# Thermal Management of HV Battery in Hybrid Electric Vehicle

[1]Dhande Suhas
[1]Director, K.R. Sapkal College of Management Studies, Savitribai Phule Pune University, Nashik, India

***Abstract:***
***The limited availability and highly unstable cost of fossil fuel and their effect on the climate change and global warming have forced alternative propulsion technologies in the automotive world. With EV & EVI norms, diesel has been faring better with $CO_2$ and fuel economy norms. However, the diesel engines across the globe have marginal improvements in the emissions and fuel economy potentials indicate that diesel is at the limits. In this scenario, diesel hybrid electric powertrains have shown promise to push the limits even further and offer the ideal platform to maximize benefits of hybridization. The performance of the demonstrator vehicles, an Indian effort in developing 'fun to drive' diesel hybrid, high voltage NiMH battery pack was characterized by conducting on-road testing in the normal road & ghat road areas, it is concluded that performance does vary considerably due to thermal conditions the pack encounters. The performance variations are due to both inherent NiMH characteristics, and the hybrid's thermal management system. Further, it gave the experience of HV battery performance in Indian environment of relatively high ambient temperature and high relative humidity.***

***Keywords***
***Thermal Management, HV Battery, Hybrid, Ni-MH, Li-Ion***

---

**Introduction**

The demonstrator vehicle is a parallel diesel-electric hybrid system i.e., the diesel engine and the electric motor are providing power/torque in parallel to the transmission. The vehicle is a mild hybrid with no pure electric drive mode. The aim of the program was to demonstrate that a hybrid vehicle can be "fun to drive" and be fuel efficient at the same time. The engine was not down-sized as compared to the conventional vehicle (Srinivas, Prasad, Satish, & Dhande, 2009). The hybrid vehicle architecture is shown in figure 1.

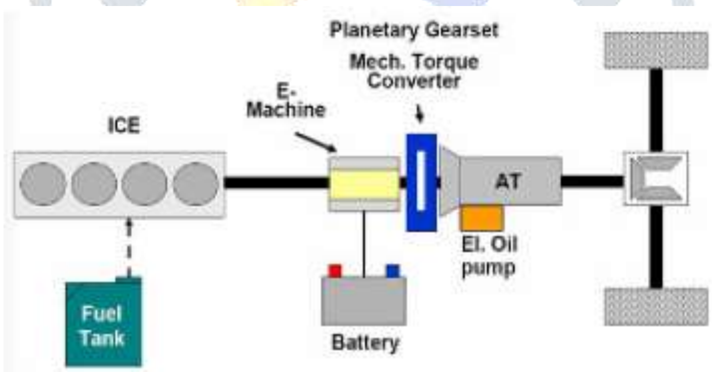


Figure 1. Hybrid Architecture/Layout

Basic configuration - The demonstrator hybrid is a parallel diesel-electric hybrid. As mentioned earlier, the engine on the hybrid is same as the conventional vehicle. It is 8-passenger Sports Utility vehicle.

The main components are
- 4 cylinder common rail diesel engine
- 39 kW Permanent Magnet Synchronous Motor (PMSM)
- Six speed automatic transmission
- 288V Ni-MH battery

Engine: - CR diesel engine with a peak power of more than 80 kW and a peak torque more than 250 Nm.
E- Motor: - Electric motor considered has a peak power of 39kW and a peak torque of 320Nm.

This paper focuses on the Hybrid battery thermal management, the vehicle's performance with its nickel metal hydride (NiMH) batteries at various temperatures, and evaluation of the NiMH pack over its full range of functionality including parking for a long-time in summer. By analyzing the demonstrator vehicle Hybrid battery pack, further improvements can be made in how packaging, thermal management, and electronic management can enhance battery packs for hybrid electric vehicles.

