DOE/EE-0834

Vehicle and Systems Simulation and Testing

VEHICLE TECHNOLOGIES OFFICE

2012

annual progress report

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

III.I. Integrated Vehicle Thermal Management – Combining Fluid Loops on Electric Drive Vehicles

Principal Investigator: John P. Rugh
National Renewable Energy Laboratory
Center for Transportation Technologies and Systems
15013 Denver West Parkway. MS 1633
Golden, CO 80401
Phone: (303) 275-4413; Email: john.rugh@nrel.gov

DOE Program Manager: Lee Slezak and David Anderson
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

III.I.1. Abstract

Objectives

- Collaborate with industry partners to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains
- Improve vehicle range and reduce cost from combining thermal management systems
- Reduce volume and weight
- Reduce advanced power electronics and electric motor (APEEM) coolant loop temperature (less than 105°C) without requiring a dedicated system.

Approach

- Build a one-dimensional thermal model of EV thermal management systems (using KULI software)
- Identify the synergistic benefits from combining the systems
- Identify strategies for combining cooling loops
- Solve vehicle-level heat transfer problems, which will enable acceptance of vehicles with electric powertrains.

Major Accomplishments

- Improved the individual thermal models of the cabin air conditioner (A/C), cabin heater, APEEM, and energy storage system (ESS) fluid loops
- Completed a baseline EV thermal system model
- Added sophisticated controls to the A/C system and energy storage system (ESS) cooling loops
- Investigated combined cooling loop strategies
- Identified advantages of combining fluid loops.

Future Activities

- 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
- Collaborate with automotive manufacturers and suppliers on a vehicle-level project to test and validate combined cooling loop strategies.

III.I.2. Technical Discussion

Background

In the first year of the project (FY 2011), Visteon Corporation, a Tier 1 automotive HVAC component supplier, supplied detailed thermal component and system information. This included drawings, thermal and flow component data, and system performance data. NREL researchers built component models in KULI using the geometry, heat transfer, and pressure drop information. The individual component models were verified to function as expected. Next we developed A/C, cabin thermal, and APEEM cooling loop models by combining the individual component models into systems. These systems were then compared to test data. This formed the basis for the complete analysis of EV thermal systems and the assessment of combining cooling loop strategies that was performed in FY 2012.

Introduction

Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) have increased vehicle thermal management complexity (e.g. power electronics, motors, energy storage, and vehicle cabin). Multiple cooling loops may lead to reduced effectiveness of fuel-saving control strategies. The additional cooling loops increase weight, volume, aerodynamic drag, and fan/pump power, thus reducing electric range. This reduces customer acceptance of electric drive vehicles (EDVs) by increasing range anxiety, and presents a barrier for the penetration of EVs into the national vehicle fleet. Our goal is to improve vehicle performance (fuel use or EV range) and reduce cost by capturing the synergistic benefits of combining thermal management systems. The overall goal is to solve vehicle-level heat transfer problems, which will enable acceptance of vehicles with electric powertrains.

The objective of this project is to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains. Currently, EDVs typically have a separate cooling loop for the APEEM components. It would be beneficial to have an APEEM coolant loop with temperatures less than 105°C without requiring a dedicated system. Range would be increased in the winter with a combined thermal management system that maximizes the usage of waste heat from the APEEM and ESS components to minimize electrical resistive heating using battery energy. With increased focus on aerodynamics, minimizing the area and number of heat exchangers in the front end of the vehicle has the potential to reduce drag. Combining cooling loops enables the capability to thermally precondition the ESS and passenger compartment as well as the thermal management fluid loops.

Approach

The overall approach is to build a one-dimensional thermal model (using KULI software). This includes APEEM, energy storage, and passenger compartment thermal management systems. The model is used to identify the synergistic benefits from combining the systems. Once promising combined cooling loop strategies are identified, bench tests will be conducted to verify performance and identify viable hardware solutions. The National Renewable Energy Laboratory (NREL) will then collaborate with automotive manufacturers and suppliers on a vehicle-level project.

