Use of a Thermal Battery with a Heat Pump for Low Temperature Electric Vehicle Operation

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***Abstract*—Below 10°C, electric vehicles suffer from reduced range, which can be as severe as a 70% reduction (at -26°C). This is due to reduced battery performance at low temperatures and increased cabin heating demand. Heat pumps have been shown to have good steady state performance, but suffer slow and inefficient transients, while thermal storage has been shown to provide large heat flows and reduced warm up times, but space for such thermal storage is limited. Here a heat pump is combined with an optimally designed thermal battery and the simulated results are presented with improvements to energy consumption demonstrated.**

I. INTRODUCTION

One common concern for electric vehicle owners is the limited range, especially for operation during the winter months or in cold climates [1]. Operatation below 10°C causes an increased demand in cabin heating, thus increasing power drawn from the battery, hence reducing electrical energy availability for propulsion [2], [3]. The cold conditions also reduce the performance of the electric battery, leading to a further reduction in range [4]. These two low temperature effects combine to give a range loss which can go up to 70% at -26°C [2].

A. Cold Climate Operational Challenges

The difficulties of operating electric vehicles in temperatures below 0°C can be separated into two categories, the heating load and low temperature battery performance. When considering the range of electric vehicles in cold climates, the dominant effect of temperature on the battery is the reduction in charge capacity. Many capacity tests have been conducted at low temperatures from both cell manufactures and independent researchers. A general consensus to this research is a 20% to 40% reduction in capacity at -20°C [4], [5], [6].

Cold climates also impact the battery's power capability and ageing rate while charging. Power capability is the maximum power that the battery is capable of supplying, which needs to be more than the driver is able to request. Where power capability is concerned, literature is mainly dominated by research into the effect of temperature on chemistries suited to hybrid vehicles. The primary cause of the reduced power capability is increased charge transfer resistance. This was concluded by Zheng and Cho who both performed power capability investigations [7], [8]. In the example of the study performed by Zheng, it was shown that at -20°C [7], the power capability could be reduced by up to 90%, while Cho showed an approximate 60% reduction in power capability when comparing $LiCoO_2$ cell at 25°C and -5°C [8]. By comparison it has been shown that lead acid and Nickel Cadmium technologies suffer 60% and 40% reductions in power capability at -20°C [9].

For automotive applications the general consensus is that end of life for a battery is defined as when the battery capacity less than 80% of the original capacity [10], [11]. At 45°C it has been shown that an $LiFePO_4$ cell can survive 2000 1C charge/discharge cycles before reaching this limit [12]. When Petzl performed 1C charge/discharge cycles at -20°C on an $LiFePO_4$ cell it lasted just 90 cycles [10]. The consensus being that low temperature charging causes lithium plating which depletes the amount of usable lithium in the cell [10], [13]. This prevents vehicles from undergoing fast charges if their battery is at extremely low temperatures.

Cabin heating is the largest auxiliary load when operating in cold climates and therefore has a large impact on the range of the vehicle [3]. In conventional internal combustion vehicles heating is not as much of a concern since the engine wastes approximately two thirds of the on-board energy as heat [14]. In comparison an electric vehicle is much more efficient, only wasting approximately 20% of the on-board energy as mechanical and electrical losses [15]. So far none of this waste energy has been used for cabin heating and so all heat is provided by positive thermal coefficient (PTC) heaters which contribute significantly to the reduction in range at low temperatures. Meyer and Reyes have performed vehicle level experiments which show at least half of the range deficit at low temperatures is caused by the heating load [2], [3].

B. Cabin Heating Solutions

As mentioned in section I-A, electric vehicles waste approximately 20% of the on-board energy as heat, either through mechanical or electrical inefficiencies [15], [16]. However until recently this wasted energy has not been used for cabin heating. Recent developments in heat pump technology mean that it will soon be possible to collect and reuse wasted heat from various parts of an electric vehicle [17]. Leighton used a test rig to show how a heat pump, capable of collecting heat from both the ambient air and the motor, could reduce the energy required for heating. He showed that the range could be improved by 2.6% at $-12°$C and 15.5% at 13°C. These improvements are a promising start to reducing the range deficit between mild (where little or no heating is required) and low temperature operation. There are currently at least two examples of heat pumps being used on production vehicles. These are the Nissan Leaf and the BMW i3 [18], [19], both of which only make use of ambient air in their heat extraction. BMW claim that the technology can give a 50% increase in efficiency and a 30% increase in range, although they do not specify the temperature range at which this can be achieved [19].

