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Design and Testing of a Thermal Storage System for Electric Vehicle Cabin Heating

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Abstract

Without the waste heat available from the engine of a conventional automobile, electric vehicles (EVs) must provide heat to the cabin for climate control using energy stored in the vehicle. In current EV designs, this energy is typically provided by the traction battery. In very cold climatic conditions, the power required to heat the EV cabin can be of a similar magnitude to that required for propulsion of the vehicle. As a result, the driving range of an EV can be reduced very significantly during winter months, which limits consumer acceptance of EVs and results in increased battery costs to achieve a minimum range while ensuring comfort to the EV driver. To minimize the range penalty associated with EV cabin heating, a novel climate control system that includes thermal energy storage has been designed for use in EVs and plug-in hybrid electric vehicles (PHEVs). The system uses the stored latent heat of an advanced phase change material (PCM) to provide cabin heating. The PCM is melted while the EV is connected to the electric grid for charging of the electric battery, and the stored energy is subsequently transferred to the cabin during driving. To minimize thermal losses when the EV is parked for extended periods, the PCM is encased in a high performance insulation system. The electrical PCM-Assisted Thermal Heating System (ePATHS) was designed to provide enough thermal energy to heat the EV's cabin for approximately 46 minutes, covering the entire daily commute of a typical driver in the U.S.

Introduction

Climate control poses a severe challenge for battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), extended range electric vehicles (EREVs), and even hybrid electric vehicles (HEVs). Cabin heating, depending on the size of the vehicle and the environmental conditions, typically requires 3.2 to 6.5 kW of battery power at the ambient of -10 °C to meet transient and steady state comfort requirements. For the larger sized electric vehicles of various genres (xEV), the required battery power may be even greater. The battery power used to generate the heating, either through a heat pump or direct resistive heating, leads to dramatic decrease in the driving range of xEVs. It is estimated that the range of a BEV with an electric cabin heater can be reduced by 20-40%, depending on the drive cycle. It is essential, therefore, to develop a reliable, cost-competitive, and more energy efficient occupant heating system that can help reduce traction battery load and increase the vehicle electrical driving range while still ensuring occupant comfort.

Thermal Energy Storage (TES) system can store sufficient thermal energy to heat the Electric Vehicle (EV) cabin for an extended period of time. Depending on the sizing of such a system, the TES can provide up to 100% of the thermal energy necessary to heat the cabin during typical commuter driving. For the present project, the goal is to design and develop a prototype TES system that is capable of extending the electric driving range by 20% and can be quickly commercialized.

The project scope includes the development of an advanced Phase Change Material (PCM) along with the component and system architecture for integration into a Grid Connected Electric Drive Vehicle (GCEDV) environment to provide heating comfort. The system performance will be demonstrated at both a bench and vehicle level.

The term "Phase Change Material" (PCM) is used to describe materials that use phase changes (e.g., melting) to absorb or release relatively large amount of latent heat at essentially constant temperature. In general, when the temperature becomes warmer than the freeze point, PCMs liquefy and absorb and store heat. Conversely, when the temperature decreases, the material will solidify and give off heat to warm a medium for productive use.

The basis of the ePATHS system is a PCM storage unit that can be thermally charged and discharged to provide hot coolant to the cabin heater. Innovative to this storage unit is that it incorporates a PCM that has up to 50% more latent heat during phase change in comparison with PCMs on the market today. Further, the storage unit is insulated with high performance insulation technology to minimize parasitic energy loss while the vehicle is parked.

Prior applications of PCM for thermal storage mainly focused on cooling storage [1, 2, 3], such as for food storage, bio-product preservation, or air conditioning. In the automotive industry, the spike in PCM storage interest is related to the Stop-Start system for gasoline driven vehicles to increase fuel economy. During a stop at traffic light with the engine shutoff, PCM stored cooling energy is used to provide passenger comfort. The more recent interest in using PCM to store high temperature heat energy is related to the development of the electrical and plug-in hybrid vehicles. For such vehicles, it is widely recognized that climate control significantly reduces driving range of the vehicle.

