Overview

Timeline
Project Start Date: FY11
Project End Date: FY14
Percent Complete: 35%

Budget
Total Project Funding: $ 750 K*
Funding Received in FY11: $ 375 K*
Funding for FY12: $ 375 K*

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)

Partners
• Interactions/collaborations
  – “Detroit 3” OEM
  – Visteon Corp.
  – Magna Steyr
• Project lead: NREL

* Shared funding between VTP programs: VSST, APEEM, ESS
Overview – Collaboration Between Vehicle Technology Programs

Hybrid Electric Systems
Dave Howell – Team Lead

Vehicle Systems
Lee Slezak
David Anderson

Energy Storage
Tien Duong
Brian Cunningham
Peter Faguy

Power Electronics & Electric Motors
Susan Rogers
Steven Boyd

Electric range and fuel consumption

Battery temperature and life

APEEM temperatures

Photo Credit: John Rugh, NREL
Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) have increased vehicle thermal management complexity

- Separate coolant loop for APEEM
- Thermal requirements for ESS

Additional thermal components result in higher costs

Multiple cooling loops lead to reduced range due to
- Increased weight
- Energy required to meet thermal requirements

Since thermal management crosses multiple groups at automobile manufacturers, cross-cutting system designs are challenging
Objective

• Collaborate with industry partners to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains

Targets

• Improve vehicle performance and reduced cost from the synergistic benefits of combining thermal management systems
• Reduce volume and weight
• Reduce APEEM coolant loop temperature (less than 105°C) without requiring a dedicated system
Approach – Overall

- Build a 1-D thermal model (using KULI software)
  - APEEM, energy storage, engine, transmission, and passenger compartment thermal management systems
  - Identify the synergistic benefits from combining the systems
  - Perform a detailed performance assessment with production-feasible component data
- Conduct bench tests to verify performance and identify viable hardware solutions
- Collaborate with automotive manufacturers and suppliers on a vehicle-level project
- Solve vehicle-level heat transfer problems, which will enable acceptance of vehicles with electric powertrains
Approach FY12 – Go/No-Go

Go/No-Go Decision Point: Based on the outcome of analysis of the thermal management system concepts, assess if building a benchtop system is justified or if further analysis is needed.

Challenges / Barriers:
- Integration of requirements and coordination of the diverse groups that have thermal management activities at the automotive OEMs and DOE
- Meeting the heat load requirements of the APEEM components, battery, engine, and passenger compartment with a thermal management system that is less costly and complex
Leverage existing DOE projects

- Vehicle cost/performance model
- Lumped parameter motor thermal model
- Battery life model
• **Thermal component and system information**
  – Visteon Corp. (Tier 1 HVAC component supplier)
  – Drawings
  – Thermal and flow component data
  – System data

• **Built components in KULI**
  – Used geometry, heat transfer, pressure drop, etc.
  – Verified component functioning as expected

• **Developed A/C, cabin thermal, and APEEM cooling loop models**
  – Connected components
  – Compared to test data
Improvements to Models

- Improved electric motor model
- Added inverter model
- Updated FASTSim model (heat generated for ESS and APEEM components)
- Improved A/C compressor control
- Adjusted heat exchanger air-side positions to more closely match current EVs
- Developed hot and cold design cases
ESS Cooling Loop Model  Battery Jacket Cooled by a Chiller  
(WEG to Refrigerant Heat Exchanger) or a Radiator

WEG = water-ethylene glycol
A/C System Model

Added Chiller Branch for ESS Cooling Loop
Baseline A/C, Cabin, ESS, and APEEM Cooling Loops
Liquid Circuits Combined into a Single Simulation

Heat Load, Cabin, and A/C

APEEM
Baseline A/C, Cabin, ESS, and APEEM Cooling Loops

Air Side – Low Temperature Radiators Behind Condenser
Baseline EV Thermal Management System

EV Test Case at Four Ambient Temperatures

- 24 kWh EV
- Environment
  - 43°C, 35°C, 30°C, 25°C
  - 25% relative humidity
- 0% recirc
- US06 drive cycle
- Cooldown simulation from a hot soak
- ESS – cooling loop with chiller & low temperature radiator
- Waste heat load from FASTSim simulations
Baseline System

At Higher Ambient Temperatures, Cabin is still Warm after 10 min.