There are three main parts to the modeling process: the vehicle cost/performance model [1], the thermal model, and the battery life model. The vehicle cost/performance model simulates an EV over a drive cycle. An output of the model is the time-dependent heat generated in the APEEM and ESS components. These data are used as an input to the thermal model. KULI [2] was used to build a model of the thermal systems of an EV, including the passenger compartment, APEEM, and ESS. The thermal model calculates the temperatures of the components and the power required by the various cooling systems, including the fans, blowers, pumps, and A/C compressor. The power consumption profile is then used in the vehicle cost/performance model, and a new heat generation is calculated. If the heat generation is significantly different from the initial run, it is entered into the KULI thermal model again, and the cycle is repeated. An overview of the analysis process is shown in Figure 1.

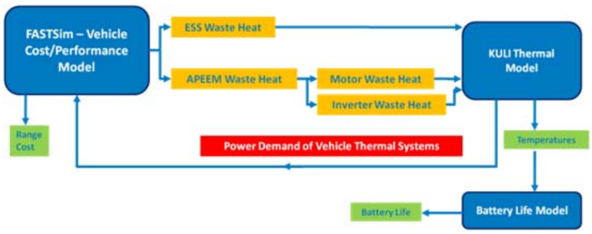


Figure 1. EV integrated vehicle thermal management analysis flow diagram.

The performance of the vehicle thermal management system was evaluated over three vehicle drive profiles, and each were created to represent different driving conditions for hot and cold environments. A summary of the drive profiles and ambient thermal conditions is summarized in Table 1.

Table 1. Drive profiles and environmental conditions

Condition	Drive Cycle Profile	Ambient Temperatures (°C)	Relative Humidity (%)
Hot soak with cooldown*	US06	43, 35, 30, 25	25
Hot soak with cooldown*	Davis Dam	43	25
Cold soak with warmup	Bemidji	-18	40

* In each of the hot soak tests, the vehicle cabin was assumed to be soaked to an initial temperature of 20°C above the ambient temperature.

The US06 drive profile [3] was selected as a standard test cycle with aggressive driving to evaluate the ability of the thermal management system to manage thermal loads over aggressive transient driving with multiple acceleration and braking events. The Davis Dam drive profile represents accelerating from a stop to 55 mph, and maintaining 55 mph up a constant 5% grade in a hot ambient environment. This profile provided a test of the thermal management system at extreme operating conditions. The Bemidji drive profile was selected to represent less aggressive driving conditions with a cold ambient temperature. The drive profile is based on the standard UDDS cycle [4]. A less aggressive drive cycle was selected to reduce the waste heat generated within the components and reduce self-heating. The intent was to provide an extreme cold weather test. A comparison of the motor heat load for each of the drive profiles is shown in Figure 2.

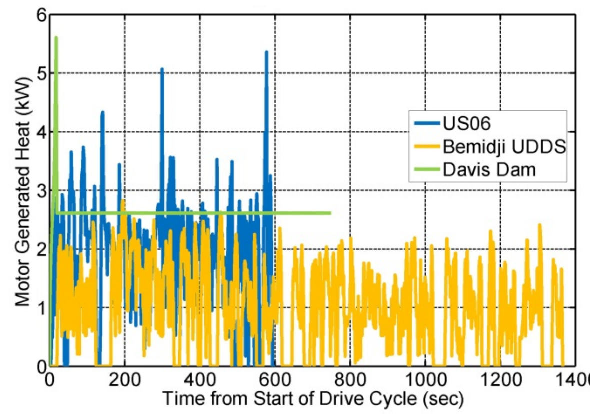


Figure 2. Comparison of drive cycles in terms of motor heat load.

The baseline electric vehicle thermal management system is illustrated in Figure 3 and Figure 4. Figure 3 provides a schematic of the thermal management system that enables heating and cooling of the vehicle passenger compartment or cabin, cooling for the electric drive system consisting of power electronics and an electric motor, and heating and cooling of the ESS or battery. Heating for the vehicle cabin is provided by an electric heater that heats a fluid loop and transfers heat to the cabin with a conventional heater core. Cooling for the vehicle cabin is provided by a conventional vehicle A/C system and an electric compressor. The power electronics and motor are cooled through a radiator that is located at the front of the vehicle behind the A/C condenser. The ESS or battery has multiple operating modes. Cooling is provided by two methods using either a chiller connected to the air conditioning system or a radiator at the front of the vehicle. The chiller is used for hot ambient conditions to provide chilled liquid coolant to the battery. Battery warmup can also be improved during cold conditions through the use of an electric heater to heat the liquid coolant circulating through the battery.