Heating Capacity and PCM Mass Specification

Gallup's annual Work and Education survey finds that American workers report spending an average of 46 minutes commuting to and from work in a typical day [4]. The 2001 National Household Travel Survey by the Department of Transportation found the average daily driving time is 55.1 minutes for people of driving age 15 and older [5], lending support to the Gallup commuting time survey. For a compact to mid-sized sedan, our analysis indicates that the cabin heating power requirement under the ambient temperature of -10ºC is about 6.5kW during initial transient and gradually decreases to 3.2kW during steady state driving [6]. Figure 1 shows a typical time history of cabin heating power use along with the time-integrated heat energy used (capacity, kWh). This energy use profile assumes a pre-conditioned cabin before leaving home, requiring only steady state heating power, and one transient heating use while leaving the work place parking lot. It can be seen that the total heating capacity requirement for a typical commuting day is about 2.7kWh.

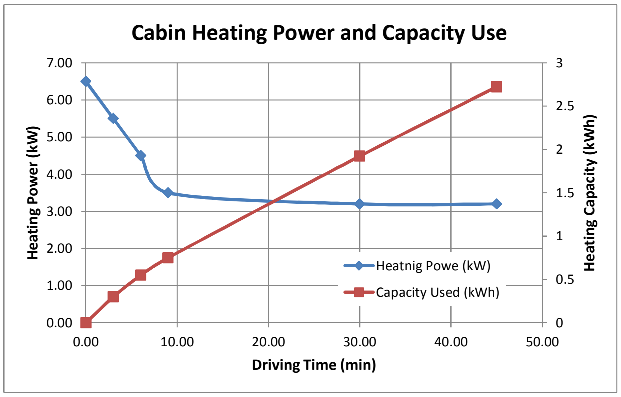

Figure 1. Cabin Heating Power and Capacity Use during Typical Trip

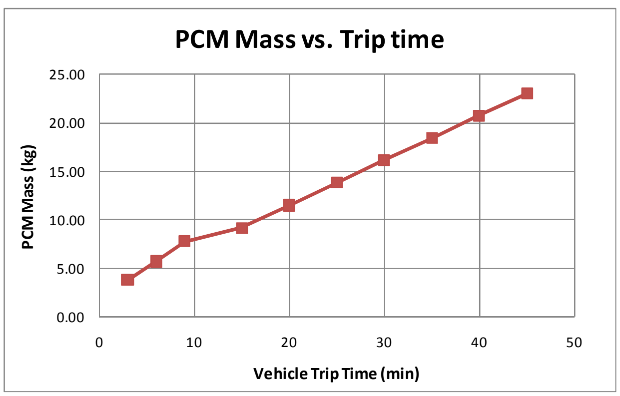

Figure 2. PCM Mass Specification as Function of Trip Time

The heating capacity requirement as a function of trip duration is translated into corresponding PCM mass requirement, as shown in Figure 2. The conversion is done assuming a PCM material with 350 joule/gram of latent heat and a sensible heat of 70 joule/gram. The operating temperature of the PCM is specified at 130ºC to make use of some sensible heat and still operate under the boiling temperature Ethylene Glycol Water (EGW) fluid mixture. As seen, for a commuting distance of 46 minutes, the required PCM mass is about 23kg, with the heat stored by the EGW and heat exchanger aluminum considered.

Based on the work of Duthie [4], the 2.7kWh heating capacity required for -10ºC ambient condition should meet greater than 90% of the heating needs in a year for the US.

System Architecture Development

The ePATHS system is designed to store heat using power from the electric grid and release heat to warm up vehicle cabin during driving in low temperature ambient conditions. The PCM heat exchanger is the core of the ePATHS system. It contains the PCM heat storage medium and internal heat transfer surfaces that allow heat to be added to the PCM material using electric heaters, or removed from the PCM material by circulating a low temperature coolant stream. A pump is used to provide the pressure head for coolant circulation. Figure 3 shows a system that also incorporates a configurable cabin heat exchanger nicknamed CapHX for deep heat recovery from the PCM heat exchanger.

The system of Figure 3 has been mechanized to achieve three modes of heating: PCM discharging, energy recovery, and PTC (Positive Temperature Coefficient heater) heating. An actuated configuration valve was prototyped to allow the CapHX function as a single-parallel heat exchanger attached to either the PCM loop or the PTC loop of the GCEDV, allowing PCM heating or PTC heating. The valve can also allow the CapHX to function as two separate heat exchangers, with the front half attached to the PCM loop to preheat the incoming cold air, and the rear half in the PTC loop to allow final heating of the airstream to fulfill the requirements of cabin heating. This is known as the energy recovery mode of operation.