In research performed by Kim *et al.* it was shown that due to the slow warm up speeds of the heat pump, a PTC heater is still required to provide sufficient cabin heat during a cold start [20]. Currently this limits the energy saving potential of the heat pump, since the PTC heater is 20% to 50% as efficient as the heat pump.

Another promising technology for reducing the range deficit is the use of phase change materials (PCM) as thermal storage. A range of materials are available for thermal storage and cover a broad spectrum of specific heat values, melting points and latent heat [21]. Promising materials in this area include paraffin wax, non paraffin waxes (with paraffin like properties), fatty acids and super saturated salt water solutions. In 2016 LaClair proposed the use of a 2.7kWh thermal battery weighing 33kg with a volume of 31L to cover the entire heating load for a 23 minute commute twice in a day (46 minutes total) [22]. The thermal battery had an operating temperature range of $60-120°$C, where 60°C was deemed the minimum temperature useful for cabin heating. LaClair assumed an electrical battery with capacity 10kWh and average heating requirement of 3.13kW, and thus concluded that adding the thermal battery increased the electrical energy available for traction by 38%. Although the thermal battery took up a similar amount of room and weight, compared to the addition of an equivalently energetic lithium battery, it is considerably cheaper to manufacture and control, which is where the benefit lies.

In the example above, the minimum temperature that the thermal battery was deemed useful was 60°C. This is because the anything less than 60°C is not sufficiently hot to warm the air in the heater core [22]. However, the thermal battery is clearly still warm and more thermal energy can be extracted, which is where a heat pump becomes useful. Using a heat pump with a thermal storage unit has been proposed previously in literature. An early example of this is the use of thermal storage to manage solar energy in a domestic housing heat pump system [23]. This was demonstrated by Kaygusuz who used an experimental set up in a house in Turkey to achieve a coefficient of performance (COP) of 4.7, compared to a COP of 3 without using thermal storage, where COP is defined as

$$COP = \frac{Q_{condensor}}{P_{compressor}}. \tag{1}$$

Here, $Q_{condensor}$ is the heat extracted from the condensor, which can then be used for cabin heating, and $P_{compressor}$ is the power consumed by the compressor. More recently Picarelli *et al.* proposed a vhicle heating system using thermal energy storage in addition to a heat pump, leading to simulated energy savings of upto 15.5% [24]. However in this example the energy storage device was not a phase change material.

It is clear that there is potential for these two technologies (heat pumps and thermal batteries) to improve energy consumption and range of electric vehicles at low temperatures. With a broad choice in PCMs with different thermal properties, and further freedom in the heat battery sizing, designing a thermal battery for use in a heat pump is not trivial. It is therefore proposed that an optimisation algorithm should be used to select the thermal characteristics of the thermal battery to suit a range of conditions.

II. Method

A vehicle level model was generated in Dymola (a physical modelling and simulation tool) which is used to test the theoretical benefit of a heat pump with a thermal battery. The model is used to simulate energy flows and calculate energy consumed during a testing cycle in an acausal fashion. Energy consumption is then used as the objective function to be minimised through optimising the design parameters of a thermal battery.

A. Model details

The vehicle being modelled is a 2500kg passenger vehicle with a 90kWh battery, which is comparable to the Tesla model X [25]. A top level view of the model can be seen in figure 1.

Lumped thermal models are used for all components and have the general equation

$$m_{comp} C_{comp} \frac{dT_{comp}}{dt} = Q_{comp} \tag{2}$$

where the subscript $_{comp}$ refers to any component being modelled and m, C, T, and Q are the mass, specific heat capacity, temperature and heat flow of any component. The heat flow, Q, is the combination of heat generated by the component, any thermal management, such as heat extraction or delivery from the heat pump, and any losses to the environment, such as in the cabin. The cabin and battery both receive heat during warm up and both lose heat through forced convection to ambient through cold air passing over their

