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DYNAMIC INSULATING SYSTEM FOR BATTERY

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Summary

Thermal conditioning is necessary to keep the battery operational in a wide range of weather conditions and the way it is implemented impacts the resulting driving range, the vehicle comfort performance and the battery lifetime. A poor thermal insulation, a deficient temperature control of the battery or a poor sealing system may reduce dramatically the driving range. Hutchinson Thermal Lab's mission is to develop, to simulate, to realize and to validate Thermal Management Systems based on the association of innovative solutions as Super Insulating Materials and formulated Phase Change Materials which allow to protect the lithium-ion cells from extreme operating conditions and to continuously maintain cells, modules and battery pack in the best conditions.

Demonstrators and tests have shown that such a protection of the Battery Pack allows to increase the range of an Electric Vehicle in winter times, its Battery Ageing during hot summer periods and also to downsize its active cooling system or the Heat Pump power to cover only normalized working conditions or fast charge times.

The benefit of such a system in term of vehicle range, battery ageing and energy consumption is also largely overcoming its extra weight and volume.

Keywords: Insulating systems, Phase Change Materials, Battery Thermal Management, Energy Saving & Battery cells Ageing

1 Battery Pack Thermal Insulation

The thermal insulation becomes a major topic for all vehicle motorizations and specifically for EVs, which are highly demanding for fire safety, low costs and electrically non-conductive and easy to apply materials to insulate battery compartments. This challenge is addressed thanks to materials specifically designed for those characteristics and performances. It is well known that extreme temperatures have strong impacts on batteries' performance. The power capacity of the battery available for the vehicle drive is strongly depending on the energy required to keep it within a defined temperature range. A thermal insulation of its compartment reduces the energy demand necessary to keep the cells at a nominal temperature when the EV is either at rest or circulating.

Temperature monitoring and conditioning functions are necessary to prevent the battery cells to reach too low or too high temperatures which would affect them. Heating and cooling either by a forced air or a temperature controlled liquid circuit are used during the operating phases. But, during short or long parking, even in extreme thermal climatic conditions, there is no thermal conditioning system considered to maintain the all battery pack volume in an optimal range of temperature.

It is therefore worthwhile to both insulate the global pack and/or its contents from the external environment, and also to manage the temperature therein within operational limits and to prevent or at least to delay during typical operations times the propagation of a disturbing heat flow towards this volume.

1.1 Materials for thermal insulation

Regardless to the external conditions (hot or cold), a thermal insulation participates in maintaining the battery cells within an optimal temperature range. The proposed solution is therefore preferably designed to operate without any external hot or cold energy supplied to the battery, or electrical energy produced by the battery. It has to be light and space-saving. That’s the reason why we’ve chosen “passive” thermal materials to design our solution.

1.1.1 Vacuum Insulating Panel - VIP

Vacuum Insulating Panels (VIP) are made of a porous or fibrous core material packed under vacuum in a tight envelope. VIP means a “controlled atmosphere structure”, i.e. either filled with a gas having a thermal conductivity lower than ambient air (26 mW/(m.K)) or under vacuum, i.e. under a pressure much lower than the ambient pressure. A pressure between 100 Pa and 10^4 Pa inside the envelop allows to drastically reduce its conductivity. The envelop contain at least one thermally insulating micro-porous material (pore sizes smaller than 10 micron). Not only the thermal performance is improved, but also its overall weight compared to another insulator. Those porous materials, for example ultra-thin fibbers, foams, silica gel or silicic acid powder (SiO_2), are compressed under a partial air vacuum and encapsulated in bags, made of metallized thermoplastic or ultrathin metallic foils.

In cooperation with the high tortuosity of the micro-porous material, the ultra-low pressure inside the foils reduces the heat transfer by gaseous conduction. VIP are therefore highly insulating solutions much more efficient (up to 5 times) than other conventional insulating materials at room pressure as shown in Figure 1.

Several core materials [1], [2] could be used like mineral wools, powder (fumed silica, perlite…), open-cells foams (phenolic foams, polyurethane foams…), aerogels, special fibers…

