Integration and Validation of a Thermal Energy Storage System for Electric Vehicle Cabin Heating

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Abstract

It is widely recognized in the automotive industry that, in very cold climatic conditions, the driving range of an Electric Vehicle (EV) can be reduced by 50% or more. In an effort to minimize the EV range penalty, a novel thermal energy storage system has been designed to provide cabin heating in EVs and Plug-in Hybrid Electric Vehicles (PHEVs) by using an advanced phase change material (PCM). This system is known as the Electrical PCM-based Thermal Heating System (ePATHS) [1, 2]. When the EV is connected to the electric grid to charge its traction battery, the ePATHS system is also "charged" with thermal energy. The stored heat is subsequently deployed for cabin comfort heating during driving, for example during commuting to and from work.

The ePATHS system, especially the PCM heat exchanger component, has gone through substantial redesign in order to meet functionality and commercialization requirements. The final system development for EV implementation has occurred on a mid-range EV and has been evaluated for its capability to extend the driving range. Both simulated driving in a climatic tunnel and actual road testing have been carried out. The ePATHS has demonstrated its ability to supply the entire cabin heating needs for a round trip commute totaling 46 minutes, including 8 hours of parking, at an ambient temperature of -10°C.

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 an ambient temperature of -10°C to meet transient and steady state comfort requirements. For larger sized electric vehicles of various genres (xEV), the required heating power may be even greater. The battery power used to generate the heat, either through a heat pump or direct resistive heating, leads to a dramatically depressed driving range for xEVs. It is estimated that the range of a BEV can be reduced 50% or more, depending on the drive cycle. Laboratory measurements have shown EV range reductions of 30-60% due to cabin heating in sub-freezing conditions [3, 4, 5, 6]. 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 maintain the vehicle electrical driving range without sacrificing occupant comfort.

The term "Phase Change Material" (PCM) is used to describe materials that use phase changes (typically melting and freezing) to absorb or release a relatively large amount of heat at essentially constant temperature. In general, when in contact with a heat source at a temperature warmer than the melting point, a PCM absorbs heat from the heat source and liquefies. Conversely, when in contact with a heat sink at a temperature lower than the freeze point, the PCM solidifies and gives off heat. While melting or freezing, the PCM temperature remains mostly at a constant temperature for a well behaved PCM material. This "latent" heat, as compared with single phase heat exchange that causes material temperature to change, is relatively large on a unit mass basis. The high heat capacity at a constant temperature is ideal for cabin conditioning. For cabin heating, the desired phase change temperature is around 85°C

The DOE funded ePATHS project aims to develop a light-weight, compact, and scalable Thermal Energy Storage System (TES) to meet a wide range of grid connected vehicles' heating needs. All the elements of an effective TES have been investigated, including PCM material, PCM-to-coolant heat exchanger, insulation materials and design, and thermal system architecture for interfacing with the HVAC air handling system. Wang et al [1] and LaClair et al [2] reported on the ePATHS research and development activities in the 2016 SAE World Congress. Extensive work has been done since then to improve on the PCM heat exchanger design and overall system architecture so as to improve functional performance and move closer toward commercialization. The present paper provides an update on the most recent development progress for the ePATHS thermal storage project, including a second generation (GEN-II) PCM heat exchanger design and vehicle system integration.

System Architecture and Components Development

System Architecture Improvement

The ePATHS system was designed to store heat using power from the electric grid and release the stored thermal energy to heat the vehicle cabin during driving in low temperature ambient conditions. The objective was to facilitate the range extension of BEVs and PHEVs. 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 using hot coolant, or removed from the PCM by circulating a lower temperature coolant stream. A pump is used to provide the pressure head for coolant circulation, and several valves are used to configure the coolant flow system for charging or discharging of the heat from the PCM material. Figure 1 shows the system design that also incorporates a "configurable" air heater (with hot coolant) in the HVAC module with two "slabs" for deep heat extraction from the PCM thermal storage.