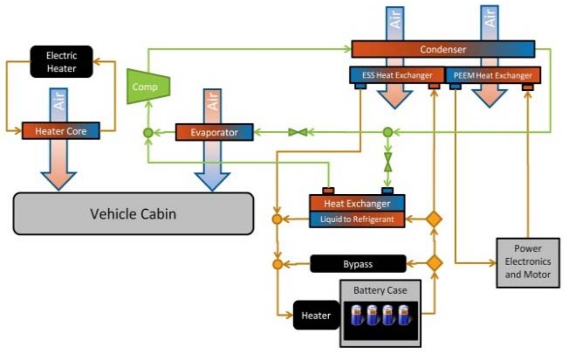


Figure 3. Baseline cooling system and primary components.

In addition to modeling the liquid and refrigerant loops of the vehicle thermal management system, the model also simulates the external airflow through the heat exchanger surfaces as shown in Figure 4. As outside air passes through upstream heat exchangers, the air is heated. For this reason, the performance of the down-stream heat exchangers are impacted by the heat rejection of the upstream heat exchangers. The model is capable of capturing this interaction between heat exchanger placement and airflow.

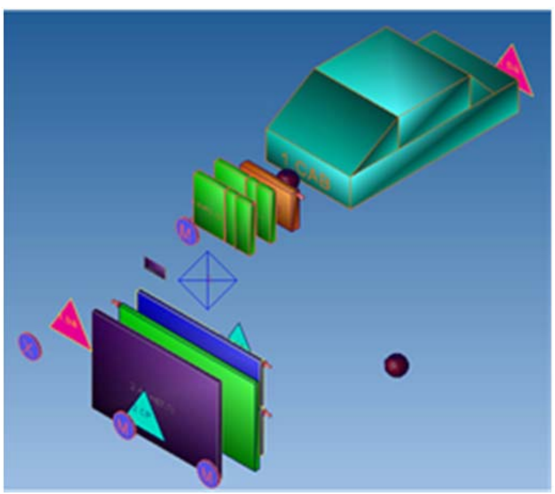


Figure 4. Air-side components of baseline thermal model.

During FY 2012, modeling work focused on improving the baseline vehicle thermal model and developing preliminary thermal models of alternative thermal management configurations. The improvements to the baseline vehicle thermal model were based on input from component specialists and comparisons to available thermal data. The baseline model improvements can be broken down into the following areas:

- System thermal loads
- System thermal model enhancements
- System controls.

The thermal loads for the battery, power electronics, and motor were revised based on the latest updates to the FASTSim vehicle model for a compact-sized electric car. In addition to updating the vehicle model, additional drive profiles were added to the vehicle model to evaluate the vehicle operation over more operating conditions (i.e. Davis Dam and Bemidji).

Improvements to the original baseline component and system thermal models include the addition of new system thermal models and the improvement of existing models based on reviews with component experts. The battery cooling loop was revised to enable multiple cooling modes for cooling and heating the battery. The ability to heat the battery coolant was added to improve battery warmup during the new cold environment tests. The updated battery thermal model thermal performance and properties were reviewed with the NREL ESS group. The power electronics and motor thermal systems were improved based on input from the NREL APEEM group. The initial motor thermal model parameters were updated, and a new inverter thermal model was created based on feedback from the Electrical and Electronics Technical Team (EETT) within US Drive. Also, thermal models for cabin heating components were created and integrated into a working cabin heating system to enable vehicle warmup tests from cold environmental temperatures. This feature was added based on previous feedback from the annual merit review. Finally, the air-side positions of the vehicle heat exchangers were adjusted to more closely match current EVs with the condenser in the front.

System controls were created for the baseline thermal model to control the battery and cabin to the desired target temperatures. The cabin temperature was controlled by regulating the airflow into the cabin, activating an electric heater, and controlling the refrigerant loop compressor speed. The battery temperature was controlled by controlling the battery coolant loop pump speed, and the valves controlling the flow through the multiple fluid loop branches. When the refrigerant loop was active to cool the vehicle cabin, the controller adjusted compressor rpm to prevent evaporator freezing. The thermal system control logic was based on a state controller with multiple operating states. The thermal management operating state was determined from the environment temperature, component temperatures, and the cooling system fluid temperatures. Each control state adjusted the control variable for the multiple actuators in the vehicle thermal system model. The control for each of the actuators was based on a proportional integrator (PI) antiwindup controller with the general logic shown in Figure 5.