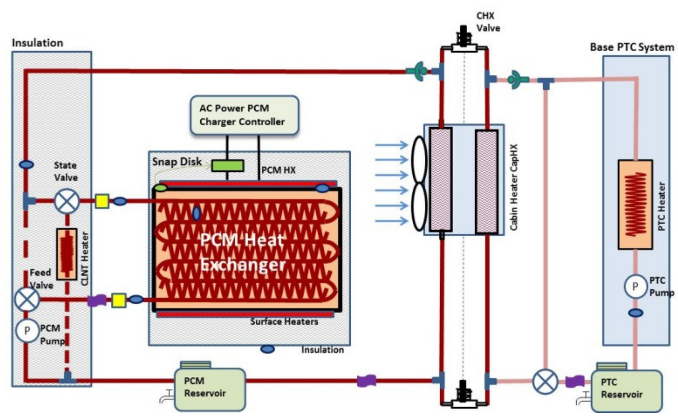

Figure 3. Mechanized ePATHS System Design

In the PCM charging mode, the operating state valve at the exit of the PCM heat exchanger is positioned to return coolant to the inlet of the pump. The coolant bypass valve at the inlet of the PCM heat exchanger is positioned to route all the coolant through the PCM heat exchanger. The pump may be operated from 0% to 100% duty cycle. When the pump operates to circulate coolant through the PCM heat exchanger in the figure-8 routing, it is expected that the PCM heat exchanger internal temperature distribution will be more uniform. When the pump is shut off, heat loss may be minimized during the charging process, but higher temperature non-uniformity is expected inside the PCM heat exchanger.

In the PCM discharging mode, the operating state valve is placed to route the coolant stream from the PCM heat exchanger left to the Tee joint, where a non-heated stream directly from the pump is mixed with the heated stream to regulate the coolant temperature going to the cabin heat exchanger CapHX. The proportion of the non-heated stream is determined by the coolant bypass valve downstream of the pump. Linear control or ON-OFF control may be implemented to control the cabin heater inlet coolant temperature using the inlet thermistor as feedback.

A third operating mode of the ePATHS system is the "energy recovery" mode. As the PCM heating mode continues to the point where even 100% coolant flow going through the PCM heat exchanger fails to provide the required air discharge temperature at the cabin heater outlet, the PCM heat exchanger is considered "exhausted", since it alone is unable to provide sufficient cabin heating. This normally happens when the coolant temperature exiting from the PCM heat exchanger becomes too low, such as less than 60 °C. However, at the ambient temperature of -10 °C or lower, there is still quite a bit of thermal energy left in the PCM heat exchanger that can be used to pre-heat the incoming cold air. The energy recovery mode allows the two halves of the CapHX to function separately in the PCM loop and the PTC loop, with the first half providing pre-heating of cold air using PCM heat and "final" heating using PTC power. It is expected that PCM energy extraction is possible in cabin air recirculation mode when the PCM temperature is above 20 °C. In the outside air mode of the climate control system, further extraction down to 0 °C may be possible.

Finally, PCM heat exchanger is unable to provide any heating energy by way of energy recovery extraction such that it is meaningless to continue circulate coolant in the PCM loop. At this point, the two halves of the CapHX are reconfigured as a single unit to the PTC heating loop to let the PTC heater provide all the heat needed for cabin heating.

Phase Change Material Development

Five families of PCM materials have been investigated to screen for potential candidates. The PCM development process starts with synthesizing a PCM compound in sufficient amount to characterize its melting temperature and latent heat of solidification. Upon synthesis, the sample is purified as required for characterization. Differential Scanning Calorimeter (DSC) is used to measure the melt temperature and the latent heat. If a candidate PCM meets the phase change temperature and latent heat targets, the sample is then thermally cycled to establish the temperature stability of the PCM.