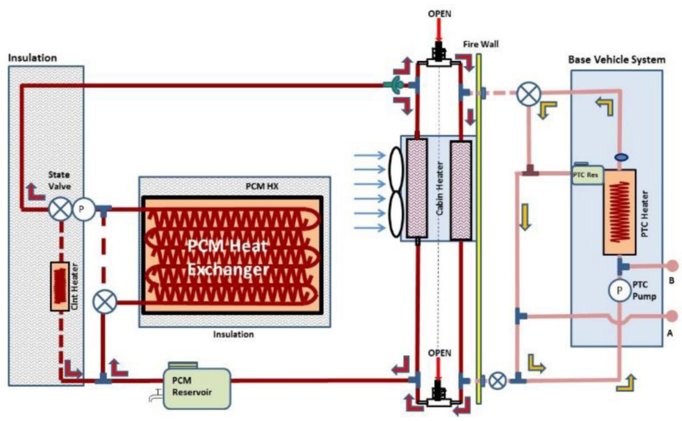

Figure 1. Improved ePATHS System Design

The system of Figure 1 has been mechanized to achieve three modes of heating—PCM discharging, PCM and PTC joint heating, and PTC heating—along with a fourth mode of PCM charging. Several valves were utilized to achieve the four modes of operation, as described in Wang et al [1]. A unique feature of the system worth reiterating is the configuration of the HVAC module cabin heater for the differing modes of operation. An actuated valve has been prototyped to configure the HVAC module cabin heater to function as a single-parallel heat exchanger attached to either the ePATHS PCM coolant loop or the vehicle's PTC coolant loop, enabling PCM heating or PTC heating. The valve also allows the cabin heater to function as two separate heat exchangers, with the front (or air upstream) half attached to the PCM loop to preheat the incoming cold air, and the rear half attached to the PTC loop to allow final heating of the airstream to fulfill the requirements of cabin heating. This is known as the joint mode of operation. Since the cabin air temperature requirement will not be satisfied after the PCM temperature decreases below a certain level, heat removal without the joint heating mode does not allow extraction of a large portion of the energy stored in the PCM. This mode therefore enables deep energy extraction from the PCM thermal storage that would otherwise not be possible.

Improvements to the system design have been made based on the learnings from the completed bench testing and vehicle trial runs. Due to the limited capability of heat to penetrate into the interior of the PCM heat exchanger from the exterior surfaces, surface heating was found to be ineffective in sustaining the required charging heat transfer rate. A high charging rate would result in excessive surface heater temperature exceeding its specification. To operate safely, the heating rate had to be reduced steadily to near zero as the PCM temperature near the surface rose to the upper limit of the charge temperature (120°C). This low heating rate resulted in a total charge time beyond the acceptable range. On the other hand, the method of charging by a high temperature coolant stream was found to be effective, as long as heat losses from the fluid lines between the coolant heater and the PCM heat exchanger are not excessive. Since the PCM heat exchanger was designed to be highly effective in transferring heat between the PCM and the coolant stream, the charging heat transfer rate became a non-issue.

Preliminary test runs of the ePATHS system in a 2016 Ford Focus Electric (a BEV) revealed coolant migration between the vehicle PTC heating system and the ePATHS heating system. The two coolant systems communicated during operating mode transitions. Replacing the PTC side check valve with an actuated isolation valve allowed the system to operate properly.

Phase Change Materials Development

The main progress in PCM materials development is in the synthesis of DPT-83, which has a phase change temperature of 83°C and a latent heat in the range 345~350 J/g, depending on the purity of the product. Compared with DPT-68 synthesis reported previously, DPT-83 is more difficult to produce in the laboratory. A great deal of effort was invested in streamlining the synthesis pathways and the determination of a proper catalyst. The separation and purification of the desired product was proven to be equally challenging. However, all the challenges were overcome and a sufficient amount of the product was produced for the final demonstration vehicle.

Material compatibility tests have been carried out for both DPT-83 and DPT-68. Preliminary indications show that DPT-83 and DPT-68 are materially compatible with aluminum heat exchangers. For the DPT-68 material, the compatibility study has been maintained uninterrupted with several prepared aluminum coupons (as shown in Table 1) soaked in 150°C melted PCM material for the last 7 months. No meaningful material loss or gain was detected in the coupons. Based on these results, it is expected that the material compatibility is satisfactory, but without long term compatibility data or development of an accelerated test method, the results are not conclusive. Until such an accelerated test is identified and carried out, the risk of material loss after an extended period of time cannot be ruled out.