**Selection of HV Battery technology**

**Pure Electric Vehicles**

Electrical energy requirements for hybrid-electric vehicles differ from those for pure electric vehicles, and these requirements affect the cell and battery design**.** For pure electric vehicles, a large amount of energy must be stored in order to transport the vehicle over an acceptable range. The energy stored in the battery serves the same function as the gasoline/diesel in the fuel tank of a conventional vehicle. Typical EV battery packs store on the order of 35 kWh. It is possible to store as much energy as desired in batteries by simply increasing their number, but this increases the weight as well as cost and cooling challenges to unacceptably high values. Therefore, an important objective in the development of batteries for electric vehicles is to maximize energy density, the energy stored per unit volume, or specific energy, the energy stored per unit mass. NIMH can be manufactured with energy densities as high as 300 W·h/L & specific energy, 80 W·h/kg.

**Power Assist Hybrid Electric Vehicles**

For power-assist hybrid vehicles, the main source of energy is the liquid (diesel in this case) fuel. The thing needed from the battery is a power boost for rapid acceleration. Therefore, the attribute of the battery to be maximized is specific power or power density. High-power nimh cells currently achieve a specific power greater than 1,000 w/kg (both pulse 50% depth of discharge, dod).

The main differences between a cell optimized for high energy density, for use in a pure ev, and one optimized for high power, for use in the hev, are the size of the cell and the relative quantities of the different materials contained in the cell. If we consider the two extremes of design — those for evs and those for power-assist hybrids, which require much higher power, relative to the available energy (the high-power cell with 1,000-w/kg specific power has a specific energy of 80 w·h/kg, about half that of the high-energy cell). Both high-energy and high-power cells utilize the same basic spiral-wound design and the same materials. However, some modifications of the designs are required to achieve the desired differences in performance. The high-power cells must be smaller than the high-energy cells in order to dissipate the higher heat load generated. In addition, high-power batteries require less total energy, so battery packs for hevs can be made smaller and lighter than those for pure evs. The different types of battery selection according to the application or usage is shown in figure 2.the comparison between li-ion battery and nimh battery is discussed in table 1. So after considering all the above points, it was planned to use nimh battery technology in demonstrator hybrid.