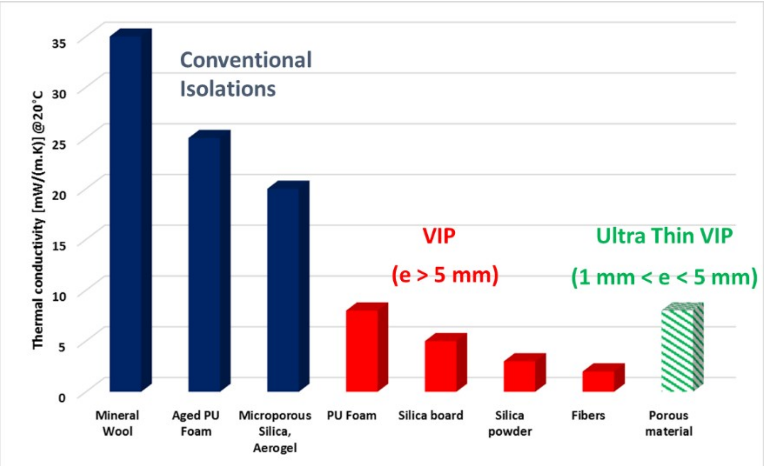


Figure 1: Thermal Conductivities of VIP compared with conventional materials

Also for some specific applications, Hutchinson has developed an Ultra-Thin super Insulating product based on Vacuum Insulation Panel (VIP) technology made of fibrous material. The core material is vacuum-packed in a multilayer film that ensures perfect sealing. The core materials' porous structure combined with the vacuum provides excellent thermal properties to the panel.

The thermal conductivity of VIPs is typically between 3 and 7 mW/(m.K) @ 20°C which makes them the most insulating material currently available on the market. However, the main issue for this product in the long-term service life because of vacuum loss during its operating lifetime.

Ageing is mainly due to the pressure increase. The main ageing factors are the residual gases left in the envelop during the vacuum packaging and the sealing process, the core material outgassing, the permeation and the leaks across the polymeric sealing area. Ageing is highly influenced by environmental conditions (temperature, humidity, pressure, mechanical constraints…), core materials structure as described in the Figure 2 and also panels dimensions.

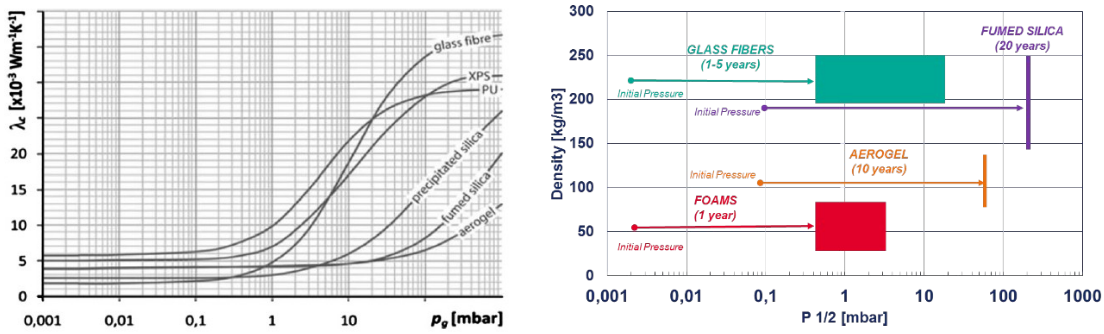


Figure 2: Effective thermal conductivity of different potential VIP core materials as function of internal gas pressure [3]

P ½ characterized the ageing. P ½ is the pressure reached when the VIP lose half of its initial thermal performance. It is strongly related to the type of core materials [4] to [7].

Typically the lifetime expected by customers is 7 years but products can even be designed to achieve a 15 years half life

Example of fumed silica:

- 10 mbar pressure initially → 4 mW/(m.K)

- P ½ = 100 mbar at 20 years → 7 mW/(m.K)

1.1.2 Dynamic Insulating System - DIS

Thermal Insulating materials and VIP serve to limit heat exchanges between the inside and the outside of the battery pack.

In addition to those insulating materials, a Phase Change Material (PCM) enables to "damp" the temperature peaks (Figure 3) for example throughout daily or yearly temperature evolutions by operating at the appropriate moments when a temperature threshold is reached. Such a protected pack interior will therefore be cooler in the daytime, during hot weather periods and warmer by night and in the morning during cold weather times.

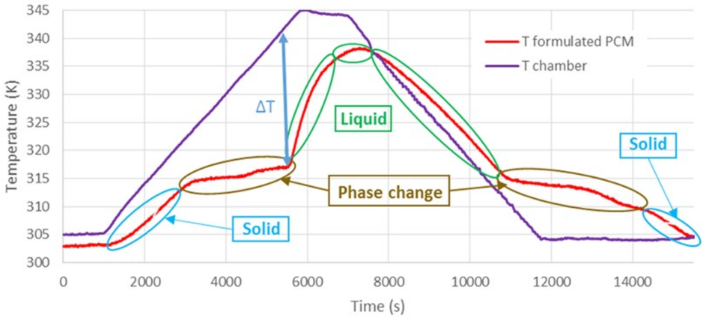


Figure 3: The temperature profile may be smoothened by using PCM to eliminate temperature peak

Combining both VIP and PCM materials will therefore makes sense especially when temperature gradients can possibly reach several tens of °C.

1.2 Formulated materials - PCsMART

PCsMART is a material based on organic PCMs micro-encapsulated in an elastomeric matrix (Figure 4).

Different formulations have been developed to overcome the main issues of paraffinic PCMs, which are low conductivity and with leakage risks.