Table 1. Sample and Exposure Time for DPT-68 Material Compatibility Study

Sample Name	Start Date	Total Exposure Time (Hrs.)	Total Exposure Time (≈ Months)
Virgin AA3003_1	02/19/2016	4992	7
Virgin AA3003_2	02/19/2016	4992	7
Dry Flux Sample_1	03/18/2016	4296	6
Dry Flux Sample_2	03/18/2016	4296	6
Wet Flux Sample_1	03/18/2016	4296	6
Wet Flux Sample_2	03/18/2016	4296	6

For the DPT-83 material, a similar compatibility study was initiated in August 2016. Preliminary assessment after two months indicated no mass loss or other compatibility issues. A second review will be performed in the first Quarter of 2017.

PCM Heat Exchanger Development

The PCM heat exchanger used for the primary thermal storage is a key component of the ePATHS system. Figure 2 shows the first generation design of the full sized PCM heat exchanger containing 20kg of PCM and 10kg of aluminum, with the targeted volume of 31 liters. The GEN-I design [1] was based on automotive radiator technology. Multiple brazed radiator units were assembled and encased in an aluminum shell and an insulation jacket. The radiators' finned side (normally the air side) forms the PCM-containing cavity along with the encasing shell. The coolant tubes and distribution headers provide the structural support for the extended heat transfer surfaces. Through design optimization, good heat transfer was achieved between the coolant stream inside the tubes and the PCM in contact with the fins.

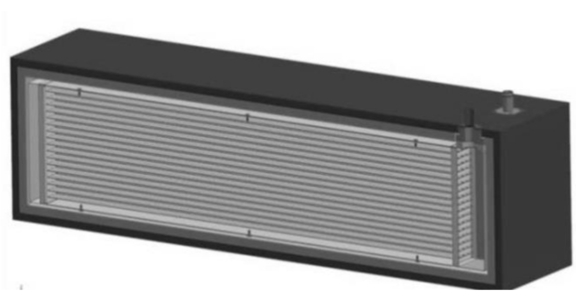

Figure 2. GEN-I Radiator-Type PCM Thermal Storage Module

While the heat transfer performance of the GEN-I design was quite satisfactory, commercialization issues were identified. The design was not amenable to mass production at low cost as several steps of manual assembly were required. Along with some design considerations to improve heat transfer performance and structural integrity, a plate-type heat exchanger was pursued for the GEN-II design.

The plate-type PCM heat exchanger design is similar to the automotive chillers and oil coolers. A pair of plates stacked back-to-back forms the PCM containing chamber, and stacking two of the pairs together further forms a coolant flow channel. Necessary heat transfer enhancement on both the coolant side and the PCM side has been designed in (Figure 3).

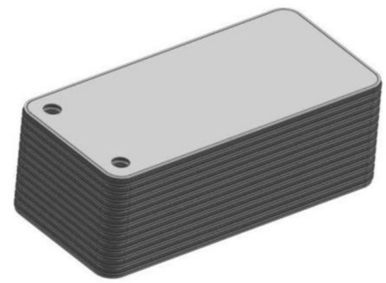

Figure 3. Plate-Type PCM Thermal Storage Module

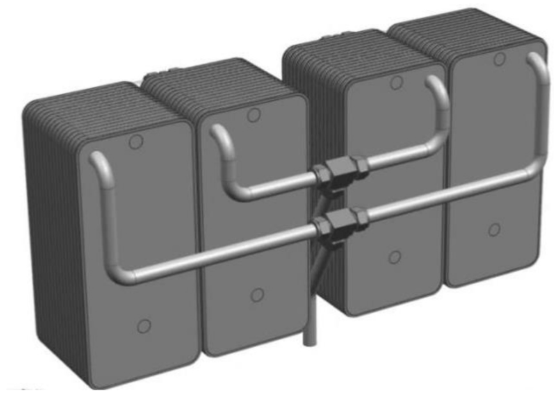

Figure 4. PCM Thermal Storage with Four GEN-II Modules with Parallel-Serial Plumbing

The plate-type PCM heat exchanger design is intended to be modular. At the individual module level, dimensional flexibility is achieved by changing the number of plates assembled into the module. The largest number of the plates, which determines the module's total thickness, is only limited by the brazing capability of the production facility and the takt time requirement. However, in the other two dimensions, flexibility is limited once the tooling design for a single plate is finalized.

To obtain a large enough PCM thermal storage system filled with DPT-68 to meet the design objective of 20% range extension, the so-called modular construction technique was used. Multiple cell-level modules out of the braze oven are plumbed together (Figure 4) to form a super-storage unit capable of holding the amount of PCM material needed to store the specified thermal energy for cabin heating. Parallel and serial plumbing of the modular units are used to optimize the coolant flow distribution and pressure drop.