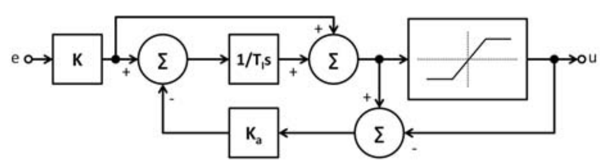


Figure 5. Antiwindup PI Controller [5.]

In addition to improving the baseline thermal model, new system thermal models were developed to investigate potential combined cooling loop strategies. The overall goal of combining cooling loops was to identify the potential use of waste heat from the electric drive components, and to evaluate concepts that could reduce the number of heat exchangers at the front of the vehicle. Figure 6 shows an illustration of the combined cooling system concept. The system enables the use of waste heat from the power electronics and electric motor for battery heating or cabin heating. The concept reduces front-end heat exchangers in the baseline system from three to one. The combined system uses a single chilled liquid loop for cabin and battery cooling at hot ambient temperatures that enables a compact refrigerant loop and heat pump operation.

The key features of the combined cooling system were evaluated to determine feasibility and effectiveness. The ability to utilize waste heat from the power electronics and electric motor was evaluated along with the ability to satisfy cooling demands during hot ambient conditions with a single front-end heat exchanger. Figure 7 shows the system schematic when operating in heating mode. The refrigerant cooling loop is off and cabin heating is provided with an electric heater, similar to the baseline thermal system. The primary difference is the connection between the electric drive cooling system, battery thermal management, and cabin. Waste heat from the electric drive system can be used to enhance the warmup of either the vehicle cabin or battery. To prevent component overheating, the radiator cooling branch can be activated as needed.

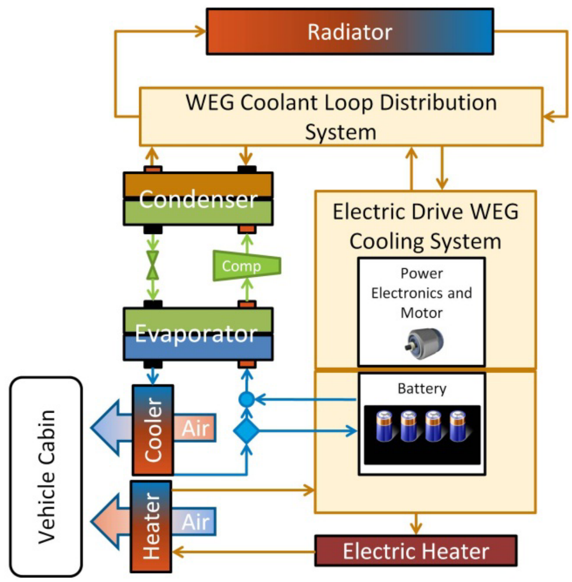


Figure 6. Combined system drawing.

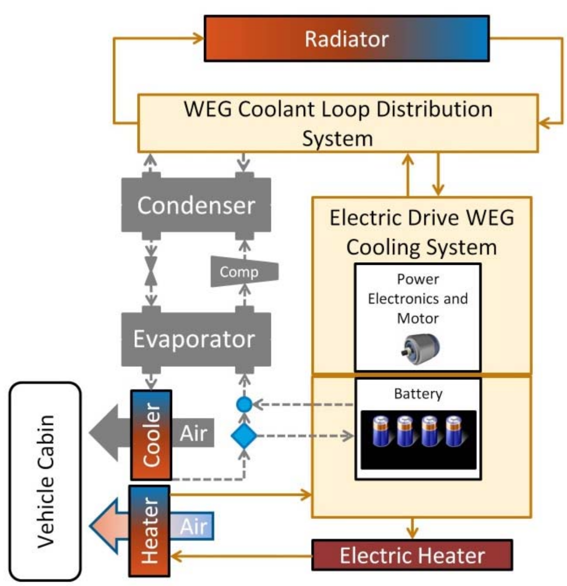


Figure 7. APEEM waste heat utilization for battery or cabin heating.