Table 1. Properties of Candidate Phase Change Materials

PCM	Melting Point (°C)	Latent Heat (J/g)	Latent Heat Ratio over Water
DPT-12	-12	267	0.80
DPT14	14	298	0.89
DPT23	23	335	1.00
DPT38	38	320	0.96
DPT50	50	343	1.03
DPT68	68	342	1.02
DPT83	83	348	1.04
DPT86	86	321	0.96

As shown in Table 1, DPT83 and DPT68 demonstrate acceptable latent heat and melt temperature. In comparison with the PCMs currently used in the vehicle market that normally have a latent heat of approximately 200 J/g, both candidates meet the requirement to provide greater than 50% latent heat. DPT68 can be adequately applied to GCEDV vehicles with supplemental PTC heating for extremely cold ambient temperatures. Cold soak in a parking lot under very low ambient temperatures is likely to require high coolant temperature near 85 °C. DPT68 based thermal storage would have used up the high temperature sensible heat in the first commute trip to work, leaving the PCM material at 68 °C, which might be insufficient to meet the transient heating needs as the car leaves the parking lot. Low power supplemental heating with the PTC heater may be needed to ensure cabin comfort.

DPT83, on the other hand, has a phase change temperature of 83 °C, which practically meets the current GCEDV coolant temperature specification of 85 °C. Therefore, it should be able to provide heating under all ambient conditions equivalent to that provided by the PTC heater for as long as there is still energy left in the PCM thermal storage.

For PHEV, both PCM materials should meet the heating requirement. A slightly different engine restarting condition needs to be defined to accommodate the differences in melting temperature.

For both DPT83 and DPT68, it has been recognized that isolation from air and moisture is required for thermal stability. This imposes special requirements during shipping and during filling into the thermal storage system. Preliminary indications also show that DPT83 and DPT68 are materially compatible with aluminum. Additional compatibility studies are being carried out.

PCM Heat Exchanger Development

The PCM thermal storage heat exchanger is a key component of the ePATHS system. Figure 4 shows the design of the full sized PCM heat exchanger. The design includes 2 PCM filling ports, 18 internal PCM temperature measurement thermocouples for development, one PCM temperature thermistor, one heating surface temperature thermistor, several panels of resistive surface heaters, coolant tubes, PCM fins, tanks, and coolant inlet and outlet connectors. The heat exchanger core composed of coolant tubes, fins and headers, once brazed, is disposed in a prismatic shell container to provide storage space for PCM material between the shell and the fin-tube surfaces. On the coolant side, the heat exchanger has a two-pass design. The coolant stream enters from the inlet, traverses the first pass of the heat exchanger tubes, and then turns around in the return tank to flow through the second pass of the heat exchanger. The coolant exits the heat exchanger through the outlet connector. As the coolant flows through the PCM heat exchanger, it is heated up by extracting heat from the PCM material. Figure 5 shows the aluminum heat exchanger construction.

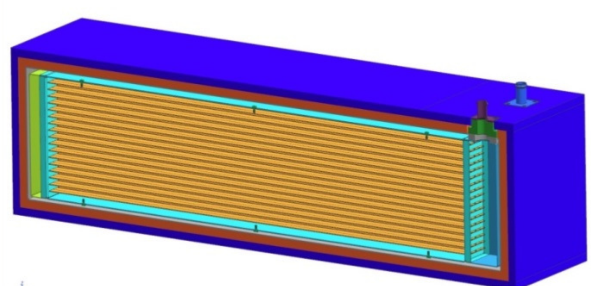

Figure 4. PCM Heat Exchanger Design

Six surface electric heaters of two different sizes provide the heating for the PCM material. These surface heaters are epoxied to the axial surfaces of the containing shell. The surface with the input and output couplers and the opposite surface have two smaller surface heaters each, while the adjacent surfaces to the aforementioned surfaces have one long surface heater each.

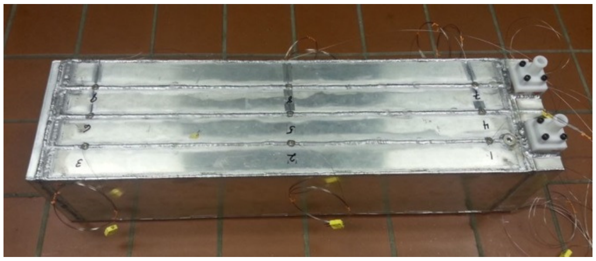

Figure 5. PCM Heat Exchanger without Insulation

The PCM heat exchanger requires an insulation system that can keep 90% of the stored heat and lose only 10% of it over an 8 hour period in the parking lot. Vacuum Insulated Panels (VIP) are used as the primary insulation technology. Individual VIP panels are prepared and assembled into a box containing the PCM heat exchanger.