Preliminary bench and vehicle testing with the GEN-II PCM heat exchanger show that all the design criteria have been met. Additionally, the design demonstrated enough flexibility to size the PCM heat exchanger either for HEVs and PHEVs, which require a relatively smaller amount of PCM for thermal storage, or for BEVs, which require a larger quantity of PCM. The product can also serve other thermal storage needs on conventional vehicles as well as in adjacent markets such as residential and commercial markets.

PCM Heat Exchanger Bench Test

The ePATHS bench tests assessed three main aspects of operation of the device: (1) the time and energy needed to fully charge the PCM heat exchanger; (2) the power and total energy output by the PCM heat exchanger during Mode 1 (PCM heating only) and Mode 2 (PCM heating with transition to PTC heating) operations; and (3) the performance of the insulation system for the PCM thermal storage. The thermal energy discharge evaluation is the primary means to assess the ePATHS' capability to maintain cabin comfort under transient and steady state cabin heating conditions. Figure 5 shows the bench constructed for this project.

Figure 5. Photos of the ePATHS Bench Prototype Hardware in ORNL's BTRIC Test Chamber

The thermal energy stored in the ePATHS system is composed of the sensible and latent heat of the PCM material, the sensible heat of the aluminum, and the sensible heat of the coolant contained within the PCM heat exchanger. Using 0°C as the reference point for enthalpy calculation, the predicted enthalpy storage with DPT-68 and the actually measured enthalpy storage are given in Figure 6. The temperatures of 25°C, 60°C, and 120°C are, respectively, the lowest energy extraction temperature, the ePATHS independent heating temperature, and the maximum system charging temperature. The thermal energy between 60°C and 120°C can be used for Mode 1 operations, and the part between 25°C and 60°C may be used in Mode 2 operations. The bench tests measured the Mode 1 thermal energy to be 2.24 kWh, and Mode 2 thermal energy to be 1.15 kWh. The total usable thermal energy is 3.39 kWh.

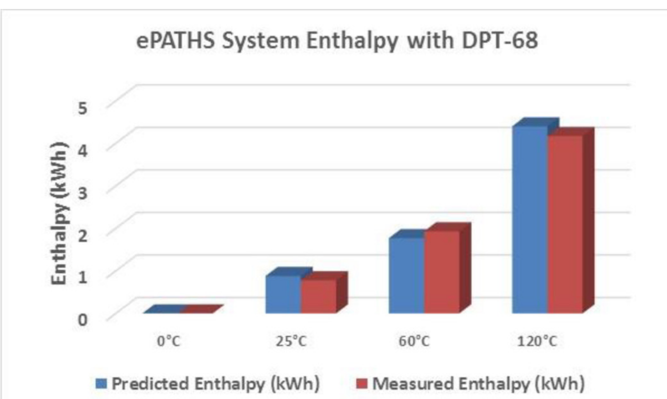

Figure 6. Total System Enthalpy with 0°C Reference Point

The thermal loss evaluation was performed by charging the PCM to 100°C and soaking the PCM heat exchanger in a temperature controlled ambient chamber. Both the ambient temperature and the PCM temperature were logged for a period of 15 hours. Since the energy loss above the PCM phase change temperature is sensible, it can be calculated easily. As shown in Table 2, the soak test showed an integrated energy loss of 8% over an eight-hour period (representing a typical work day) at the ambient condition of -10°C. In the low (lower than the phase change temperature) PCM temperature range, the integrated heat loss was estimated to be around 4% over an eight-hour period. The measured performance satisfied the ePATHS project design target of a maximum 10% loss over an eight-hour period.

Table 2. Thermal Loss Evaluation during Cold Soak (Cooling from 100°C to 72.6°C)

Temperature Change (°C)	**27.4**
Time (Hours)	**14.8**
Total Energy Storage, kJ (120-50°C) for 20kg PCM	**11418**
Energy Loss, kJ (Based on 18.2 kg Actual PCM mass)	**1701**
Percent Energy Loss/Hour	**1%**
Percent Loss During 8 Hour Cold Soak	**8.%**

Vehicle Build and Tunnel Testing

System Integration and Instrumentation

A 2016 Ford Focus Electric was retrofitted with the ePATHS thermal storage system. The PCM heat exchanger itself is installed in the trunk space (Figure 7 right), along with the support components of the system, which include a coolant pump, coolant routing and mixing valves, and a 3kW coolant heater to provide the hot coolant for PCM charging.