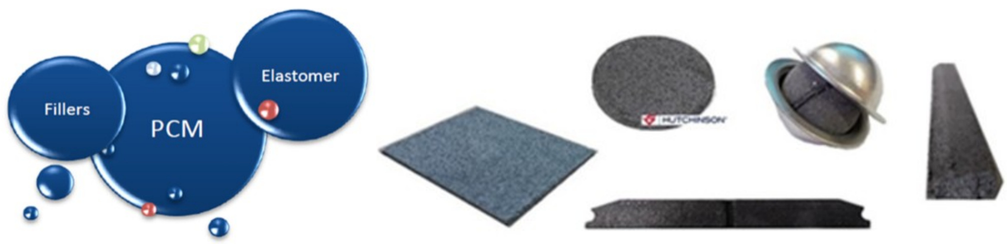


Figure 4: Rectangular, spherical or moulded, PCsMART is a cost efficient material, easy to integrate

Specifics formulations have been developed with adapted melting temperatures from 5°C to 75°C and improved thermal conductivity from 0.9 to 2.5 W/(m.K). Their other physical properties as density (< 1160 kg/m3), electrical non-conductivity (1,4 Ω.m) and flame resistance (UL94V0), make those materials particularly well adapted for E-mobility applications.

The PCM mass content inside the matrix is comprised between 40% to 70%. The elastomeric matrix has the capacity to absorb the volume variations when the PCM change its state from solid to liquid or when the cells thermally expand. The material is physically stable with no leakage risk during operations.

Another very interesting property of this elastomeric materials is its ability to be moulded. That facilitates its integration with various shapes for battery applications and cells surroundings.

1.3 Battery with PCM and Thermally Insulated Housing: Dynamic Insulation System for Battery - DIS

Assembling thermal insulation with a combination of “hot” and “cold” PCMs is effective with respect to our previous objectives. The battery is surrounded by a Thermal Barrier (Figure 5). This barrier will be subject to the same operating conditions than the vehicle wherever and whenever it will be used. This Thermal Barrier is very easily assembled in a real vehicle.

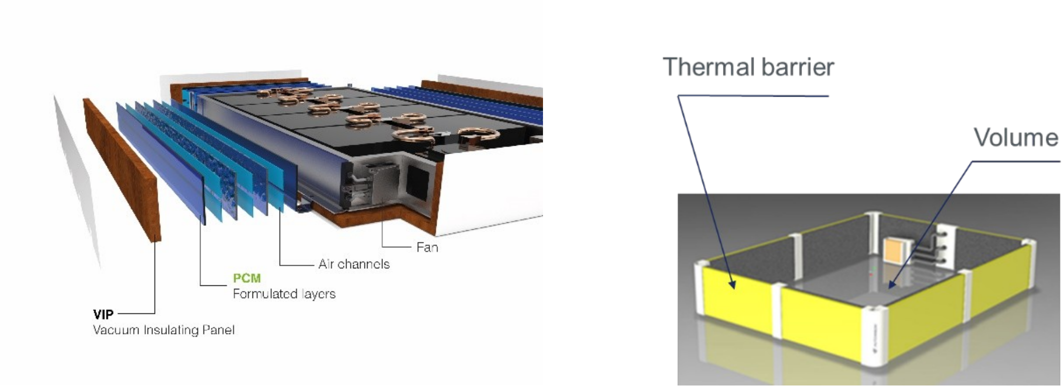


Figure 5: Thermal Barrier definition and overview

The aim is to maintain the temperature of the battery within a predetermined range, while the outer of the barrier is subject to the external environment which mays encounter extreme and highly variable temperature.

For that, the barrier comprises at least, starting from the interior (Figure 6):

- a first element containing at least one PCM material storing or releasing thermal energy by change of state and **having a first change-of-state temperature (T1; hereinafter hot PCM**),

- a second (or several**) element containing at least one PCM material** (hereinafter **cold** PCM), **having a second change-of-state temperature (T2), lower than the first**,

- a third element containing at least one PCM material (hereinafter once again hot PCM), having a third change-of-state temperature (T3), higher than the second (T2),

- and at least a last element, **the Thermal Barrier**.

During the parking periods, thermal management of the cells, or of the batteries in general, will be favourably ensured overall by this peripheral enclosure set to maintained a predetermined temperature between 20°C and 35°C. Specifically, for Li-Ion batteries it is recommended to adjust the change-of-state temperature of the coldest PCM between 15°C and 25°C, and the warmest PCM between 30°C and 40°C.