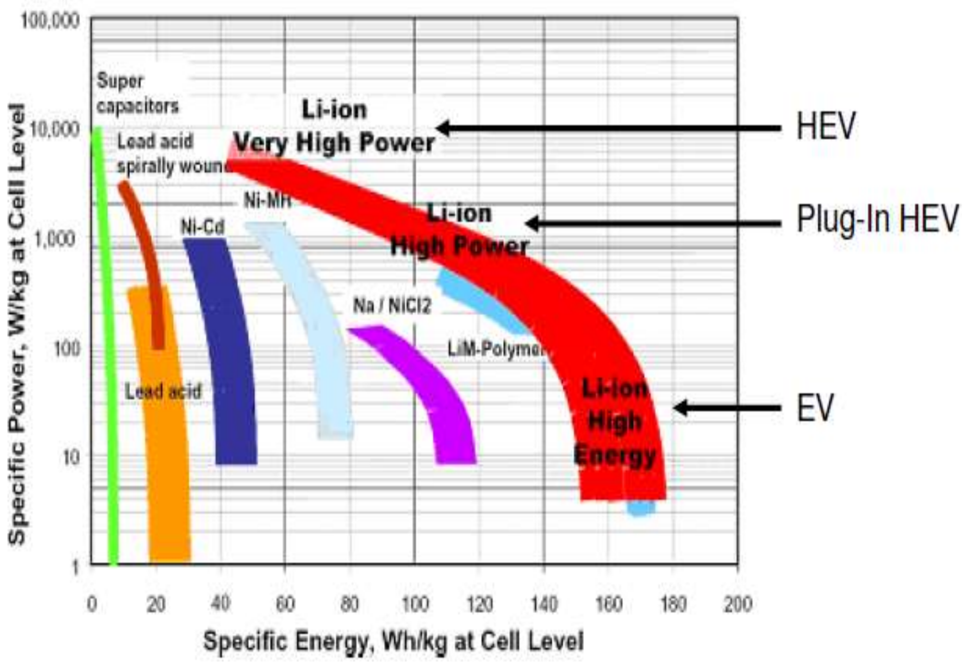


Figure 2. Application dependent Battery selection

Table1. Li-ion and NiMH battery comparison

| Battery Technology | Ni-MH Battery | Li-ion Battery | Comparison |
|---|---|---|---|
| Typical Voltage | Approx. 1.2 V | Approx. 3.6V | Li-ion battery is higher |
| Energy Density (Wh/Kg) | 100% | 180% | Li-ion battery is higher |
| Power Density (W/Kg) | 100% | 200% | Li-ion battery is higher |
| Reliability | Time-proven in HEV market over along period | In Development | Ni-MH Battery is more time-proven |
| System Design Cost | Simple<br>Ni cost becomes more stable, Ni-MH mass production makes more competitive | Complex<br>Cost reduction threshold | Ni-MH Battery is good<br>Ni-MH battery has advantage, in terms of creating a low-cost system |
| Application | Mild HEV, Strong HEV (Compact car).Used in Low-cost system | Strong HEV, PHV,BEV etc. | Ni-MH battery is better for a small system emphasizing cost.<br>Li-ion battery is better large system emphasizing energy. |

**Battery Pack Description**

The demonstrator Hybrid uses High power prismatic NiMH modules from Cobasys. Each module consists of ten 1.2 V cells connected in series. The module has a nominal voltage of 12 V, the capacity of 8.5 Ah, The modules are stacked side by side and then compressed together in a rigid, non-expandable structure that prevents expansion from internal pressures. The complete battery pack consists of the battery stack, enclosure for structural support and airflow, battery electronic control unit/monitor, relays and safety switch. The total pack has 24 modules to deliver 288V .The weight of the complete pack is 92 kg and has overall dimensions of 405 mm (W) X 193 mm (H) X 930 mm (L).The pack is horizontally positioned in the trunk of the vehicle partially under the back seat. Further notable features are as follows:

- A hydrogen vent provides for release of hydrogen through a manifold under gassing conditions,
- Terminals on each side provide clean connections,
- Tie down bolts secure the modules to structural supports,
- A plastic case lowers mass.

The discharge and regenerative power performance of the pack are shown in Fig. 3. Discharge power capability of the pack is around 20 kW at 45% SOC with a regenerative capability of 30 kW at 25□C.The HV battery performance of demonstrator hybrid at full load acceleration is shown in figure 3. The power capability increases with higher temperatures and decreases at lower temperatures. Active thermal management can improve power capability at lower temperatures.

.