As the vehicle build was carried out after the bench test and the GEN-II PCM heat exchanger had been tooled and prototyped, this heat exchanger design was used instead of the GEN-I PCM heat exchanger for the Focus BEV build. Four of the 16-plate heat exchanger modules were connected in series-parallel formation, as shown in Figure 4, to form an integrated PCM heat exchanger with a design capacity of 20 kg of DPT-68 material. Two considerations went into the packaging design. The serial-parallel configuration allows the PCM heat exchanger to provide sufficient coolant flow velocity during normal operation without undue pressure drop, and the linear arrangement of the four heat exchanger modules allowed the use of an already-fabricated Vacuum Insulation Panel (VIP) container designed for the GEN-I PCM heat exchanger.

However, the linear arrangement did lead to sub-optimization of the overall packaging of the PCM heat exchanger for the vehicle build. Being a one-of-a-kind build, the PCM heat exchanger internal plumbing was not as compact as it could be and the VIP container had to be updated with some enlarged panels to host the PCM heat exchanger assembly. This resulted in a sizable air space within the VIP container.

A coolant reservoir was installed in the back end of the vehicle. The coolant reservoir holds about 2 liters of reserve coolant to allow the system to function properly. The coolant reservoir is located along the return path from the HVAC module cabin heater. During the PCM heat discharge mode, coolant flows from the pump in the trunk to the HVAC module cabin heater in the front of the vehicle through insulated lines and hoses under the carpet, and returns from the HVAC module cabin heater to the reservoir and then back to the PCM heat exchanger. For the PCM charging mode operation, coolant flows only in the back end of the car. Coolant can flow from the reservoir to the charging system as needed during charging but it does not directly flow through the reservoir.

A system controller has been developed to allow the ePATHS system to operate in the previously defined 4 modes of operation. The controller is mounted on top of the PCM heat exchanger along with the data logger and other supporting instrumentation and devices.

At the front end under the hood (Figure 7 left), a power switching relay box was installed to manage the traction battery and PCM charging processes. The ePATHS controller provides the pilot signal to the external charging station to signal readiness to receive charge. The charger sends electric power to the high voltage relay box, and the ePATHS controller decides where to dispatch the electrical power. The controller manages the charging process by monitoring the vehicle activities on the CAN bus, with priority given to vehicle preconditioning and traction battery charging before allowing the PCM heat exchanger to charge.

Figure 7. Retrofitted EV with PCM Thermal Storage System

A Campbell Scientific CR9000X data logger was used to record data from the instrumentation installed in the vehicle. The instrumentation includes thermocouples in the coolant loops of the ePATHS system, battery cooling loop, Power Electronics and Electric Machinery loop, etc. There are also coolant flow meters in the same loops. On the air side, thermocouples were used to measure ambient and in-car air temperatures, air temperatures at various points in the HVAC module, and air temperatures in the air distribution ducts. Finally, a family of climatic tunnel parameters such as dynamometer torque, vehicle speed, airflow speed, and temperature and humidity of the tunnel air are logged into the data logger.

During vehicle testing, three streams of data are collected by a locally developed data logging software, Karti, and logged into a single ASCII text file using a data format (CSV) that is compatible with Microsoft Excel. A uniform time stamp is employed to facilitate data processing.

Performance Evaluation in Climatic Tunnel

The impact of the ePATHS system on vehicle range was evaluated in MAHLE Lockport Technical Center's climatic tunnel. The range test procedures were devised with reference to the Urban Dynamometer Driving Schedule (UDDS) and a Constant Speed Cycle (CSC) [7]. For the UDDS cycle, the climatic tunnel controller was programmed to provide the correct speed profiles for the dynamometer and wind speed. With the vehicle traction battery fully charged, i.e. an initial State of Charge (SOC) of 100%, the UDDS cycle driving is run repeatedly until the displayed traction battery SOC reaches zero. The driving range is recorded with the data logger and tunnel data system.

For the CSC cycle, the vehicle again began with a fully charged traction battery and was run without interruption until the traction battery SOC reaches zero. The CSC cycle was run at a constant speed of 50 kph instead of the standard specification of 90 kph.