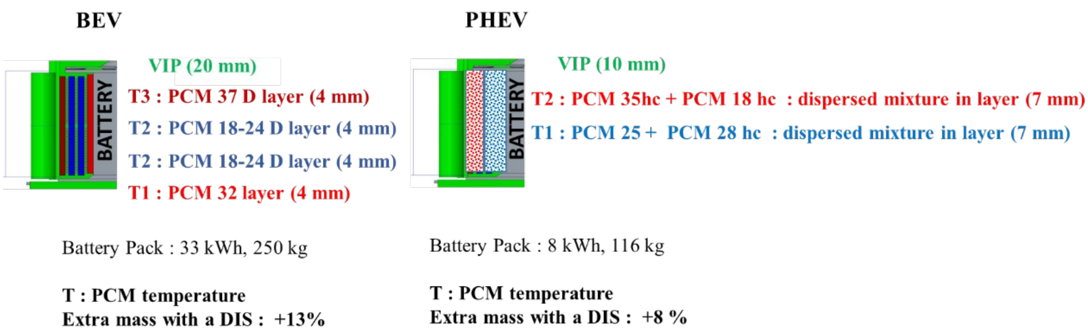


Figure 6: PCM / VIP layouts around xEV's battery pack and integration of this Thermal Management Systems with not adding much extra weight

The barrier effects are strengthened if at least one of the second and third elements comprises several dispersed PCM materials or several layers of material, each containing a PCM material, having a different change-of-state temperatures from one another. Then regardless of the external conditions encountered, typically from -20°C (cold winter) to 45°C (hot summer) and for a duration of 8 to 15 hours (typically overnight parking or daily parking for working), it will be possible to maintain the all battery at an appropriate temperature range. The overall barrier thickness will be comprised between 24 to 36 mm (i.e.: 2 successive layers of cold and hot PCMs, respectively, or the equivalent with dispersed PCMs.) **This added volume and weight will be largely compensated by the reduction of battery cells number it will allow.**

2 Thermal Conditioning Strategies

Integration of new components and functionalities on the vehicle will support the advent of the 3rd and 4th generation of electrified vehicles. Major concern on contemporary electric vehicles is the high dependency of their maximum range on ambient temperature conditions. In some cases, the range of an EV can drop by more than 50%. The main reasons for this is the energy demand of the auxiliary components required for the thermal conditioning of the passenger compartment and the thermal management of the battery when operating in extreme conditions. If one now calls:

- EB the operating status of the battery: ON (driving operations) or OFF (switched off, parking periods),

- TA, the ambient temperature of the external environment, which is variable between **-**20°C and +45°C,

- TB the temperature of the cells, which is therefore assumed to be maintained between +25°C and +35°C, the temperature when EB is ON with an active cooling mode and when EB is OFF, after 12 hours between 10°C Min and 30°C Max with a Thermal Barrier and hot and cold PCM layers. The main functions (F) aimed at achieving this thermal management during the second status are the following:

- F1: for TA =<25°C and battery in EB OFF status, limit the action of ambient cold on battery cooling,

- F2: for TA >= 35°C, limit the action of ambient heat on battery heating,

- F3: for TB =<35°C, limit the heat from the battery leaving towards the outside,

- F4: for TB >= 35°C, take part to the heat transfer from the battery towards the outside.

When 25°C =< TA =< 35°C and 25°C =< TB =< 35°C and EB is OFF, the thermal barrier is inactive. As for the other operating modes, we can define them in relation to cold or hot temperature.

When EB passes to ON, 25°C =< TA =< 35°C and 25°C =< TB =< 35°C, the thermal barrier is inactive.

2.1 DIS system functionalities during cold temperature

When TA < 25°C and TB tends towards 25°C and EB is OFF, the functions F1 and F3 are implemented. The thermal barrier becomes active. The insulating layers play their role successively, from the outside towards the inside. The cold PCM layers crystallise when their temperature reaches =< 25°C, which delays propagation of cold to the battery. The heat accumulated by the cells during their operation is maintained, since arrival of the cold front is delayed by the layers and the losses are delayed by those keep TB above the low range temperature 25°C.

2.2 DIS system functionalities during hot temperature

When TA >35°C and TB tends towards 35°C and EB is OFF, function F2 is implemented. The thermal barrier is active. The insulating layers play their role successively, from the outside towards the inside. The hot PCM layers melt when their temperature reaches =>35°C, which delays propagation of heat to the battery by absorption of the heat energy.

2.3 DIS system functionalities during start-up procedure

As for the channels for circulation of fluid, such as air in particular, they will also be favourably found in the elements based on cold PCM and hot PCM (Figure 7), in order to facilitate their regeneration (liquefied state for the cold PCM and crystallised state for the hot PCM). The implementation of those channels is therefore without additional weight.