For the full sized PCM heat exchanger, initial studies indicate that 21 kg of PCM material would be sufficient to provide the energy for 20% range extension. The reduction of PCM mass estimate from the initial specification mostly comes from the sensible heat provided by the entire PCM heat exchanger when charged to 120 °C. With the low temperature thermal energy recovery considered, the total thermal energy will be greater than the original target of 2.7 kWh. The surplus amount of energy may be used to trade off the total weight and volume of the PCM heat exchanger, currently specified at 33 kg and 31 liters.

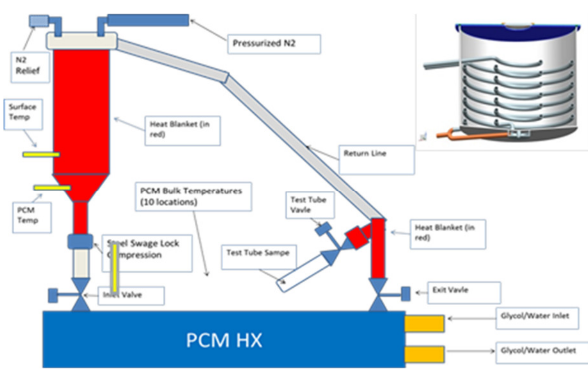

Figure 6 PCM Filling System

The PCM material for thermal storage is in a solid state under normal ambient temperatures. In order to fill the material into the PCM heat exchanger, it is necessary to preheat the PCM into a liquid for it to flow into the heat exchanger freely. Also, due to the tendency for DPT68 and DPT83 to react with air and moisture, isolation must be provided during the filling process. Figure 6 shows a custom designed filling system that accommodates both of the requirements. Nitrogen is used to pre-purge the PCM heat exchanger and provide isolation during filling. The PCM holding tank uses hot coolant to melt the PCM inside.

System Controls Development

An HVAC development controller is used to control ePATHS system operations. It is an automotive grade controller meeting validation requirements for automotive applications. The controller is equipped with a 7 inch color touch screen interface for displaying and inputting system data and control values. It can communicate with the vehicle CAN bus through a bridging module. A laptop PC may be used to directly communicate with the controller for calibration and data logging. Sufficient input and out channels, both digital and analog, are available to allow the ePATHS system to be controlled effectively.

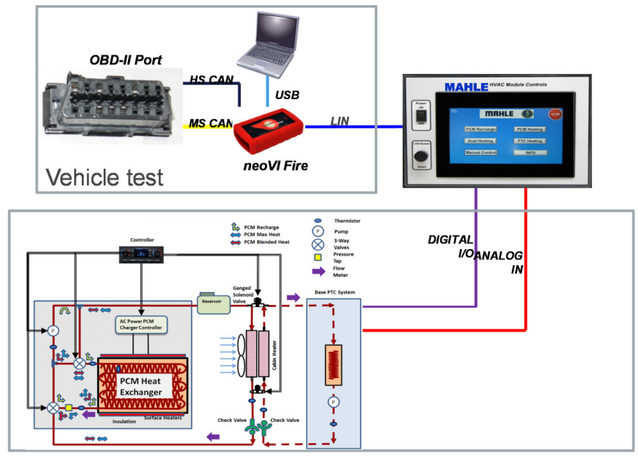

Figure 7. ePATHS System Control Design

As shown in Figure 7, the development controller is interfaced to the vehicle OBD-II port by using neoVI Fire as a bridging device. The controller communicates with neoVI Fire using LIN bus. The neoVI Fire unit communicates with the vehicle using CAN protocol. A message forwarding script is used inside the neoVI Fire unit to allow two-way communication.

On the ePATHS side, the development controller controls the valves, pumps, and the HVAC blower to accomplish various modes of operation, including PCM charging, PCM heating, PTC heating, and energy recovery (dual heating). As shown in Figure 8, these modes of operation can be selected using the touch screen display. There is an additional manual mode operation that allows direct control of any individual component in the system.