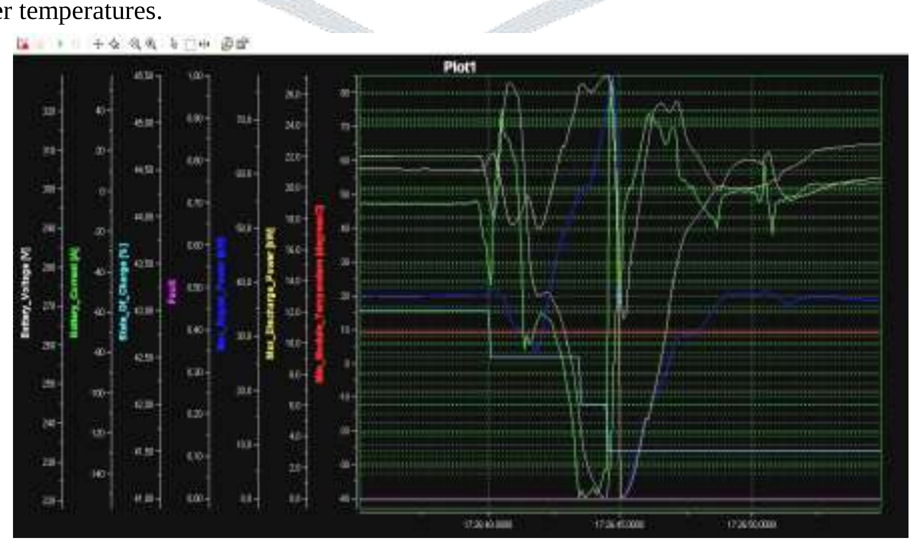


Figure 3. HV battery performance at full load acceleration

**Pack Thermal Management**

Generally, the purpose of a battery thermal management system is to keep the batteries operating at a desirable temperature range; prevent the batteries from exceeding a high temperature limit that can damage the batteries and/or reduce life (Pesaran, 2001); and maintain battery temperature variations to low levels to prevent highly imbalanced batteries. Thru-life impacts of driver aggression, climate, cabin thermal management, and battery thermal management on battery electric vehicle utility (Neubauer & Wood, 2014). Pack imbalances can reduce performance and can also damage the battery and/or reduce life. The goal of a thermal management system in an HEV is to maintain an acceptable temperature range in a battery pack (dictated by life and performance trade-off) with even temperature distribution (or only small variations between the modules and within the pack). However, the pack thermal management system has to meet the vehicle manufacturer's requirements like it must be compact, lightweight, low-cost, easily packaged, and compatible with location.

A thermal management system may use air for heating, cooling, and ventilation (Figure 4), liquid for cooling/heating (Figure 5), insulation, thermal storage such as phase change materials, or a combination of these methods. The thermal management system may be passive (only the ambient environment is used) or active (special components provide heating and cooling at cold or hot temperatures). First, a cooling / heating system was designed to extract/ supply heat to the battery pack. Second, the battery controller adjusts the vehicle's use of the battery pack based on the conditions in the batteries, the environment, and the vehicle demand.

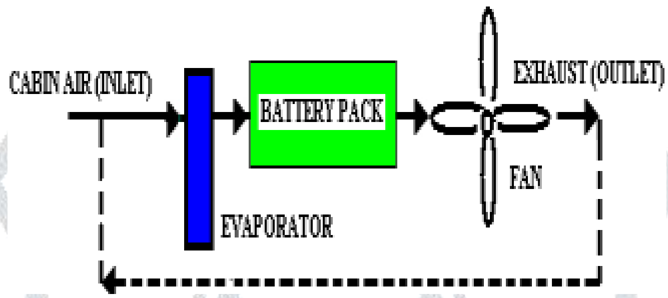


Figure 4. Schematic for Air cooling cabin air

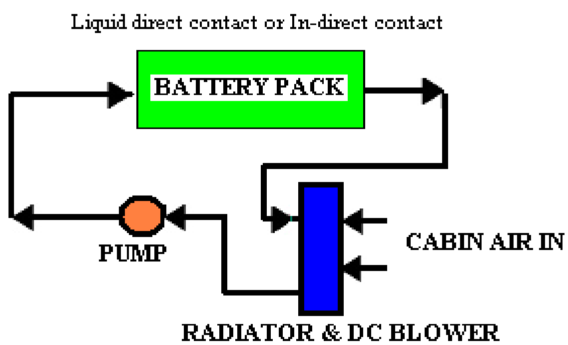


Figure 5. Schematic for Liquid cooling cabin air

NREL has investigated various elements that affect the thermal management of battery packs and has proposed a systematic approach to designing and evaluating a battery management system. (Kim & Pesaran, 2006) Passive systems work well in mild climates; however, an active system is needed in more extreme climates. In an active system, ambient air or a circulating liquid is cooled through heat exchange with a heat sink such as evaporators run by a vapor compression system. The source and type of heat sink depend on vehicle design and the location of the battery pack. However, it was briefly discussed air versus liquid cooling as it has a general impact on thermal performance.

The heat transfer medium has a significant impact on the performance and cost of the battery thermal management system. Heat is transferred with air by directing or blowing the air across the modules. Heat is transferred with liquid through discrete tubing around each module; with a jacket around the module; by submerging modules in a dielectric fluid for direct contact; or by placing the modules on a liquid heated or cooled plate (heat sink). Using air as the heat transfer medium may be the simplest approach, but may be less effective than heat transfer by liquid.

For the same flow rate, the heat-transfer rate for most practical direct-contact liquids such as oil is much higher than with air because of the thinner boundary layer and higher fluid thermal conductivity. However, because of oil's higher viscosity and associated higher pumping power, a lower flow rate is usually used, making the oil heat transfer coefficient not only 1.5–4 times higher than with air. Indirect-contact heat transfer liquids such as water or water/glycol solutions generally have lower viscosity and higher thermal conductivity than most oils, resulting in higher heat transfer coefficients. However, because the heat must be conducted through walls of the jacket/container or fins, indirect contact effectiveness decreases. An ideal controlled coolant system for a battery may look like in the future (Allen & Lasecki, 2001).