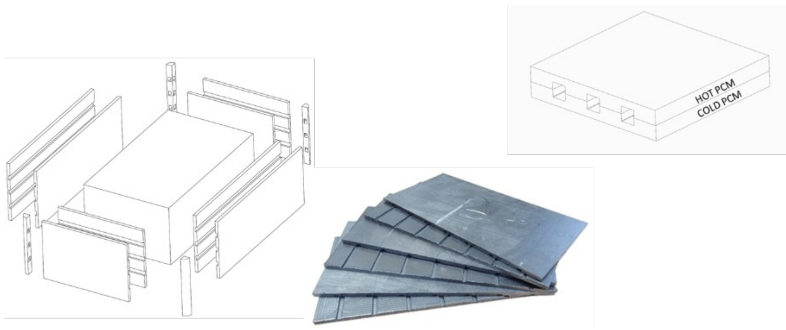


Figure 7: Integrated device for PCM regeneration

When EB passes to ON, TA < 25°C and TB tends above 25°C, the function F4 is implemented. The thermal barrier becomes active. Because of TA <25°C, the hot PCMs are crystallised when the vehicle starts up. If TA << 25°C, the cold PCMs are crystallised too; they can only liquefy if they are reached by heat from the battery or if the environment temperature (battery compartment) increases during the day to more than 20°C and will subsequently recrystallize on stopping again due to TA <25°C or TA << 25°C.

When EB passes to ON, TA < 25°C and TB tends towards 35°C, the function F4 is implemented. The thermal barrier becomes active. By providing circulation of a fluid in the channels, it is possible to maintain this temperature TB at around 35°C.

When EB passes to ON, TA >35°C and TB < 35°C The thermal barrier is active. The insulating layers play their role successively limiting external heat loads, from the outside towards the inside. The hot PCM layers are melted. If the night has been cool (TA<35°C and typically TA <25°C), the layers have crystallised and will melt again during the day. With the night temperature having been fresh, it will have been possible to store so-called cold energy in the cold PCM. This cold PCM will return to the liquid state by absorbing energy during diurnal temperature increase.

When EB is ON, TA >35°C and TB >35°C, the function F4 is implemented. The insulating layers still play their role successively. This could be improved by means of natural convection through specific air channels integrated in the DIS, or even air conditioning under 25°C.

3 Test results and implementation

To evaluate the influence of the ambient temperature on the vehicle range, an electro-thermal optimization of the overall system must be performed, including the HVAC (Heating, Ventilation and Air Conditioning) and the cooling system. Aiming at a minimal use of the main battery energy, the functionalities are ranked according to their energy consumption, then energy and power are routed by applying smart derating and automatic switching-off of non-safety-critical functions.

Those new thermal management concepts have been measured on real battery packs set up in climatic chambers to create extreme temperatures and their interactions on vehicle level have been simulated by using Simcenter AmeSim. The first results coupling the effects of a battery temperature control during the parking phases to the restart of the vehicle according to a specified scenario are given by Figure 8.