Figure 8. Operation Mode Control

Figure 9 shows the integrated charging system design that allows the vehicle traction battery and the ePATHS TES to be charged using the same EVSE (charger), power cable, and plug. A relay added to the vehicle switches the 220V or 120V power to charge either the vehicle traction battery or the PCM storage system. The HVAC controller intelligently manages the charging sequence. When charging the PCM thermal storage, proper pilot signal is provided to the EVSE to enable power flow.

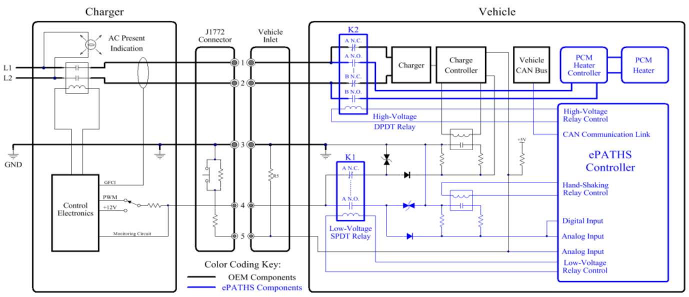

Figure 9. Integrated PCM and Traction Battery Charging System

The electric power to the surface heaters are controlled by a Solid State Relay (SCR) controller (Figure 10). The HVAC controller output a Pulse Width Modulation (PWM) signal to control the power flow. The electric power to the surface heaters can be varied from 0 to 3 kW, based on availability and need. The electric power is measured and communicated to the controller for status monitoring.

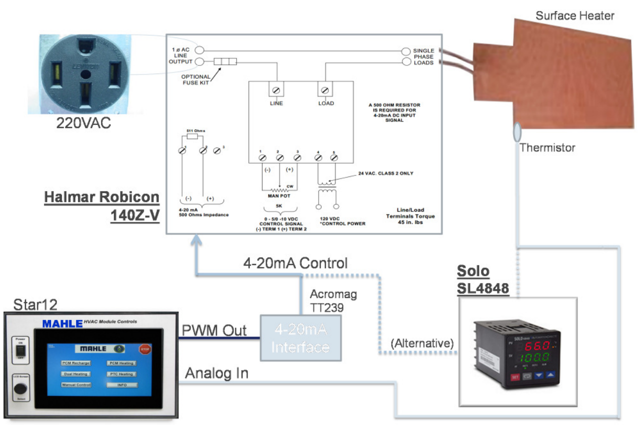

Figure 10. PCM Charging Surface Heater Power Control

Bench Build

The ePATHS system has been integrated on a bench (Figure 11) to support system functionality and performance testing. The test bench system uses a Ford Focus Electric HVAC module for air handling. The OEM heater in the module has been replaced with the CapHX to support energy recovery operation. The coolant loop with pumps and valves has been instrumented with thermocouples, flow meters, and pressure transducers, with the pressure transducers intended for both safety monitoring and for pressure drop measurement. The HVAC controller has been programmed with custom designed software to support various modes of testing. As part of the controller software, a State of Charge (SOC) calculation routine has been established with DPT101 and will be updated for DPT68. Initial debugging of the control software using a quarter-sized PCM heat exchanger filled with a surrogate PCM material DPT101 has been completed. A full sized PCM heat exchanger with DPT68 will be used for final bench testing.