Figure 8 shows the schematic when operating in cooling mode for a hot ambient condition when a chiller is needed for cabin and battery cooling. The battery is cooled using a common chilled fluid that is also used for cabin cooling. For the illustrated condition, the battery is located downstream from the cabin cooling heat exchanger. For this reason, the battery coolant inlet temperature is affected by the cabin cooling airflow.

The intent of the analysis is to evaluate a worst-case condition where the cabin cooling airflow is set at the maximum value with a hot ambient temperature. The heat removed from the chilled liquid is transferred through another liquid loop that circulates through a radiator at the front of the vehicle. In addition to rejecting heat from the chilled liquid system for the air conditioning and battery, the radiator also rejects heat from the power electronics and electric motor.

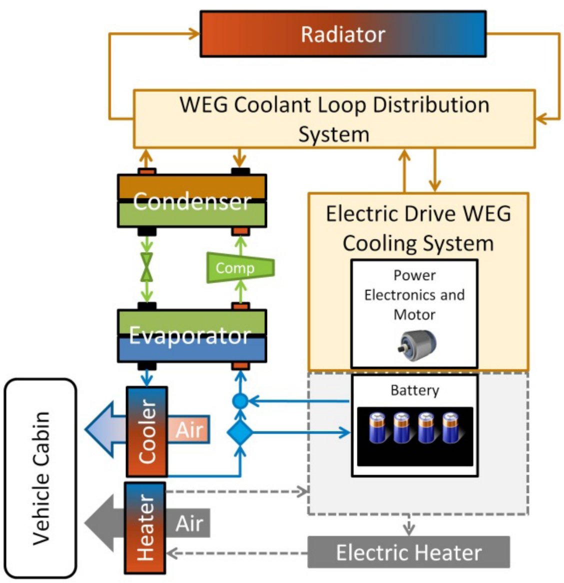
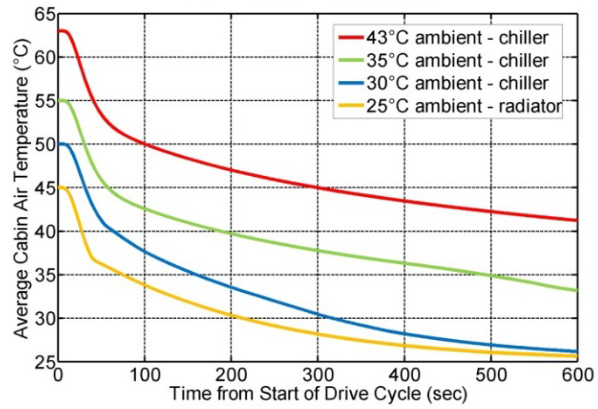


Figure 8. Combined radiator system and cabin/battery chiller.

Results

The performance of the baseline thermal management system is shown in Figures 9-12 over the US06 aggressive transient drive cycle at multiple ambient temperatures. The initial soak temperature of the vehicle cabin is assumed to be 20°C above ambient, and the initial soak temperature of the battery was assumed to be 1.6°C above ambient. The cabin target temperature was set to 25°C, and the battery cell target temperature was also set to 25°C.

The cooldown curves for the cabin in Figure 9 show reasonable cooldown profiles. The cooldown curves for the battery cell temperature are shown in Figure 10. The reason for the increasing battery cell temperature for the 25°C ambient test case is because the system controls were adjusted to force cooling through the radiator in the moderate environment.



.Figure 9. Baseline cabin air temperature over the US06 drive profile.

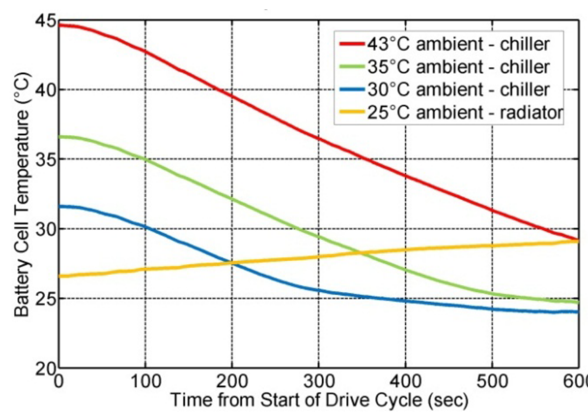


Figure 10. Baseline battery cell temperature over the US06 drive profile.