It is to be noted that the range obtained in the MAHLE climatic tunnel was not meant to qualify or validate the OEM's declared range. Since the equipment design specification of the climatic tunnel was mainly intended for air conditioning and engine thermal management systems development, the characteristics of the dynamometer were not evaluated or calibrated for powertrain driving evaluations. However, test history at MAHLE has shown that the dynamometer's loading offers a fairly accurate representation of actual road load conditions and it was deemed adequate for the purpose of an A-to-B range comparison.

For each range test, the vehicle automatic climate control system was set to run at 70°F (~21°C) in automatic mode, except for the baseline range test when the climate control system was switched off.

To achieve a fair comparison between PTC electric heating and PCM thermal storage heating at the -10°C ambient (the nominal design point of the ePATHS system), special provisions had to be made for the cabin heater coolant temperature control on the part of the ePATHS system. With the PTC heating, the vehicle controller would output a coolant temperature target and power the PTC heater at 100% duty cycle until the coolant temperature met the target, which typically took 5~10 minutes to occur. For the ePATHS system, it is initially charged to 120°C. The system would achieve the posted coolant target temperature with very minimal delay. This was great for "instant heating", but consumed the stored heating energy just a bit too quickly to offer a meaningful range comparison. To reconcile the behavioral differences, the actual warmup profile achieved during the PTC heating was captured at -10°C ambient conditions and implemented for the ePATHS system to use as a control target.

To improve repeatability of the range tests, all the vehicle runs were preceded by a 3 hour ambient temperature soak, such that the entire vehicle could acquire a uniform initial thermal condition.

The first set of tests was conducted to evaluate range reduction on the unmodified test vehicle from cabin heating. In this case the baseline range was established by running the vehicle with no cabin heating (with the HVAC system turned off). After the baseline run, the HVAC system was turned back on and the range test procedures were re-run, including both the CSC and the UDDS cycles, to measure the impact of the PTC cabin heating.

Figures 8 and 9 compare the ranges of the unmodified baseline vehicle with and without PTC cabin heating using the CSC test evaluation method. Figure 8 shows that, with the PTC heater turned off, the breath level temperature (typically used to gauge the comfort level in the vehicle cabin) remained practically at the same temperature as the tunnel ambient of -10°C through the entire duration of the test. No heat transfer was registered at the HVAC module cabin air heater, as no coolant flow was detected. At the constant speed of 50 kph, the vehicle was able to achieve a distance of 133.9 kilometers.