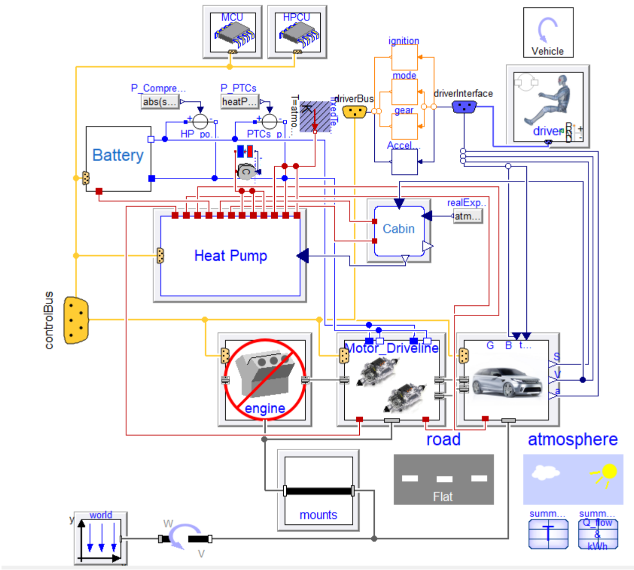


Fig. 1: A top level view of the Dymola model with all relevant submodels.

exterior surfaces. The heat pump can extract heat from ambient which is modelled as an infinite capacity heat sink, from which the evaporator extracts heat through a thermal resistor. The heat pump may also extract heat from the thermal battery, this heat transfer is also modelled using a thermal resistor. The thermal battery needs to encompass the phase change and the latent heat stored. As such its specific heat capacity is a function of temperature and a large spike in specific heat capacity is used to represent the latent heat of melting. This is achieved by increasing the specific heat capacity from $2.20\text{kJkg}^{-1}\text{K}^{-1}$ to $169\text{kJkg}^{-1}\text{K}^{-1}$ in the temperature interval 75-76°C. Although in the work of Ukrainczyk *et al.* [26] it was shown that the latent heat is released over a temperature range, for simplicity it has been assumed that the latent heat is released over a 1°C interval, the same assumption was made in the thermal battery sizing work of Taylor *et al.* [27].

B. Test Routine

Some baseline tests were conducted, against which the optimised thermal battery will be compared. Two drive cycles will also be used to compare the results. Firstly the initial testing scenarios were run on a World harmonized Light vehicle Test Procedure (WLTP) test profile, as this is in-line with standard testing procedure. The second cycle is a non standardised 5400 second warm up cycle, with a focus on steady state operation. Tests on the WLTP will be carried out at 23°C, 14°C and −7°C. These temperatures are currently used in WLTP and New European Drive Cycle (NEDC) (the NEDC cycle will not be tested) testing and will give a good comparison of the energy required for a cold start compared to normal operating conditions [28]. One criticism of heat pump technology is the power consumption during its warm up phase. Since the WLTP is the shorter (1800s compared to 5400s) of the two test cycles being used, it should help to identify the benefits of using a thermal battery to reduce warm up time and power consumption of the heat pump.

The second drive (Warm Up) cycle used focuses more on steady state warm up and power consumption. It consists of 30 minute cruises at 50km/h followed 100km/h and the 30 minutes at rest. The Warm Up cycle is simulated over a larger range of temperatures to get a broader understanding of the heat pump and thermal battery performance. The temperature range used is −20°C to 10°C with 2°C intervals. −7°C and 14°C were also simulated so that energy consumption between the two cycles could be directly compared.

Four different tests were performed before optimising the parameters of the thermal battery. The cycles were first tested using only the PTC heater, this gives baseline results representative of current electric vehicle heating technology. Next the heat pump was turned on and used in its most basic mode, extracting heat from ambient air; this is the current state of heat pumps on production vehicles such as the Nissan Leaf and BMW i3 [18], [19]. Next the heat battery was introduced and tested with the heat pump. Finally the heat pump and thermal battery were run without the aid of the PTC heaters. This is intended to show that the use of PTC heaters can be negated by the inclusion of a thermal battery. These results produce a baseline before the optimisation procedure takes place. As such some initial parameters were needed to be defined for the thermal battery, this was done by taking a representative example of a thermal battery from literature. The optimisation was then performed and results are given in section III.

TABLE I: Thermophysical properties of Paraffin 70-75, the PCM selcted to for optimal sizing.