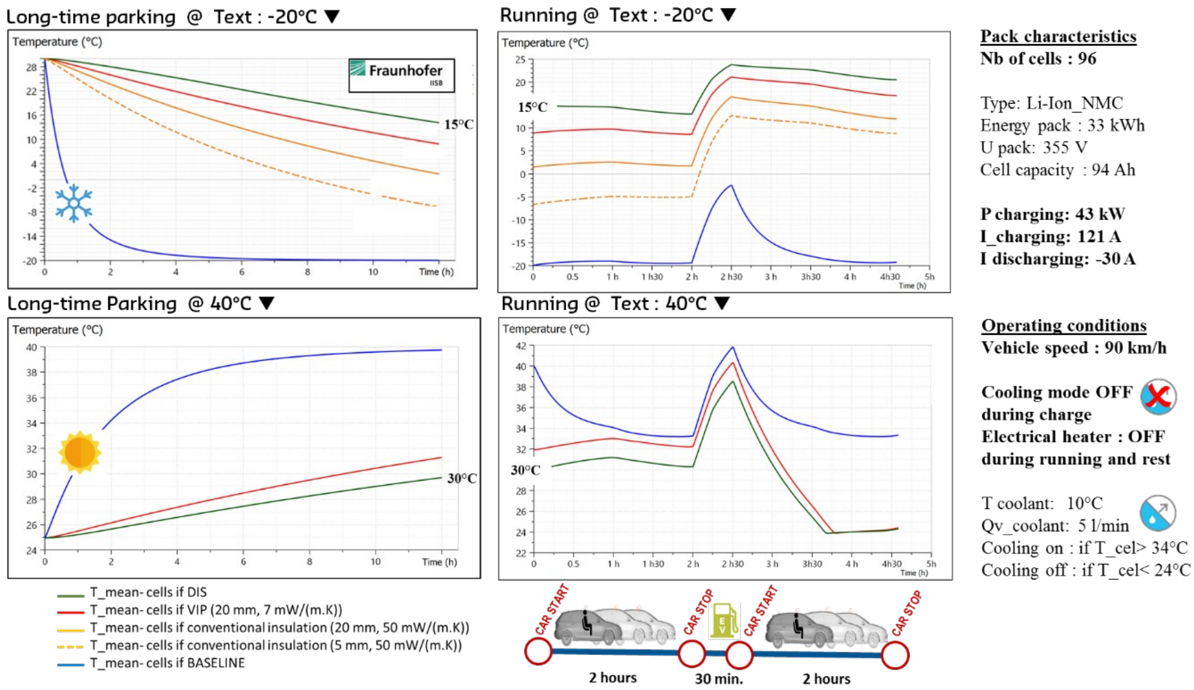


Figure 8: Measurements and simulations in hot & cold conditions

For very low temperatures, the objective to maintain the battery compartment above 15°C after 12 hours of parking is reached only with the DIS. It allows in this scenario to restart without any energy consumption to bring the compartment back to its optimal temperature range. Measurements and calculations show that other Insulation Systems are not performing enough to provide the desired thermal function. All other configurations will require a thermal conditioning by an electric element that will dramatically impact the distance that can be covered by the user in winter season. Several other scenarios will be discussed later to evaluate customer benefits by considering a full year.

Integrated thermal management during parking periods with an advanced DIS (insulating materials and phase change material in an elastomeric matrix) does not need higher performance for the liquid cooling system during hot season. The average temperature of the battery after a rest of 12 hours allows to start again with a temperature level requiring less cooling energy to keep it in the optimal range already described. In addition, if during hot seasons, lower average temperatures can be maintained in the battery compartment during parking phases when outdoor temperatures are close to or above 30°C, they will help to significantly reduce ageing.

4 Use cases and operating modes

Thermal conditioning during parking periods is necessary to keep the battery operational in a wide range of weather and the way it is implemented impacts the resulting driving range, the battery performance and its lifetime. Technically, this will lead to a higher energy efficiency and results in an overall cost reduction of the EV and its total cost of ownership (TCO). For next generations of BEVs, improvement of the driving range without major restrictions in terms of passenger’s comfort or battery ageing/safety is becoming crucial. Compared to a DIS (Dynamic Insulating System), increasing the capacity of the battery is no more a viable option, because it would drastically increase weight and cost, much more than the DIS.

4.1 Benefit of a DIS during cold temperature

Improved energy efficiency is depending on scenarios and external parameters as shown in Figure 9.