Although liquid cooling/heating is more effective and takes up less volume, it has drawbacks. It could have more mass, may leak, may need more components (comparing Figures 4 and 5), and could cost more. Maintenance and repair of a liquid cooled pack are more involved and costlier. Indirect liquid cooling, with either jackets or cold plate, is easier to handle than direct liquid cooling. On the positive side, a liquid cooled system offers the flexibility of placing the pack in areas that air could not be easily available or should be sealed from the road environment. Because of its effectiveness, better temperature distribution, and flexibility for location in a vehicle, liquid cooled systems are more suitable for HEVs. Indirect liquid cooling is a more practical form than direct liquid cooling though it has slightly lower cooling performance (Chen, Jiang, Kim, Yang, & Pesaran, 2016). Temperature impacts battery sizing and life and thus cost (Rugh, Pesaran, & Smith, 2013).

By taking all the above points into consideration current hybrid HV battery has indirect contact heat transfer liquid cooling thermal management system. It is incorporated into the NiMHax 288-60ic to ensure the optimized operation, safety, and life of the battery system. The battery pack's thermal system is self-contained within the enclosure and is maintenance free. The system is designed to operate at a lifetime average inlet air temperature of 25ºC. The liquid cooling system within the battery pack assembly consists of two strings connected in series flow, with six modules in each string connected in parallel flow. The battery system requires a coolant composition of 50% ethylene glycol and 50% deionized water.

## COOLING TRIALS OF HV BATTERY

The demonstrator hybrid vehicle performance was tested under real world usage profile (environmental condition) without A/C 'ON' because cabin air was used for cooling coolant inside the battery. By conducting cooling/temperature trails on two different roads 1.Parking in summer day sunlight. 2. Normal road and 3. Ghat road

**Parking**

The vehicle was parked in daylight in summer at an ambient of 38°C max. The cabin temperature soared to 60°C, whereas the battery max. safe temp. is 55°C.

**Normal Road**

The normal roads have the following features like less traffic, normal to moderately high (but not top) speed to test drive the vehicle in minimum hybrid functionalities like average boost and regeneration. Ambient conditions at the time of trials were 38$^{o}$C and dry humidity. Normal road temperature trials report is shown in figure 6.

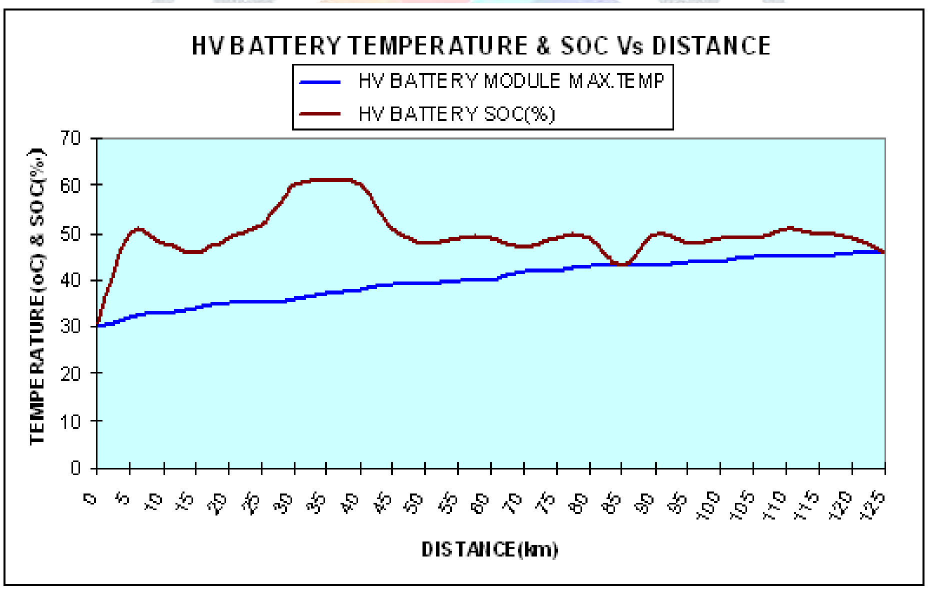


Figure 6. HV battery performance in normal road temperature trials

**Ghat Road**

The ghat roads have the following features like big descending and climbing to test drive the vehicle in high hybrid functionalities like high boost during climbing and very high regeneration during descending. Ambient conditions at the time of trials were 39$^{o}$C and dry humidity. Ghat road temperature trials report is shown in figure 7.