Parameter	Value
Material	Paraffin 70-75
Melting Point	75°C
Specific heat (solid)	2.06 kJ kg^{-1} K^{-1}
Specific heat (liquid)	2.34 kJ kg^{-1} K^{-1}
Latent heat	169 kJ kg^{-1}

C. Optimisation

A specific PCM has been chosen for use in the thermal battery based on work done by Ukrainczyk *et al.* [26]. The material chosen is Paraffin 70-75, a material sample which Ukrainczyk *et al.* characterise in their work. The specifications of this paraffin are given in table I.

For the optimisation the design parameters will be;

- Mass
- Thermal power (How much heat (kW) can be extracted)
- Initial temperature

Due to the nature of the problem there is no well known equation for the energy consumption, and its value must be obtained by running the model and processing the resulting data. Hence an indirect search algorithm, which requires the use and existence of 1^{st} and sometimes 2^{nd} order derivatives cannot be used. Instead, a mesh search was used to evaluate the parameter space and return an optimum design. For the mass and thermal power, the mesh was set to find energy consumption at 1kg and 1kW intervals between 1kg and 30kg, and 1kW and 20kW, respectively. To reduce the number of iterations needed to perform the mesh, only 4 charge temperatures have been used, 40°C, 70°C, 100°C and 140°C. The upper limits for the search are based on previous studies from literature. The mass and charge temperature are in line with the largest values seen in literature [22], [29]. The maximum power was chosen to exceed 16.5kW, which was the maximum heating capacity of the PTC and heat pump used in this model. It was expected that at this power the heat battery will be able to provide sufficient thermal performance to replace the PTC heater.

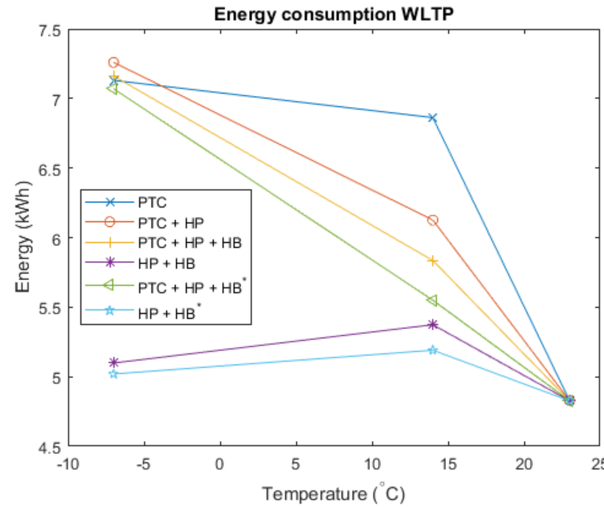
An initial set of parameters for the thermal battery was devised to get baseline test results. The mass was chosen to be 10kg, thermal power 6.5kW and 140°C starting temperature. The maximum temperature was chosen to minimise the mass needed. The mass was then chosen so that the stored energy was equivalent to 1.39kWh, which just exceeds the energy used by the PTC heater during a 20 minute warm up period. The thermal power was chosen to be in-line with the maximum value seen in literature [22].

III. Results and discussion

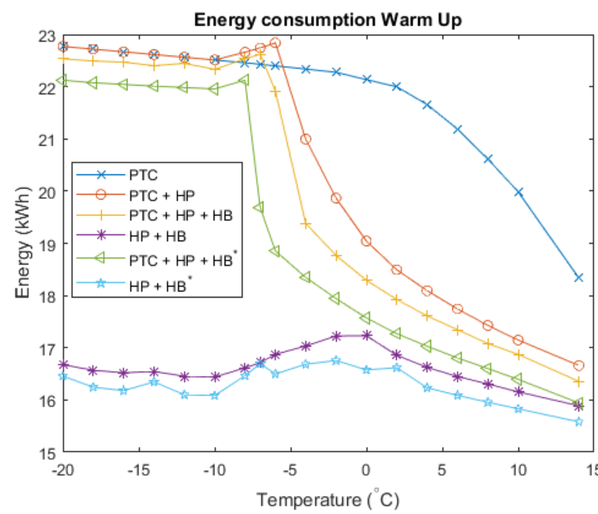
The mesh search to find the optimum design parameters for the heat battery gave the following results, 30kg mass, 16kW of thermal power and 140°C initial temperature. The optimum heat battery was subjected to the tests described in section II-B. The energy usage from the WLTP cycle and the Warm Up cycle are shown for different operational modes in figure 2. Here HP refers to the heat pump and HB refers to the baseline heat battery while HB* refers to the optimised heat battery.