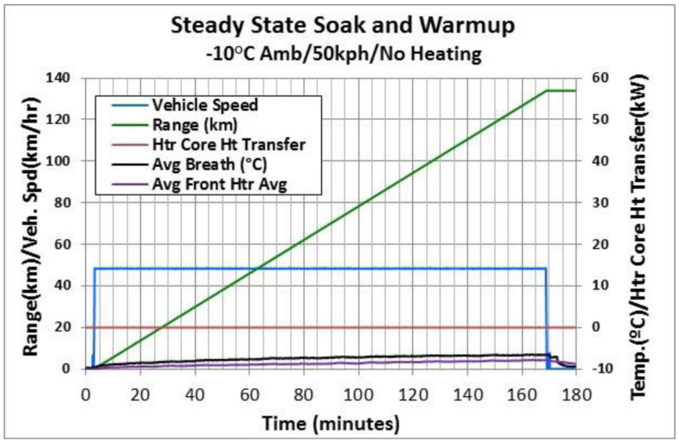

Figure 8. Constant Speed Cycle (50 kph) Range Test without Cabin Heating

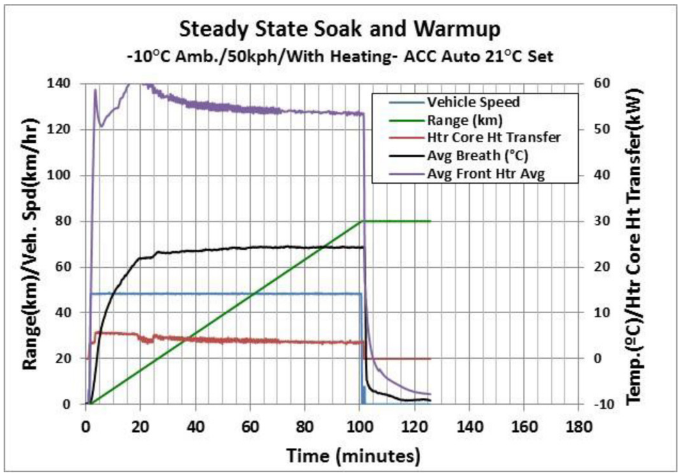

Figure 9. Constant Speed Cycle (50 kph) Range Test with Cabin Heating

The CSC test was re-run with the climate control system turned back on and set at 70°F (21°C) on the control head. Figure 9 shows the same set of information as that contained in Figure 8. It can be seen that the average breath level temperature was raised and maintained at 24°C by way of PTC heating. During the transient part of the cabin heating, the HVAC module cabin heater registered 5.9 kW of heat transfer, whereas during the steady state cabin heating period, it registered 3.5 kW of heat transfer. The cabin heater outlet thermocouple grid measured an average temperature between 53°C and 62°C through the driving period. The cabin comfort, however, came at the cost of driving range. The vehicle was only able to achieve a range of 80 kilometers before the traction battery was fully discharged. This represents a range reduction of 40%.

Figures 10 and 11 compare the driving ranges of the unmodified baseline vehicle running on the UDDS cycle. When run without cabin heating, the car achieved a respectable range of 95 kilometers, but on the repeat run with the cabin heating turned on, the driving range reduced to 50 kilometers. The range reduction relative to the no-heating UDDS test was 47%. Similar to the CSC heating run, the cabin breath level temperature was maintained at approximately 24°C, and the tunnel ambient temperature was maintained at -10°C.

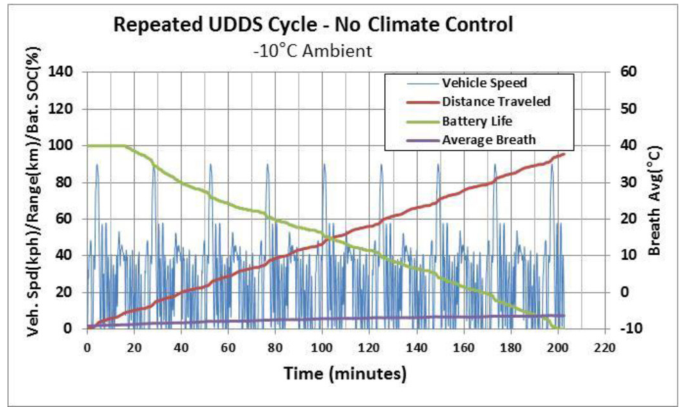

Figure 10. UDDS Cycle Range Test without Cabin Heating

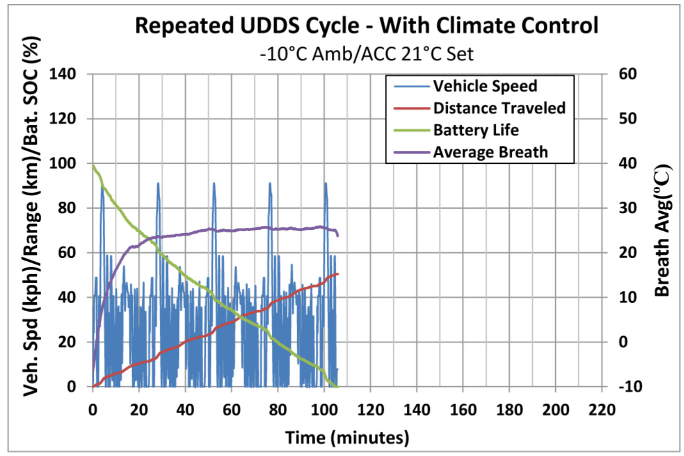

Figure 11. UDDS Cycle Range Test with Cabin Heating

Further range tests were carried out with the ePATHS heating system enabled. As designed, the vehicle started the cabin conditioning with the heat from the PCM thermal storage system only. The coolant control valve in the ePATHS system metered a partial stream of coolant flow into the PCM heat exchanger to extract heat from the PCM material, which initially was in the liquid state at 120°C. The remaining partial stream bypassed the PCM heat exchanger and recombined with the heated flow to provide the required coolant temperature according to the ACC control target. The combined coolant stream was then sent to the HVAC cabin heater to generate the heated air that was circulated to the cabin.

While running the repeated CSC cycles, the ePATHS system was observed to provide independent heating for approximately 43 minutes at the -10°C ambient temperature. Afterwards, with 100% of the coolant going through the PCM heat exchanger, the coolant temperature could not meet control target set by the car. At this point, the ePATHS system made the transition to “PCM and PTC” joint heating mode, otherwise known as Mode 2. In this mode, coolant flow into the first half of the HVAC module cabin heater was obtained from the PCM coolant loop to extract residual heat from the PCM heat exchanger to preheat incoming cold air at -10°C. The preheated air was then further heated up to the temperature target set by the automatic climate control system in the second half of the cabin heater using hot coolant from the PTC heater.