The ability to cool the battery through the radiator and not the chiller is reflected in the reduced power needed for the thermal management system in Figure 11. The coolant inlet temperature to the APEEM system is shown in Figure 12. The coolant temperature is below the 70°C maximum inlet temperature limit [6]. Figure 12 also shows the interactions between the air-side heat exchanger placement and the coolant loops. For the 30°C ambient case, the cabin and battery approach the target temperature and the total vehicle thermal management power drops. The reduced cooling demand on the condenser reduces the outlet air temperature of the condenser and reduces the inlet air temperature to the APEEM radiator.

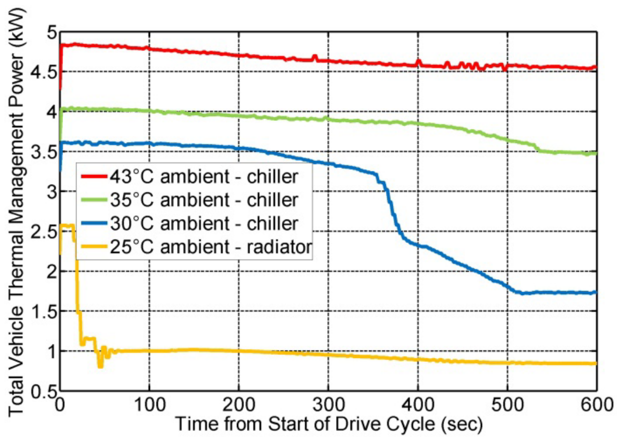


Figure 11. Baseline vehicle thermal management power over the US06 drive profile.

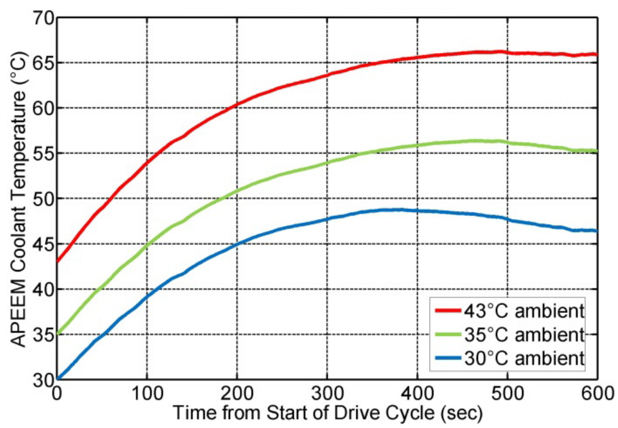


Figure 12. Baseline APEEM coolant inlet temperature over the US06 drive profile.

The baseline heating performance over the Bemidji test profile is shown in Figures 13-15. The baseline heating performance uses 7 kW for cabin heating and 1 kW to supplement the battery warmup. The baseline results are compared against two different combined cooling loop strategies using the APEEM waste heat (Figure 7). The first scenario links the APEEM cooling system with the cabin heater. The cabin heater power is reduced to 5.8 kW and the waste heat from the APEEM components is used to maintain equivalent cabin heating performance as seen in Figure 13. While meeting the same cooling performance, the coolant temperature to the APEEM components remains below the upper temperature limit of 70°C as seen in Figure 14. The second scenario links the APEEM cooling system with the ESS thermal management loop. The waste heat from the APEEM system is used to improve the warmup of the battery, and the 1 kW battery heater is off (Figure 15). The total vehicle thermal management power was reduced 1 to 1.2 kW with these configurations.