Reasonable cooldown profiles

Photo Credit: Charlie King, NREL
Baseline System

Battery Cells Cool Quickly with the Chiller

Control temperature for cells (between 15°C and 35°C)*

Baseline System

Battery Cells Cool Quickly with the Chiller

With radiator, battery temperature increases

Control temperature for cells (between 15°C and 35°C)*

35°C Ambient – Cabin and ESS Cooling
Initially Less Than 50% of the A/C System Capacity is Going to the Cabin

![Graph showing heat transfer over time for Evaporator and Chiller]

- **Evaporator**
- **Chiller**
35°C Ambient – Cabin and ESS Temperatures

Tradeoff between Battery Cooling and Thermal Comfort

- Cabin Air
- Battery Cells

Cabin Air: Occupants likely uncomfortable

Battery Cells: Desired cell temperature quickly attained
Baseline System

Electric Motor Temperatures

Motor is at elevated temperature, but within the 130°C limit*

Baseline System

APEEM Fluid Temperatures – Critical to Inverter Maximum Temperature

Temperatures reasonable compared to design guideline (<70°C maximum inlet temperature desired)*

Baseline System

VTM Power including Compressor, Fans, Blowers, Pumps

- Hotter ambient temperatures require more power
- Power drops off when battery cell temperature reaches control level

Photo Credit: John Rugh, NREL
Baseline System
VTM Power including Compressor, Fans, Blowers, Pumps

- Hotter ambient temperatures require more power
- A/C evaporator antifreeze control limits A/C compressor power
- Power drops off when battery cell temperature reaches control level
- Less power required with radiator cooling of the battery

Photo Credit: John Rugh, NREL
Baseline EV Thermal Management System

EV at Davis Dam – Exploring the Hot Design Limits

- **Davis Dam drive cycle**
  - Acceleration, then constant 55 mph up a constant 5% grade
- **24 kWh EV**
- **Environment**
  - 43°C
  - 25% relative humidity
  - 850 W/m²
- **Cooldown simulation from a hot soak**
- **ESS – cooling loop with chiller**
- **Waste heat load from FASTSim simulations**
Baseline System - Davis Dam

In extreme conditions, APEEM components within thermal limits

Ambient Temperature = 43°C

- Motor - USO6
- Motor - Davis Dam
- APEEM Fluid - USO6
- APEEM Fluid - Davis Dam
Baseline EV Thermal Management System

EV at Bemidji – Exploring the Cold Design Limits

- Bemidji drive cycle
  - UDDS
- 24 kWh EV
- Environment
  - -18°C
  - 25% relative humidity
  - No solar load
- Warm-up simulation from a cold soak
- Waste heat load from FASTSim simulations

Photo Credit: Mike Simpson, NREL
Collaboration

• **Visteon Corp.**
  – Data
  – Engineering support

• **“Detroit 3” OEM – CRADA is in approval process**

• **Magna Steyr**
  – KULI software
  – Engineering support

• **VTP Tasks**
  – Vehicle Systems
  – Energy Storage
  – Advanced Power Electronics and Electric Motors
Future Work

• Using the KULI model, analyze concepts for combining cooling loops
  – Assess benefits
    o Maximum temperatures
    o Battery life
    o Cost
    o Range
  – Add new components
  – Improve model as required

• Based on the analysis results, select, build, and evaluate prototype systems in a lab bench test to demonstrate the benefits of an integrated thermal management system

• Lead a vehicle-level project to test and validate combined cooling loop strategies
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

• **Overall Approach**
  – Build a thermal 1-D model (using KULI software)
    o APEEM, energy storage, engine, transmission, and passenger compartment thermal management systems
    o Identify the synergistic benefits from combining the systems
  – Select the most promising combined thermal management system concepts and perform a detailed performance assessment and bench top tests
  – Solve vehicle-level heat transfer problems, which will enable acceptance of vehicles with electric powertrains
• **Technical Accomplishments**
  – Developed a modeling process to assess synergistic benefits of combining cooling loops
  – Improved A/C, cabin, APEEM cooling loop KULI models and built ESS cooling loop KULI models
  – Assembled the KULI models into a baseline simulation of a Nissan Leaf-sized EV
    – Produced reasonable component and fluid temperatures
  – Assessment of combined cooling loop concepts underway

• **Collaborations**
  – Collaborating closely with OEM, Visteon Corp. and Magna Steyr
  – Leveraging previous DOE research
    – Battery life model
    – Vehicle cost/performance model
    – Lumped parameter motor thermal model
  – Co-funding by three VTP tasks demonstrates cross-cutting
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