The third mode of operation, the "PTC Only" heating mode in the system was never activated, because the PCM temperature did not drop below a prescribed threshold to trigger the transition. The traction battery would drain to 0% SOC while the ePATHS system was still operating in the joint heating mode.

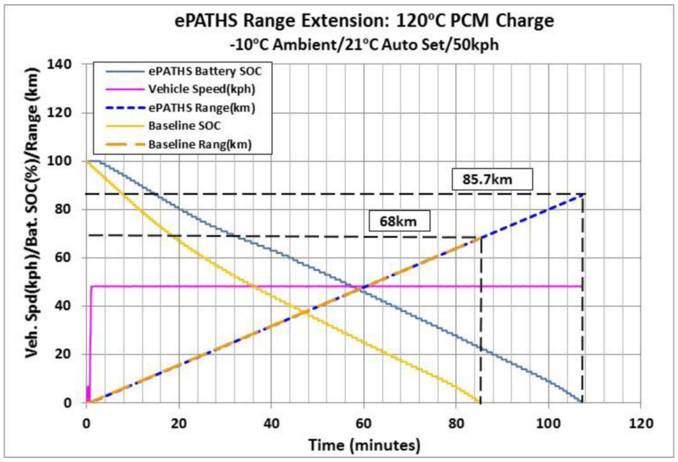

Figure 12. PCM Thermal Storage Range Extension over PTC Heating during CSC Range Test

Figure 12 shows a comparison of PTC heating and ePATHS heating using the modified CSC range test at the speed of 50 kph. It is gratifying to observe the driving range improvement offered by the ePATHS heating system over that of the PTC heating baseline. The negatively sloped diagonal lines in the chart represent the SOC of the traction battery being depleted as a function of time for the PTC heating baseline and ePATHS heating cases. The orange line depicts the traction battery SOC decreasing at a substantially higher rate than the case of the ePATHS heating, which is depicted by the solid blue line. As can be seen from the positively sloped diagonal lines in the chart, the driving range with the PTC was measured to be 68km, whereas the range with the ePATHS was measured at 85.7km, indicating a range improvement of 26%.

Summary and Conclusions

The ePATHS system development has seen a leap forward from a bench top construction to a vehicle integrated system complete with controls and User Interface devices, and the necessary instrumentation and data acquisition system for performance evaluations. An entire set of climate tunnel tests has been completed. With it, the range extension potential of PCM thermal storage heating has been demonstrated.

This was enabled by progresses in PCM material synthesis and PCM heat exchanger engineering development. Major advances were made in the synthesis, purification, and pilot production of the DPT-68 and DPT-83 PCM materials, with a sufficient amount produced for application validation. A fundamental redesign of the PCM heat exchanger was also completed and validated. The GEN-II PCM heat exchanger was designed with strong commercialization criteria in mind. It is more reliable, less costly to fabricate, and more flexible to configure for both high capacity and low capacity applications.

Even though the climatic test data have not all been analyzed, preliminary indications show that EV and PHEV cabin heating by PCM thermal storage is a viable option. It is projected to be more competitive once it achieves the scale of production expected in the automotive industry.

One lingering question is how to decide between adding more battery vs. adding a thermal storage system. If the battery cost was a non-issue, adding battery would be the obvious choice. In the meantime, thermal storage offers a relative inexpensive way to enhance winter driving range. This option can be further improved if one can use the carried mass of the system to assist with summer time air conditioning.

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Definitions/Abbreviations

ACC - Automatic Climate Control

BEV - Battery Electric Vehicle

CSC - Constant Speed Cycle

EREV - Extended Range Electric Vehicle

ePATHS - Electric Phase Change Material Assisted Thermal Heating System

HEV - Hybrid Electric Vehicle

kph - kilometers per hour

ORNL - Oak Ridge National Laboratory

PCM - Phase Change Material

PEEM - Power Electronics and Electric Machinery

PHEV - Plug-in Hybrid Electric Vehicles

PTC (heater) - Positive Temperature Coefficient (heater)

SOC - State of Charge (traction battery or thermal storage)

UDDS - Urban Dynamometer Driving Schedule

VIP - Vacuum Insulation Panel

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