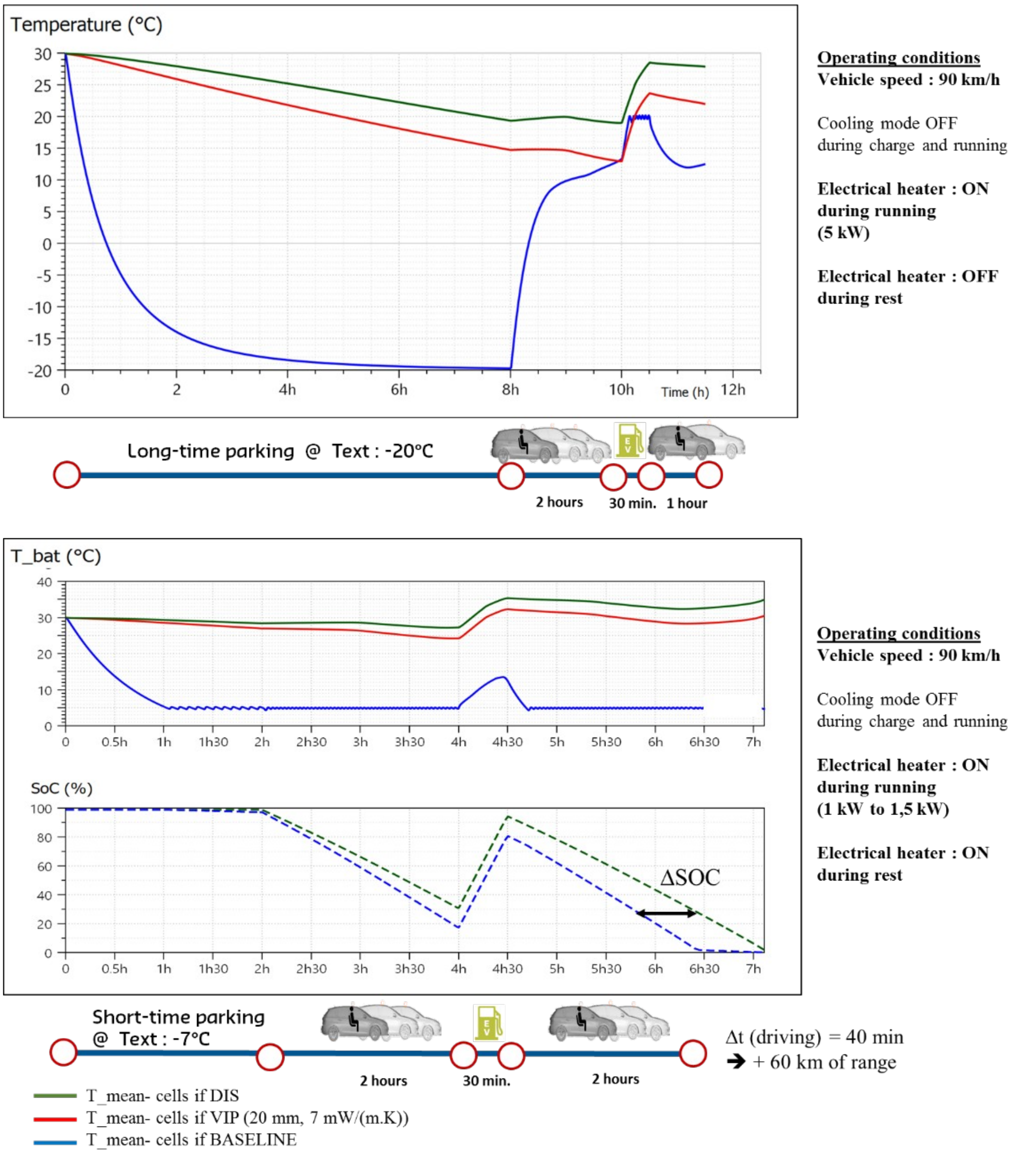


Figure 9: Two scenarios where additional electrical energy consumption is required to maintain or increase the battery temperature

During short parking phases, there is a limited impact of an energy consumption to keep the cells above 5°C, due to a small electric power need. This is no longer the case when the vehicle starts to move because the amount of heat produced by the cells is not high enough to maintain the temperature. There is a need to heat the battery compartment through an electric heating system. The status of charge in the case of the less restrictive scenario (7°C) is higher at the end of the recharge and the difference in capacity due to the lack of energy consumption for the thermal conditioning of the battery allows an extra 60 km under the given conditions.

During long parking phases, a higher electrical power will be required to install the required conditions for battery operation. In a situation where the vehicle would not be connected to the electrical grid, it is not realistic to maintain the temperature of the compartment with an electrical resistance…

As explained in 2.3, it should be noticed that the Thermal Barrier will be reactivated for a future parking when the cold PCMs will liquefy again and so when the heat reaches the latter from the battery. This will of course be possible only if the temperature conditions inside the battery compartment allow to do so which is not the case for all other insulation systems introduced by Figure 8.

Simulations to fulfil the temperature targets with respect to the 12 hours parking period are achieved.

Our next step is to target 15 hours to 24 hours. Tests and demonstrations on real vehicles are underway…

4.2 Customer Benefits with a DIS

Customers are well aware of the correlation between climate conditions, comfort needs and range. Based on publications showing variations of up to 50% from the nominal driving range, there is a widespread feeling of mistrust regarding range estimations and a concern about limited autonomy. This implies a great demand for providing a predictable mileage. Potential buyers of 3rd and 4th generation EVs expect the same level of comfort and safety as current conventional cars, when many BEV taxi drivers in Paris have to wear a pullover and a bonnet in winter…

Temperature distribution throughout a year (Figure 10) is a decisive factor in analysing the actual benefit of a DIS in the context of daily use of an electric vehicle. Depending on the location, it appears that temperatures are often below or above the limits considered for an optimal temperature condition for a battery: HELSINKI 353 days / year below 15°C and SEVILLA 203 days / year above 25°C.

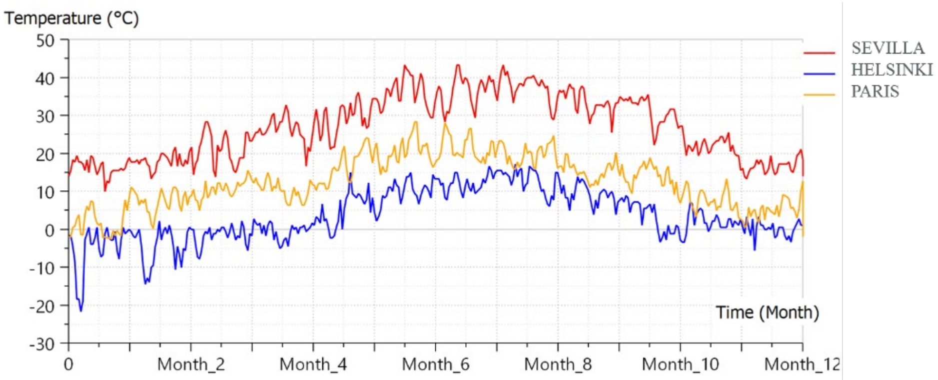
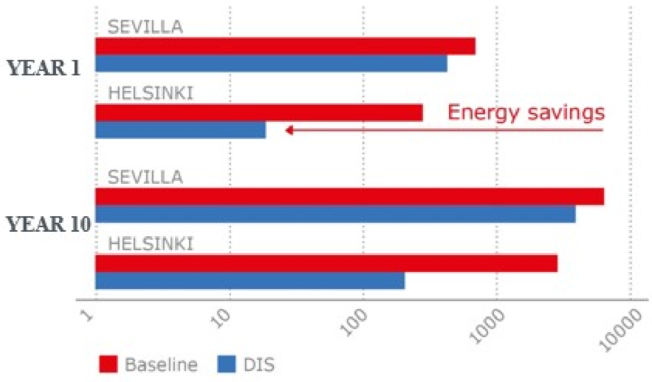