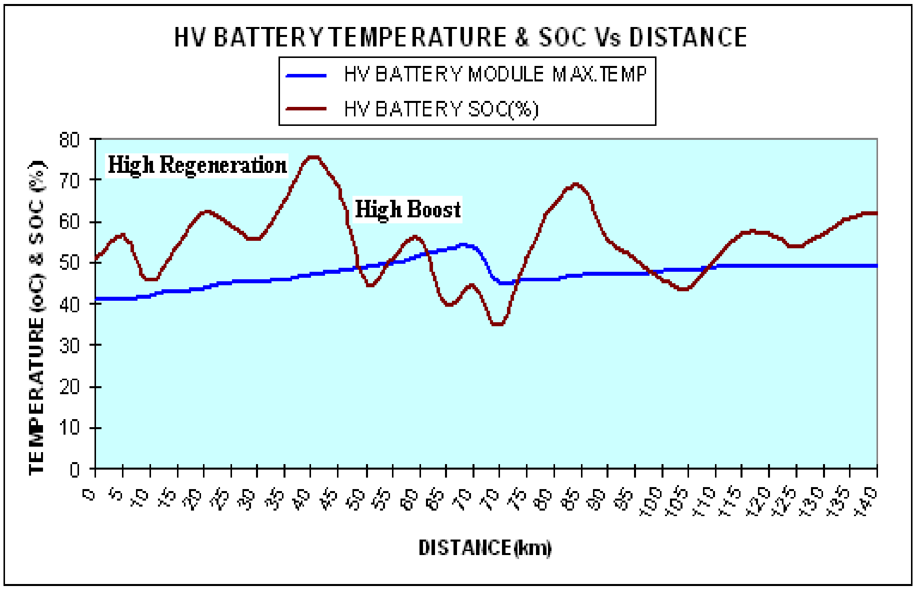


Figure 7. HV battery performance in Ghat road temperature trials

Maximum allowed (safe) temperature of battery is 55$^{o}$C.when battery temperature reaches 54$^{o}$C vehicle halted for 1 hour to cool down battery from 54°C to 45°C, then even after slow running (min. boost & regeneration.),after 45 km, battery again raised to 53°C.

Once the problem of temperature rise of HV battery was analysed, it was found the some part of hot air coming out of HV battery is again going to air inlet (short-circuit) because air inlet & outlet are very near, The NiMH HV battery and its inlet & outlet of cooling system is shown in figures 8 & 9. A duct was made for hot air so that hot air will be sucked by fan powered by 12 V supply and will not get mixed up with air inlet to battery cooling fan. After this arrangement has made, the significant temperature difference was noticed in HV battery module before and after providing a separate duct for hot air coming out of HV battery, its improved cooling circuit & thermal management efficiency. The cooling circuit components inside HV battery pack is shown in figure 10. The duct made to suck hot air coming out if HV battery is shown in figure 11.


Figure 8. The hybrid NiMH HV battery pack

Figure 9. The NiMH HV battery cooling inlet & outlet

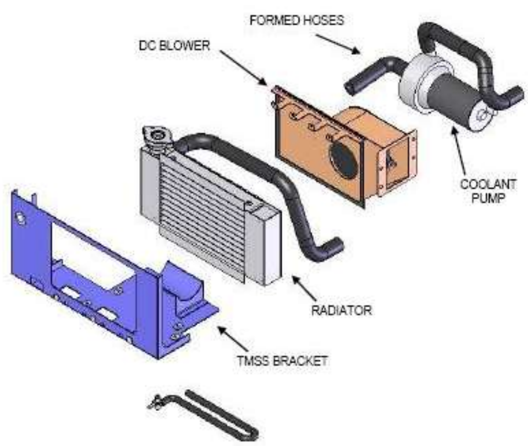


Figure 11. NiMH HV battery cooling circuit outlet duct modification

The cooling circuit within the battery pack assembly consists of two strings connected in series flow; with six modules in each string connected in parallel flow coolant hose is shown in figure 12.