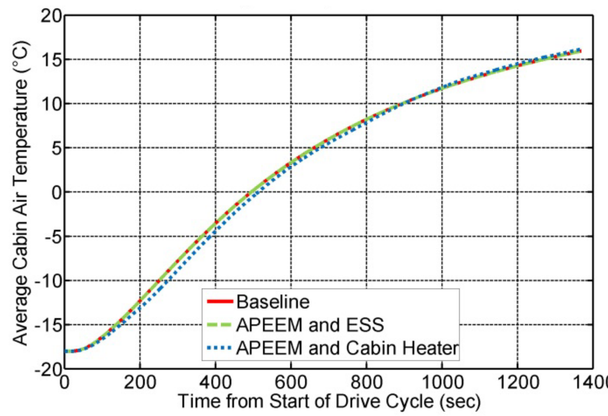
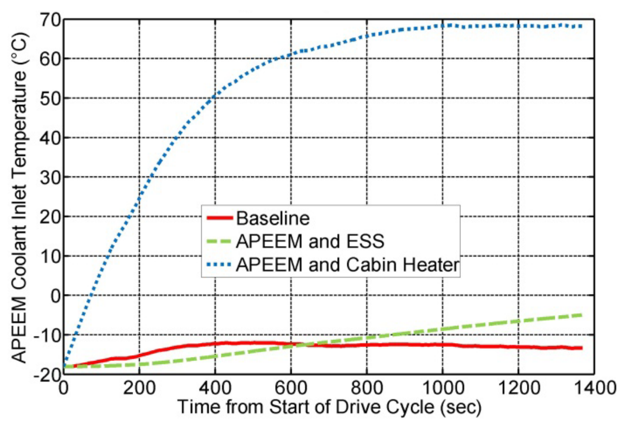
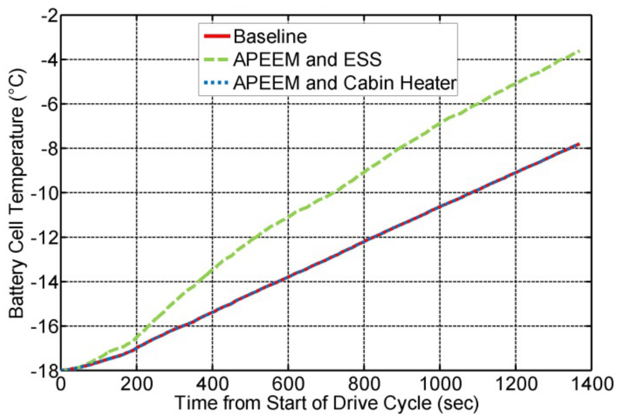


Figure 13. Comparison of cabin air temperature for baseline and alternative heating configurations for Bemidji -18°C condition.



.Figure 14. Comparison of APEEM coolant temperature for baseline and alternative heating configurations for Bemidji -18°C condition.



. Figure 15. Comparison of battery cell temperature for baseline and alternative heating configurations for Bemidji -18°C condition.

Besides the alternative warmup configurations, the ability to reduce the front-end heat exchangers from three to one (as shown in Figure 8) was evaluated. In this configuration, the condenser, APEEM radiator, and ESS radiator are combined into a single low-temperature radiator. The air-to-refrigerant condenser and evaporator are replaced with a liquid-to-refrigerant condenser and evaporator. The results of the combined system are compared with the baseline system in Figures 16-18. The single radiator configuration uses a radiator that is 0.71 m tall and 0.51 m wide with a maximum airflow per frontal area of 3.87 kg/(s-m^2). Both the size and airflow are within the range of typical automotive radiators.

Figure 16 compares the cabin cooldown performance and shows the combined system has slightly reduced cabin air cooling performance. This reduced cooling performance is typical for a secondary loop system. The reduced performance in cooling the battery (Figure 17) is because of the increased emphasis on cabin cooling in the combined cooling system. Both the cabin and battery are cooled with the same secondary loop chiller, although the battery is placed downstream of the cabin cooling heat exchanger. The impact on the battery could be mitigated by adjusting the cabin cooling airflow.

Figure 18 compares the coolant temperature for the APEEM system. The combined cooling configuration provides a lower temperature coolant temperature relative to the baseline system, and eliminates the dedicated liquid loop and heat exchanger for the APEEM system.

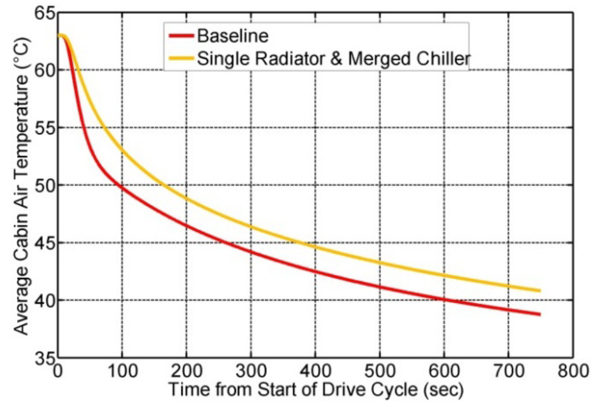


Figure 16. Comparison of cabin cooldown performance of baseline and combined configuration for Davis Dam 43°C condition.

