

Combined Fluid Loop Thermal Management for Electric Drive Vehicle Range Improvement

Daniel Leighton
National Renewable Energy Laboratory

ABSTRACT

Electric drive vehicles (EDVs) have complex thermal management requirements not present in conventional vehicles. In addition to cabin conditioning, the energy storage system (ESS) and power electronics and electric motor (PEEM) subsystems also require thermal management. Many current-generation EDVs utilize separate cooling systems, adding both weight and volume, and lack abundant waste heat from an engine for cabin heating. Some use battery energy to heat the cabin via electrical resistance heating, which can result in vehicle range reductions of 50% under cold ambient conditions. These thermal challenges present an opportunity for integrated vehicle thermal management technologies that reduce weight and volume and increase cabin heating efficiency.

Bench testing was conducted to evaluate a combined fluid loop technology that unifies the cabin air-conditioning and heating, ESS thermal management, and PEEM cooling into a single liquid coolant-based system. This system has separate hot and cold fluid streams that are directed to the thermal components as required. The advantages include PEEM waste heat recovery to supplement cabin heating and heat pump operation without refrigerant cycle reversal. A bench test apparatus was constructed to apply transient drive cycle loads to the thermal system and measure the performance under ambient temperatures from -12°C to 43°C . The system proved capable of meeting component thermal requirements at all tested conditions. Furthermore, the system demonstrated a 9% range increase on a nationally weighted basis that accounts for vehicle usage and ambient temperature. The range improvement is expected to be greater for an optimized in-vehicle system.

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INTRODUCTION

Relative to traditional internal combustion engine vehicles, electric-drive vehicles (EDVs) have increased vehicle thermal management complexity through the addition of a battery pack, also known as the energy storage system (ESS), as well as power electronics and electric motor (PEEM) components. These drivetrain subsystems have specific thermal requirements that have necessitated a separate thermal loop for each subsystem. The ESS must be cooled during hot ambient conditions to prevent degradation of battery cell life and must be heated during cold ambient conditions to enable adequate discharge power. The typical range of temperature control for the ESS battery cells is 15°C to 35°C [1]. The PEEM systems must be cooled so that they remain below their maximum operating temperature limits to prevent thermal damage or failure. The typical thermal limits for the PE and EM components are around 150°C [2, 3].

Separate cooling loops typically entail additional heat exchangers at the front end of the vehicle, water/ethylene glycol (WEG) coolant, piping, and WEG pumps. The disadvantage of multiple cooling loops is that they increase vehicle weight, aerodynamic drag, and fan/pump power, thus reducing EDV range. Due to the lack of abundant engine waste heat that is typically available in traditional vehicles, EDVs also suffer from significant range loss when heating the cabin in cold

weather conditions. Cold-weather range loss can be as high as 50% [4], which reduces customer acceptance of EDVs by increasing range anxiety, and presents a barrier for the penetration of EDVs into the national vehicle fleet. The goal of the combined fluid loop (CFL) technology is to improve EDV range and reduce thermal system weight and volume by capturing the synergistic benefits of unifying the thermal management systems.

The CFL technology being investigated unifies the cabin, ESS, and PEEM thermal management into a single coolant-based system with separate hot and cold fluid streams that are directed to the thermal components as required. The unified system has a single heat exchanger at the front end of the vehicle that either rejects or absorbs heat based on the CFL system's operating mode. The design of the system piping allows the coolant to be directed based on operating requirements, including actively heating or cooling the ESS, using the high-temperature coolant stream to cool the PEEM, and recovering the waste heat from the PEEM to supplement cabin heating. The CFL system also enables hot or cold coolant to be directed to the passenger cabin, which means that the system can act as either an air-conditioner or heat pump without reversing the refrigerant cycle. This is advantageous because refrigerant cycle reversal induces refrigerant charge and oil migration issues, as well as

requiring the heat exchangers to act as both condensers and evaporators depending on the operating mode. This dual usage of the heat exchanger makes heat exchanger design more difficult because performance trade-offs must be made so that the heat exchangers perform adequately in both operating configurations rather than optimizing each for a single application.

It is expected that the CFL system will increase cold-weather EDV range by minimizing electrical resistance heating of the cabin through recovery of PEEM waste heat and heat pump operation. Minimizing the area and number of heat exchangers at the front end of the vehicle has the potential to reduce the aerodynamic drag of the vehicle. An additional benefit of combining fluid loops is that the ESS, passenger compartment, and thermal management fluid loops can be preconditioned when the vehicle is connected to grid power.