Across the warm up cycle, seen in figure 2b, PTC+HP+HB* and HP+HB* give an average energy saving of 12.1% and 25.3% respectively, with peak savings of 21.5% and 27.6% when compared to PTC only. It is also noticable that the best performance gains are found in the region -10°C, with an average energy saving of 16.8% and 23.8% when comparing PTC+HP+HB* and HP+HB* to PTC only in this region. Below this temperature the heat pump is unable to extract energy from the ambient. There are 2 significant consequences to this, firstly the cabin heater becomes more dependant on the PTC heater, secondly, the heat pump no longer draws power. The second consequence explains why convergence can be seen between PTC and PTC+HP, and why the vehicle energy consumption reduces as ambient approaches -10°C for HP+HB and HP+HB*.

To evaluate whether using a heat battery can effectively replace a PTC heater the time to cabin target temperature (22°C) was considered. A comparison of warm up times is given in figure 3. Here 5 of the 6 operational modes are shown, as the PTC only configuration was unable to reach cabin target temperature under any ambient condition. It can be seen that PTC+HP+HB* was the best performer in terms of cabin warm



(a) The total vehicle energy used to complete the WLTP test cycle at -7°C, 14°C and 23°C is shown for the different operational modes. At 23°C heating is not required hence the energy usage for all operational modes converges



(b) The total vehicle energy used to complete the Warm Up test cycle at -20°C to 14°C is shown for the different operational modes.

Fig. 2: Vehicle energy consumption on WLTP and Warm Up drive cycles.

up time. It is also significant that HP+HB* performs almost equivalently to PTC+HP.

The optimisation was able to reduce energy expenditure with an average savings of 4% and 2% accross the warm up cycle, and peak savings of 14% and 3.8%, when comparing PTC+HP+HB with PTC+HP+HB* and HP+HB with HP+HB* respectively. This saving was acheived by increasing the mass of the thermal storage from 10kg to 30kg. When considering the energy saving given by a 10kg thermal battery the overall payoff for tripling the size seems small, however it did allow for the optimised heat battery to effectively replace the PTC above -4°C. This is an important acheivment if thermal batteries are to be considered for use in EVs.

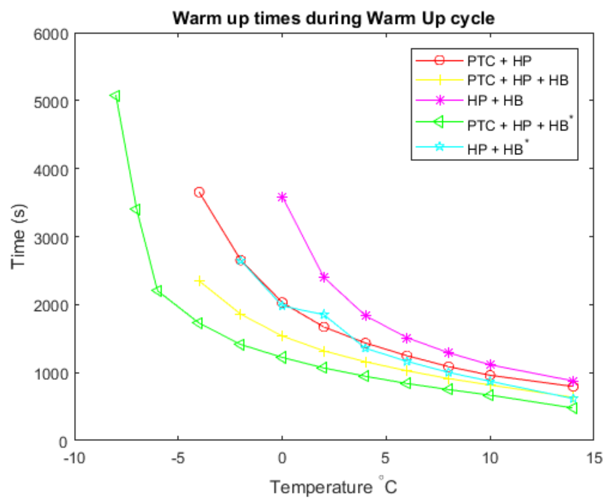


Fig. 3: The time taken for the cabin to reach 22°C. HB and HB* denote the first approximation and optimised heat batteries respectively.

IV. Conclusion

It has been shown that the inclusion of a thermal battery into an ambient source heat pump system can reduce vehicle energy consumption over a drive cycle by up to 27.6% under certain conditions. It was also shown that using an optimised thermal battery could make an effective replacement for a PTC heater above -4°C. However, continuing to use a PTC heater, as in PTC+HP+HB*, allows for a significant energy reduction at moderate temperatures while improving the warm up performance of the system at low temepratures. Further work should be carried out on PTC control to moderate the gap in energy consuption between PTC+HP+HB* and HP+HB* while maintaing acceptable levels of warm up performance. In Summary, an optimised thermal battery can greatly reduce the dependancy on a PTC heater, but given the limitations at extremely low temperatures, it is not able to completely replace it when designing a vehicle.

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