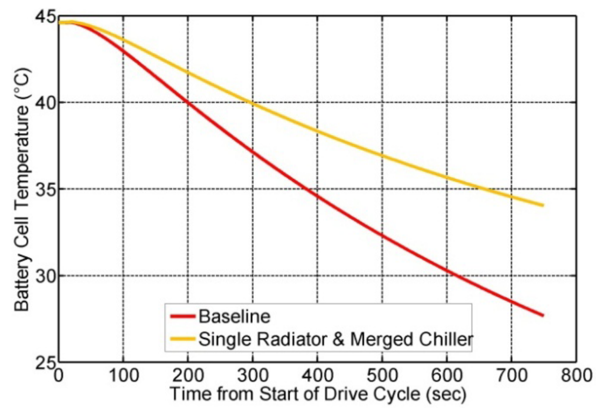


Figure 17. Comparison of battery cell temperature of baseline and combined configuration for Davis Dam 43°C condition.

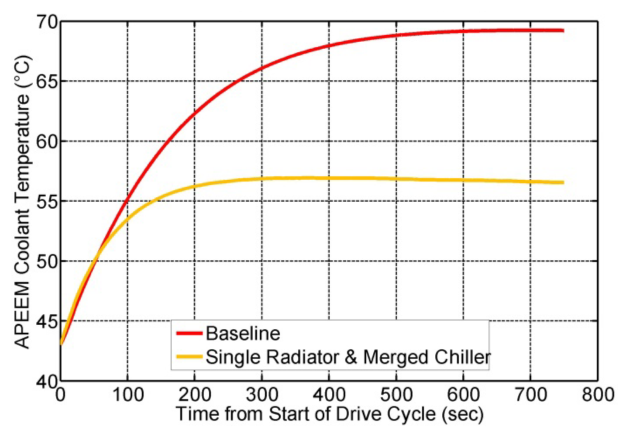


Figure 18. Comparison of APEEM coolant temperature of baseline and combined configurations for Davis Dam 43°C condition.

Conclusions

NREL researchers developed a modeling process to assess synergistic benefits of combining cooling loops. A KULI thermal model of a compact-sized EV was built, which produced reasonable component and fluid temperatures. This model was then used to assess combined cooling loop strategies. By using the waste heat from APEEM components, the total vehicle thermal management power was reduced. Replacing the air-to-refrigerant heat exchangers with refrigerant-to-liquid heat exchangers resulted in slightly reduced cabin air and battery cooldown performance. By adjusting component sizes and flowrates, it is likely the baseline cooldown performance could be matched, and the benefits of a secondary loop and perhaps heat pump systems realized.

References

1. "NREL: Vehicle Systems Analysis - Future Automotive Systems Technology Simulator." [Online]. Available: nrel.gov/vehiclesandfuels/vsa/fastsim.html. [Accessed: 01-Oct-2012].
2. "Kuli: Overview." [Online]. Available: kuli.ecs.steyr.com/. [Accessed: 01-Oct-2012].
3. U.S. EPA, "EPA US06 or Supplemental Federal Test Procedure (SFTP) | Emission Standards Reference Guide | US EPA." [Online]. Available: epa.gov/otaq/standards/light-duty/sc06-sftp.htm. [Accessed: 01-Oct-2012].
4. U.S. EPA, "EPA Urban Dynamometer Driving Schedule (UDDS) | Emission Standards Reference Guide | US EPA." [Online]. Available: epa.gov/otaq/standards/light-duty/udds.htm. [Accessed: 01-Oct-2012].
5. G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*. Addison-Wesley, 1994.
6. "Electrical and Electronics Technical Team Roadmap." [Online]. Available: eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_12-7-10.pdf. [Accessed: 11-Oct-2011].

Acknowledgements

- Susan Rogers, Steven Boyd, DOE VTP
- Kevin Bennion, Kandler Smith, Aaron Brooker, Jana Jeffers, NREL
- John Meyer, Visteon Corporation
- Albert Tuertscher, Magna Powertrain-Engineering Center Steyr