projects
  - Vehicle cost/performance model
  - Lumped parameter motor thermal model
  - Battery life model
Approach – Future Automotive Systems Tool

- Simplified vehicle simulation plus cost and battery life
- Approach: Include most critical parameters
  - Powertrain components (engine, electric motor, battery)
  - Auxiliary loads
  - Regenerative braking
  - Speed vs. time simulation
  - Battery life estimates
  - Cost estimates

- Application to vehicle thermal management project
  - Calculate heat generation
  - Assess impact of combined cooling loop strategies on vehicle range while maintaining equivalent cost
Approach – Battery Life Model

- Assesses the impact of temperature on battery life
- Accounts for degradation due to
  - Resistance growth
  - Capacity fade
- Includes life prediction using real-world Li-ion test data
Approach – KULI Thermal Model

- 1-D thermal/fluid models using automotive industry commercial software package (KULI)
- Incorporate multiple vehicle cooling systems
  - Heating and cooling (HVAC)
  - Passenger compartment
  - Energy storage
  - Engine
  - Power electronics
  - Electric machines
  - Transmission
Approach – continued

• **Address Targets**
  – Improved range at equivalent cost from combining thermal management systems
  – Reduce the APEEM coolant loop temperature without requiring a dedicated system
  – Reduced volume and weight

• **Uniqueness**
  – Combining APEEM, energy storage, engine, and passenger compartment thermal management systems
### Approach – Go/No Go Decisions and Milestones

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- **Develop KULI Model**
- **Assess Combined Fluid Loops**
- **Go/No Go Decision Point**
- **Document results of KULI analysis**
Accomplishment – Built A/C Component Models

- High quality detailed component data
  - Provided by Visteon (Tier 1 HVAC component supplier)
- Built component models in KULI
Accomplishment – Built A/C System Model
Accomplishment – A/C Model (cont.)

- A/C model results compared well to Visteon test data
Accomplishment – Built Cabin Model

- Cabin soak and cooldown model results compared well to NREL test data

- Small sedan
- 2 hr soak, 21 minute cooldown
- Solar = 870 W/m²
- Air temperature = 22.3 °C
Accomplishment – Combined A/C and Cabin Models with PID Control

- Cooldown simulation demonstrates
  - Reasonable cooldown
  - Robust control

![Graph showing temperature change over time](image)

- Small sedan
- 21 minute cooldown
- Solar = 870 W/m²
- Air temperature = 22.3 °C
- Blower on high flow
- Outside air
- Initial interior temperature = 49 °C

PID = Proportional-Integral-Derivative
Accomplishment – Built APEEM Cooling Loop Model

Drive Cycle Q gen

x\text{Out}

\text{Radiator [l]}

\text{[Water/}\text{Glycol]}

\text{Fluid Mass}

\text{Electric Pump}

\text{Inverter p drop}

\text{Inverter}

\text{EM}

\text{EM p drop}

\text{Stage Controller}

\text{External Heat Supply}

\text{Entry temperature}

\text{1.\text{EFan}}

\text{Fan stage}

\text{External Heat Supply}

\text{Input Speed 5000 \text{1/min}}

\text{Input speed}
Accomplishment – Heat Generation in the APEEM Components Input into APEEM Model

- Vehicle performance model output
- Nissan Leaf
- Drive Cycle: EPA Highway Fuel Economy Test
Accomplishment – APEEM Cooling Loop Model
Produced Reasonable Fluid and Motor Temperatures

- Air temperature = 45 °C
- 5 L/min
- 50/50 Water – Ethylene Glycol
Accomplishment – Combined A/C, Cabin, and APEEM Cooling Loop

Heat Load/Cabin

A/C

APEEM
Collaboration

- Visteon
- EE Tech Team
- VTP Tasks
  - Vehicle Systems
  - Energy Storage
  - Advanced Power Electronics and Electric Motors
Future Work

• FY11 (March-September)
  – Build an ESS cooling loop model
  – Combine ESS model with A/C, cabin, and APEEM KULI models
  – Assess baseline thermal performance
  – Assess combined cooling loop strategies

• FY12
  – Based on the FY11 analysis, select, build, and evaluate a prototype system to demonstrate the benefits of an integrated thermal management system
  – Validate the KULI model with bench data and improve the model with updated component data as it becomes available
  – Engage automobile manufacturers and secure strong support from at least one OEM
Summary

• **DOE Mission Support**
  - Combining cooling systems in EDVs may reduce costs and improve performance which would accelerate consumer acceptance, increase EDV usage, and reduce petroleum consumption

• **Approach**
  - Build a 1-D model (using KULI software) of the APEEM, energy storage, engine, transmission, and passenger compartment thermal management systems
  - Identify the synergistic benefits from combining the systems
  - Select the most promising combined thermal management system concepts and perform a detailed performance assessment with production-feasible component data
  - Solve vehicle-level heat transfer problems which will enable acceptance of vehicles with electric powertrains
Summary (cont.)

• Technical Accomplishments
  – Developed a modeling process to assess synergistic benefits of combining cooling loops
  – Built A/C and cabin KULI model
    o A/C and cabin models individually validated
    o Combined system produces reasonable cooldown
  – Built APEEM KULI cooling loop model
    o Produces typical component and fluid temperatures
  – Ran performance model of a Nissan Leaf to provide APEEM heat generation

• Collaborations
  – Collaborating closely with Visteon
  – Leveraging previous DOE research
    o Battery life model
    o Vehicle cost/performance model
    o Lumped parameter motor thermal model
  – Co-funding by three VTP tasks demonstrates cross-cutting
### Acknowledgements, Contacts, and Team Members

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- David Anderson
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  *Vehicle Technologies Program*
- EE Tech Team

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