APPROACH

Feasibility Study

Using component bench data, National Renewable Energy Laboratory (NREL) researchers conducted an initial feasibility study to predict CFL thermal performance through software simulation. The key results of this study were that the ESS and PEEM thermal demands could be met using a combined approach without significant impact on cabin conditioning [5]. This is an important finding because CFL technology must be capable of maintaining the PEEM component temperatures below the required limits using the hot coolant circuit instead of the cold coolant circuit, which would have a large negative impact on cabin cooling capacity. After determining feasibility through simulation, an experimental bench test system was constructed using available prototype components to validate the simulation findings and measure thermal system performance for cooling and heating conditions. Although sufficient for bench testing, it is expected that the prototype components could be further optimized for improved system capacity and efficiency.

Bench Test Apparatus

To perform the experimental study, a bench test apparatus capable of evaluating the steady-state and transient performance of EDV thermal systems was constructed. The purpose of the test apparatus is to measure the impact of the CFL technology on EDV range. The test apparatus is a hardware-in-the-loop system that imposes actual thermal loads on the experimental system and measures the resulting energy consumption and thermal performance. To impose realistic EDV loads on the thermal system, the test bench incorporates a vehicle powertrain model, thermal and efficiency PEEM and ESS models, and a thermal cabin model. The model-based portions of the bench test apparatus are adapted into a control and data acquisition LabVIEW program for continuous feedback based on thermal system performance. The vehicle powertrain model is a LabVIEW adaptation of NREL's power-based FASTSim model [6], the PEEM and ESS models are based on the previous NREL CFL simulation work [5], and the cabin model is from prior work by Gado [7]. The PEEM, ESS, and cabin models are all lumped capacitance physics-based models. Some of the basic parameters of the models are given in Table 1.

Table 1. Selection of basic model inputs

Vehicle type	Mid-sized battery electric vehicle
Battery capacity	24 kWh
Usable state of charge range	90%
Maximum powertrain power	80 kW
ESS mass (including housing)	348 kg

The physical bench test apparatus consists of two separate air ducts, a cabin air simulator, and an outdoor air simulator, as shown schematically in Figure 1. The cabin air simulator recreates the conditions seen inside of the heating, ventilation, and air-conditioning (HVAC) module in the instrument panel of a vehicle, and therefore houses the experimental system's heater core and cooler core heat exchangers. It can achieve air flow rates up to 425 m³/hr. and can simulate temperatures from -30°C to 63°C. The outdoor air simulator recreates the conditions seen by the heat exchangers at the front end of the vehicle, and therefore houses the front end heat exchanger of the experimental system. It is capable of air flow rates up to 3,400 m³/hr and can simulate temperatures from -30°C to 43°C. The airflow rate is continuously scaled based on the simulated vehicle speed to capture the effect of vehicle ram air on heat exchanger performance. To simulate a given ambient temperature condition, the test apparatus draws in fresh air from the laboratory and heats it to the control temperature. The bench test apparatus is not capable of actively cooling the intake airstream and therefore must always be operated in an environment that is at a lower temperature than the simulated ambient temperature.

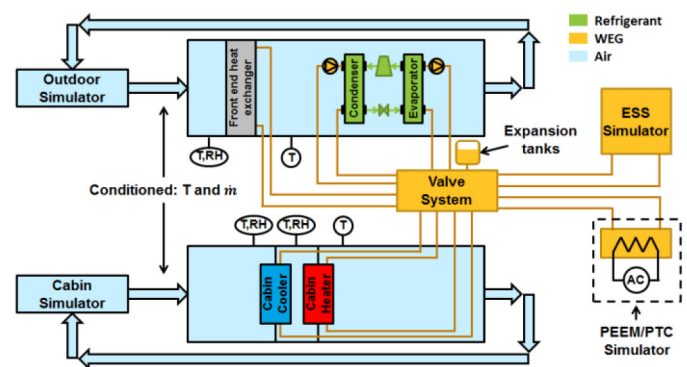


Figure 1. Basic schematic of CFL bench test apparatus

The bench test apparatus has two electrical resistance coolant heaters, one to simulate the heat from the vehicle PEEM and supplemental heat from the positive temperature coefficient (PTC) electrical resistance heater; and the other to simulate the heat from the hot-soaked ESS. The ESS simulator also has a coolant-to-air heat exchanger that can reject heat to the ambient laboratory air when simulating the thermal load of a cold-soaked ESS. The coolant outlet conditions from the PEEM and ESS components were predicted with the software models for a virtual vehicle and imposed on the actual experimental system with the coolant heaters. In the model, the full coolant mass flow rate passes through the PE before subsequently passing through the EM; however, this is imposed on the experimental system as a single coolant load. A picture of the assembled bench test apparatus is shown in Figure 2.



Figure 2. CFL bench test apparatus. Photo by Daniel Leighton, NREL.

Experimental CFL System

The experimental CFL system was constructed with six heat exchangers and a thermostatic expansion valve (TEV) provided by Delphi. The heat exchangers included a production radiator as the front-end heat exchanger, a production heater core, a prototype cooler core that was a coolant-to-air heat exchanger used to cool the cabin, a prototype plate-type evaporator, a prototype plate-type condenser, and a prototype plate-type sub-cooler. To complete the system a prototype electric automotive compressor was provided by Halla Visteon Climate Control. The electric compressor was powered with a high-voltage direct current (DC) power supply that simulated the power provided by an EDV traction battery pack. The compressor was a variable speed scroll-type, and the refrigerant used was R-134a. The refrigerant system components are shown in Figure 3.