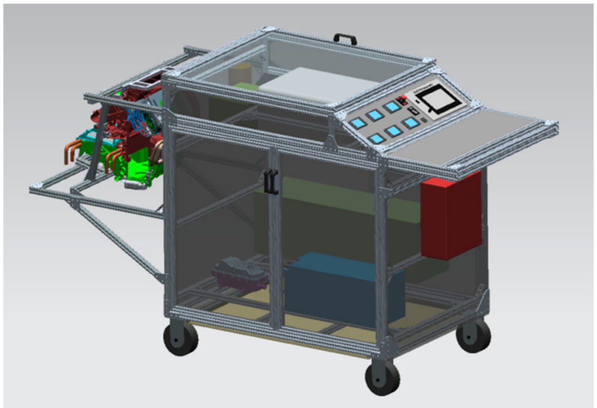

Figure 11. ePATHS System Test Bench

Initial Test Results and Analysis

PCM Heat Exchanger and Insulation System

Initial tests were performed on a quarter-size prototype PCM heat exchanger. As a build quality test for fin bonding, the quarter-size PCM heat exchanger was installed on a radiator test stand and dissipation tests for heat transfer performance (from coolant to air) were run. The coolant-to-air heat transfer performance was compared to predictions made by heat exchanger analysis software. Very good agreement with the prediction was achieved. Discrepancies are generally within 8% of predicted values, as shown in Figure 12. The discrepancy in heat transfer between testing and simulation may have resulted from differences between actual test conditions and those assumed in the analysis. Since the heat transfer analysis was only intended for initial brazing quality check and not used for heat exchanger design optimization, it was deemed a sufficient indicator of good brazing. Additional tests were run on the radiator test stand to confirm that the temperature variations across the core face area were acceptable. A maximum temperature spread of 2.2 ℃ was seen from the top of the core to the bottom of the core. On the coolant side, good coolant distribution was achieved which will allow the PCM material to melt and freeze uniformly across the entire core.

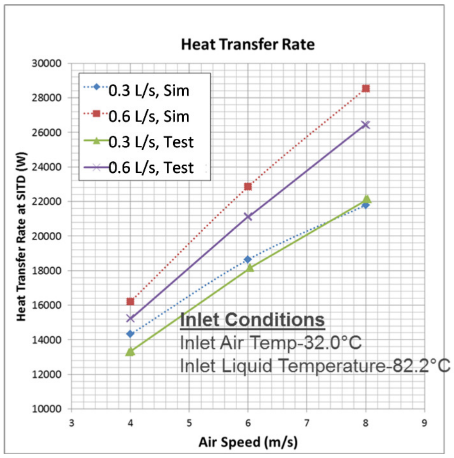

Figure 12. Heat Transfer (Predicted vs. Test)

Subsequent to the air-coolant quality test, the quarter-size PCM heat exchanger was tested with a PCM having latent heat of 175 J/g and a melting temperature of 101 ºC. Even though this PCM has significant lower latent heat than DPT68 and DPT83, the charging and discharging of the heat exchanger should still be indicative its ability to transfer heat. Figure 13 shows the PCM temperature profiles at various locations within the heat exchanger. It can be seen that the quarter-size PCM heat exchanger was charged after about 8 minutes with a 120 ºC coolant stream at 0.75 gallons/minute flowrate.

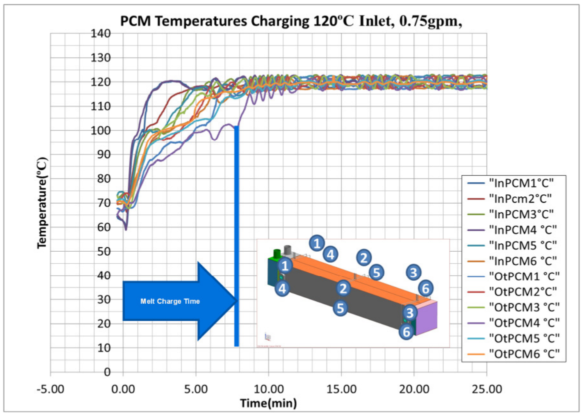

Figure 13. Charging Time and Temperature Profiles

The heat transfer rate during charging is shown in Figure 14. A maximum rate of 9 kW was achieved in the beginning of charging and the rate gradually decrease to zero as the PCM material became fully charged. Figure 14 also shows the total energy stored in the quarter-size PCM heat exchanger. At the end of charging, the total energy was 0.64 kWh.