Figure 10: Annual Temperature at Sevilla (SP) T°C : Tmin = 10°C / Tmax = 43,4 °C
and at Helsinki (FI) T°C : Tmin = -22°C / Tmax = 17 °C

Along the year and the ten years (Figure 11), a daily cycle (1 WLTC + 11 hours parking (work) + 1 WLTC + 12 hours parking (home)) will be simulated for a BEV (33 kWh) with a battery T°C set cooling = 20°C, a battery T°C set heating = 5°C and a cooling system active during running and charging phases when T_cell > 34°C.

All results from the AMESIM simulations take into account the DIS mass penalty.



10 Years	BASELINE (kWh)	DIS (kWh)	ENERGY SAVING (kWh)
HELSINKI	2876	188	2688
SEVILLA	7297	4482	2815

Figure 11: Energy Consumption Baseline versus a DIS after 1 year and 10 years

Based on an ECO mode driving (11 kWh/100 km), cumulated energy saving during 10 years with a DIS for hot & cold climates brings an additional range of 26 000 km. Based on 3 kW charging phase, 85 less charging cycles on 10 years with a DIS, saving more than 900 hours.

Due to an optimal temperature conditions for discharging for hot climates, the impressive benefit (Figure 12) for the customer is a cell capacity of its battery increased by a factor 2 (cells capacity after 10 years 60% with a DIS and only 30% without).

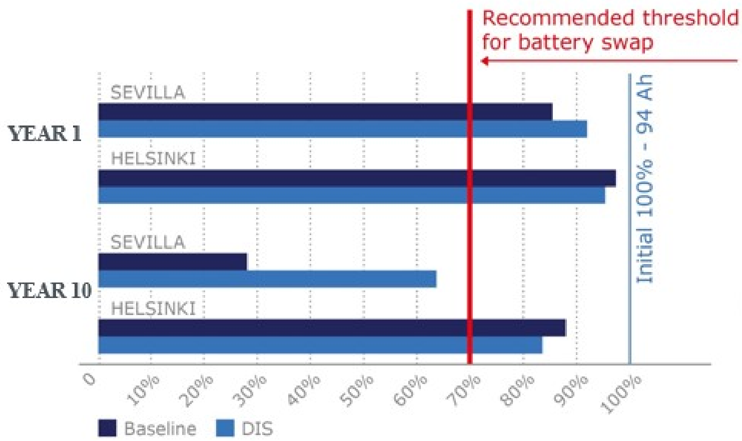


Figure 12: Ageing with or without a DIS after 1 year and 10 years

If initially the battery capacity allowed him to drive 270 km, the impact of the temperatures on the ageing of the cells would lead after 10 years to a situation where only 78 km could be travelled. With a DIS, this distance would be 173 km. Due to a higher average temperature conditions during discharging for cold climates, cell capacity after 10 years will be slightly impacted. Initially 100% - 94 Ah, then, 83,8 Ah without a DIS or with 76,6 Ah, but still above the recommended threshold for a battery swap.

Due to an optimal temperature conditions during charging for hot & cold climates, parking time and occupation of charge station are reduced…. Thus, the customer benefit is lowering its overall travelling time.

Similar positive impacts for PHEV with a DIS could be reached with especially a higher driving range in pure electric mode. Then up to 40% CO_2 reduction could be expected for cold & hot climates.

5 Discussion and conclusions

The battery is the most valuable asset in modern electric vehicles. The most critical factors for buyers when deciding between xHEV or BEV are their usability, their price, their comfort, their durability, their resale value. Ultimately they will also be concerned by their recyclability and their re-usability.

Battery temperature for future electrified vehicles, especially for full electric and plug in hybrid, will have to be all the time managed inside an optimal range, whatever the ambient conditions and wherever they are used. Battery Packs equipped with Thermally Super-Insulated Housing and PCM can extend the range of the EV up to 30%, reduce both EV cost and TCO cost and at the same time significantly reduce charging time.

Hutchinson's Dynamic Insulating System will guaranty more mileage, more comfort, more performance in the worse adverse driving conditions and a higher durability of the battery.

Acknowledgments

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Dr Chopard joined Huchinson in 2014 as Director of the Thermal Management Laboratory. Here is in charge to set up an efficient organization and a successful road map to be able to face all thermal management challenges in vehicles and engine applications. Dr Chopard holds a degree in engineering, a Ph.D. in thermal systems and an MBA degree in Business Management.