Figure 12. Cooling module

**Result**

The HV battery system is designed to operate at a lifetime average inlet air temperature of 25°C. Further, the maximum allowed safety temperature of the battery is 55°C. At and ambient of 38°C, after 125 km running on the normal road, the battery temperature was 42-43°C and thus in control. This was the case with minimal hybrid functionalities like average boost and regeneration.

In ghat section, where hybrid functionalities are high like high boost and high regeneration, battery temperature shoots up. At an ambient temperature of 39°C and just about 70 km drive, the battery temperature reached to the threshold of 54°C, as the limit is 55°C max.

At parking, the cabin temperature raised up to 60°C against the safety temperature of 55°C.

The inefficiency of new ducting arrangement highlighted the limitations of passive cooling in Indian environmental conditions.

**Conclusions**

HV battery is one of the important and decision-making components in hybrid vehicle system architecture. The HV battery system is designed to operate at a lifetime average inlet air temperature of 25°C and the maximum allowed safety temperature of the battery is 55°C.

The current experiment demonstrated that in high hybrid functionalities, the battery temperature reached to threshold of 54°C, in very short distance, at an ambient of 39°C. In India, some places, the peak temperature crosses 50°C and very dry. That leaves very marginal scope for battery to operate from ambient to threshold temperature. So passive cooling system is not at all useful and active cooling system is mandatory for any practical hybrid vehicle in Indian and similar conditions.

At parking, the cabin temperature raised up to 60°c against the safety temperature of 55°c. This can hamper shelf life of the battery as well as can create a safety issue. So battery manufacturers need to clarify on this. Further, Li-ion is more critical in terms of thermal management than Ni-MH. So Li-ion should be addressed more carefully in Indian ambient.

**Acknowledgments**

The author acknowledges the cooperation of the OEM for giving the opportunity to the author to handle and take trials on the demonstrator vehicle. Also, author acknowledges the guidance and cooperation of the team working on the demonstrator vehicle.

**Declaration of conflicting interests**

The author declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

**References**

**[1]** Allen, D., & Lasecki, M. (2001). Thermal Management Evolution and Controlled Coolant Flow. *SAE Technical Paper 2001-01-1732* (p. 20). SAE International.
**[2]** Chen, D., Jiang, J., Kim, G.-H., Yang, C., & Pesaran, A. (2016). Comparison of different cooling methods for lithium ion battery cells. *Applied Thermal Engineering*, 846-854.
**[3]** Kim, G. H., & Pesaran, A. (2006). Battery Therman Management System Design Modeling. *INternational Battery, Hybrid and Fuel Cell Electric Vehicle Conference and Exhibition (EVS-22)* (pp. 1-19). Yokohama, Japan: National Renewable Energy Laboratory.
**[4]** Lou, Z., & Sabhapathy, P. (2004). *Patent No. US20040069546 A1*. US.

**[5]** Neubauer, J., & Wood, E. (2014). Thru-life impacts of driver aggression, climate, cabin thermal management and battery thermal management on battery electric vehicle utility. *Journal of Power Sources (Elsevier)*, 262-275.

**[6]** Pesaran, A. (2001). Battery Thermal Management in EVs and HEVs: Issues and Solutions. *Advanced Automotive Battery Conference*, (pp. 1-10). Las Vegas, Newada.

**[7]** Rugh, J., Pesaran, A., & Smith, K. (2013). Electric Vehicle Battery Thermal Issues and Thermal Management Techniques. *Alternative Refreigerant and System Efficiency* (p. 16). Arizona, USA: SAE International.

**[8]** Srinivas, A., Prasad, T., Satish, T., & Dhande, S. (2009). Diesel Hybrids - The Logical Path towards Hybridisation. *SAE International*, 10.