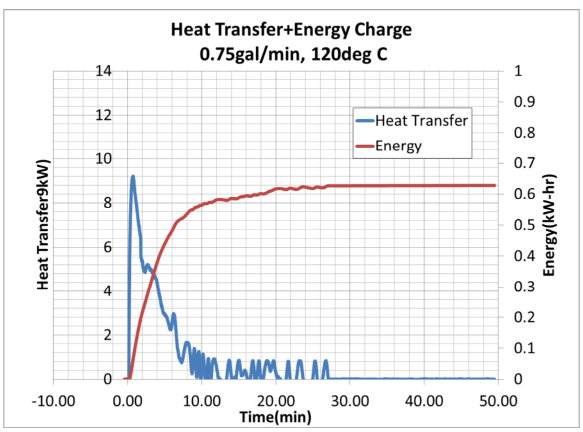

Figure 14. Heat Flux during Charging and Energy Storage in PCM Heat Exchanger

For insulation system development, a 10% scale PCM heat exchanger was filled with 345g of DPT101. The 10% scale PCM heat exchanger with aerogel was heated to 120 ºC to charge the PCM, then removed from the heating chamber, and immediately placed into the prototype VIP insulation jacket. The VIP and heat exchanger were then placed into a second chamber at -10 ºC to measure the amount of thermal energy loss. Figure 15 presents the temperature profile at various points of the insulated 10% scale PCM heat exchanger. The tests indicate that the prototyped VIP technology's loss rate is over 20% of the stored energy over a period of 8 hours. Analysis indicates that with improvement in VIP insulation construction, and with the smaller surface to volume ratio for the full sized PCM heat exchanger, the target insulation performance of 10% over 8 hours can be achieved.

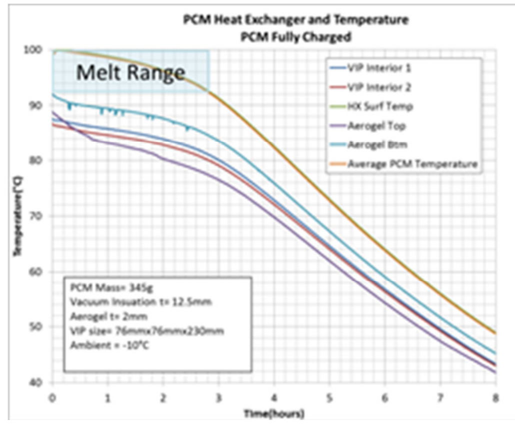

Figure 15. Freezing of PCM in VIP

Summary and Conclusions

The present paper reported on the progress made in the design and development of a PCM based thermal energy storage system to extend the electrical driving range of GCEDVs. In particular, five areas of development have shown significant progress:

1. System architecture has been defined to achieve PCM charging, discharging, and residual energy recovery.

2. PCM synthesis and characterization yielded two candidates, DPT-68 and DPT-83 that demonstrates excellent melting temperature and high latent heat for meet the requirement of the thermal storage system.

3. Several prototype PCM heat exchanger designs have been built for initial testing of VIP insulation capability and energy storage capability.

4. System controls hardware and software has been developed to coordinate the operations of the ePATHS system.

5. An integrated PCM and traction battery charging system has been designed and prototyped.

Development testing so far with the quarter-size (0.64 kWh) PCM heat exchanger shows that the objective of extending winter driving range by 20% using a 2.7 kWh thermal energy storage system is possible and within our current capability. With the CapHX functioning as a heat recovery device, it is likely that the original target of 20% range extension may be exceeded. For the final vehicle development, tradeoff may be made to improve overall mass and packaging volume, currently specified at 33 kg and 31 liters. Overall, it is believed that a thermal storage system can substantially extend the driving range without incurring as much of the cost penalty associated with enlarging the capacity of the traction battery.

References

1. Kowsky, C., Wolfe, E., Chowdhury, S., Ghosh, D. et al., "PCM Evaporator with Thermosiphon," SAE Technical Paper 2014-01-0634, 2014, doi:10.4271/2014-01-0634.
2. Aikawa, Y., Yamanaka, Y., Suzuki, T. and Kume, M., "Vehicle Air Conditioner With Cold Storage Unit", US Patent No. 6701731, Denso Corporation, March 9, 2004.
3. Bo, H., Gustafsson, M., Setterwall, F., "Paraffin Waxes And Their Binary Mixture As Phase Change Materials (PCMs) For Cool Storage In District Cooling System", IEA Annex 10, Phase Change Materials and Chemical Reactions for Thermal Energy Storage First Workshop, pp. 16-17, Adana, Turkey April 1998.
4. Carroll, Joseph, "Workers' Average Commute Round-Trip Is 46 Minutes in a Typical Day", GALLUP News Service, August 24, 2007.
5. Bureau of Transportation Statistics, US DOT, "Highlights of the 2001 National Household Travel Survey, Bureau of Transportation", NHTS 2001 Highlights Report, BTS03-05, Washington DC, 2003.
6. Kowsky, C., Wolfe, E., Leitzel, L. and Oddi, F., "Unitary HPAC System," SAE Int. J. Passeng. Cars - Mech.Syst. 5(2):2012, doi:10.4271/2012-01-1050.

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