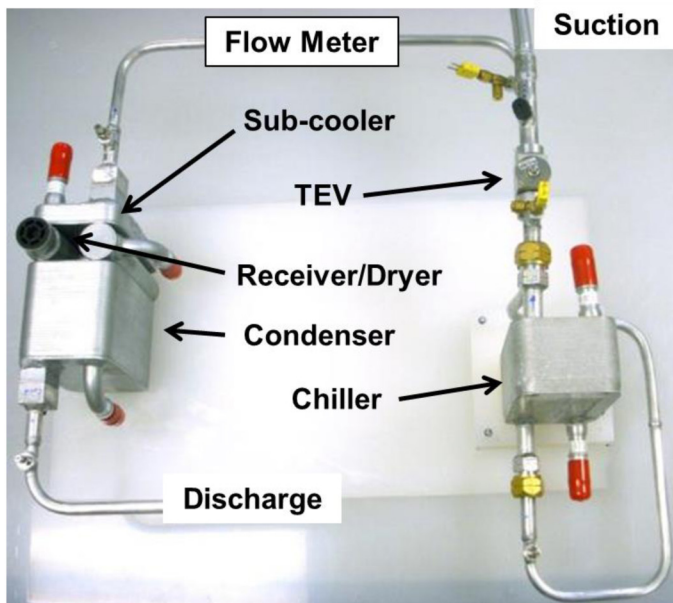


Figure 3. Delphi prototype refrigerant system components. Photo by Daniel Leighton, NREL.

The flow path of the refrigerant system was configured so that low-temperature, low-pressure vapor is compressed by the compressor to a high-temperature, high-pressure vapor. The refrigerant vapor then passes through the condenser, where it rejects heat and condenses to a high-pressure liquid before passing through the sub-cooler where further heat is rejected to achieve a sub-cooled liquid. The liquid is then expanded through a TEV to a low-pressure, low-temperature two-phase refrigerant that is passed through the evaporator to absorb heat and vaporize the remaining liquid. The low-temperature, low-pressure vapor then completes the circuit back to the compressor.

The experimental system used a 50%/50% mixture of water and ethylene glycol by weight as the coolant working fluid. The coolant circuit was formed with $\frac{3}{4}$ -in. inner diameter automotive radiator hose, with two automotive 12-V direct current electric coolant pumps that separately pumped the hot and cold fluid loops. The coolant pumps were operated at full speed for all test conditions and consumed approximately 60 watts each. The flow rate of the pumps depended on the pressure drop of the operating configuration and the coolant temperature for each given test condition. The volumetric flow rate of the pumps varied from approximately 8 L/min to 14 L/min. Laboratory-grade ball valves were used to control the circuit flow paths and to provide variable bypass capability of the heat exchangers. The experimental system piping and valving arrangement was designed to allow maximum flexibility for experimental bench testing, and is not representative of the configuration expected for in-vehicle applications. A schematic of the fully assembled experimental system is shown in Figure 4.

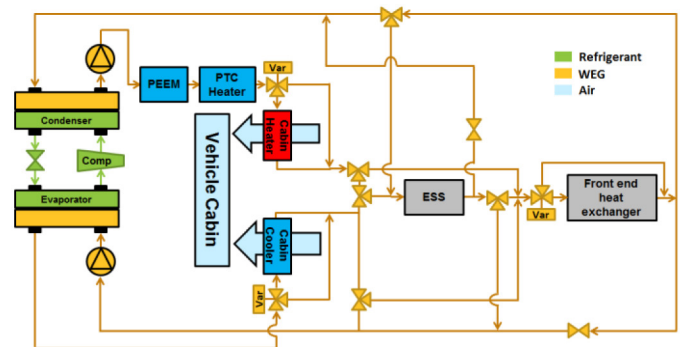


Figure 4. Schematic of full experimental CFL system

The experimental CFL system piping and valving design allows for a number of test configurations, including cooling of the PEEM and ESS systems when the compressor is deactivated by using the ambient air as a heat sink via the front-end heat exchanger. For the purposes of this study, there are two main configurations of interest that can be used to judge the energy efficiency of the system-cooling mode and heating mode. In the cooling mode configuration, the hot-side coolant sequentially absorbs heat from the condenser, absorbs heat from the PEEM systems, rejects heat through the front-end heat exchanger, and finally completes the hot circuit back to the condenser. On the cold-circuit side, the coolant sequentially rejects heat to the evaporator, absorbs heat from the cabin, absorbs heat from the ESS, and completes the cold circuit back to the evaporator. This configuration enables cabin air-conditioning (A/C),