Experience in the development of an effective thermal management system for the high-voltage battery of the vehicle

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Abstract. For the effective operation of the vehicle, which includes a high-voltage battery (HVB), it is first necessary to understand what conditions it is designed for. There are a number of criteria for the selection of HVBs for vehicles. One of them is the thermal management system, which ensures the operation of a HVB in an optimal temperature mode. In HVBs, it is necessary to maintain an optimum temperature for maximum efficiency and service life. The article discusses the preferred thermal management system of the main manufacturers of vehicles with HVB. The technical solutions, the applied designs and the development trends of the designs of the temperature control of HVBs are described. On the basis of the considered structures, operating conditions and prospects for the development of the market for such vehicles, the concept of creating an effective thermal management system for HVBs for projected vehicles has been proposed. A classification of the thermal management system of HVBs as part of a vehicle, depending on the climatic conditions of operation, is proposed. One of the developed variants of perspective designs of high-voltage batteries of a vehicle operated in a wide range of temperatures is presented.

1. Introduction
Today, based on the main advantages of hybrid electric vehicles (HEVs), associated with efficiency, environmental friendliness and running characteristics, more and more automakers produce new models of these vehicles. Energy efficiency of HEVs is highly dependent on the performance of high-voltage battery, which must meet a number of requirements: capacity, cost, size, weight, operating temperature range, etc. In this case, the temperature mode is one of the main criteria for the functioning of the hybrid.

Temperature mode affects the charging time of a HVB. The results of studies of the dependence of the charge of a HVB on temperature differences show that the full charge of the battery reaches a maximum in the range from plus 20 °C to plus 40 °C. [2,3]. Although this range may have deviations depending on the chemical composition of the cells used by the manufacturer, but on average this value corresponds to the main types of battery cells used in HVBs on hybrid vehicles.

Temperature mode also affects the service life of a HVB. When charging and discharging, the HVB must be protected from overheating. Overheating of the battery cells above the maximum value indicated for them leads to cell degradation, which significantly reduces the life of the high-voltage battery, up to 50%. [3, 6].

It should also be noted that when charging a cold battery, cell degradation and loss of capacity also occur. A cold battery must not be used if the vehicle has a recovery mode. Operation of a HEV at low ambient temperatures significantly reduces the power reserve (up to 30 – 40 %). Based on the foregoing, the task of thermal management system of a HVB is very important. [4].
2. Overview of high-voltage batteries with thermal management systems of serial-produced vehicles on the electric traction

Figure 1 shows the design of the high-voltage battery Chevrolet Volt. The battery is located in the middle part of the HEV and takes place in the central tunnel and under the rear seat. The battery consists of 288 lithium-ion battery cells, which are divided into three modules and outputs a voltage of 360 V with a total capacity of 16 kW*h. Through the inlet tube, the coolant enters the HVB. Inside the battery, there are heat channels that allow coolant to flow through the cooling plates between the flat cells of the batteries. These channels allow cells to be cooled or heated depending on operational requirements. If the temperature of the battery is lower than the operating temperature, the heating element located on the input channel of the cell is activated and powered directly from the HVB [1, 4].

Figure 2 shows the high-voltage battery of the hybrid electric vehicle VW Jetta. The battery is located above the rear axle. Purified air from the cabin is used for cooling. The VW Jetta high-voltage battery has 60 lithium-ion cells with a total capacity of 1.1 kW*h and allows the vehicle to drive exclusively on electric traction over 1.6 km at a speed not exceeding 70 km/h.

Figure 3 shows the high-voltage battery of a BMW i3 eDrive electric vehicle with a Range Extender. The battery has a complex thermal management system, which is a grid of eight flat aluminum tubes 2.0 mm thick, which regulate the temperature of eight modules. To heat the battery, a high-voltage heating strip is used, fixed on each flat tube. Lithium-ion battery is located at the bottom of the electric vehicle. The body of the electric vehicle is made of lightweight materials. Thanks to a well-thought-out design, it was possible to place a HVB with a capacity of 22 kW * h with a voltage of 360 V, which allows the vehicle to travel 130-150 km with a fully charged battery. But the design feature of the "electric" i3 is the version of the Range Extender, which has a fuel tank of 9.2 liters of gasoline for an additional motor-generator. This allows the vehicle to travel an additional 70-80 km.
3. Classification of high-voltage battery thermal management systems

There are different methods of cooling and heating high-voltage batteries [5, 2]:

3.1. Cooling and heating with air

Air is used for cooling and heating. Air intake can be direct from the atmosphere or from the cabin, and can also be processed by cooling or heating in the cabin microclimate system. Schemes of air thermal management systems can be passive and active. In both cases, the air is forced through the fan. Figure 4 shows the air schemes of the active and passive battery thermal management system.

![Passive system diagram](Passive_system_diagram)

![Active system diagram](Active_system_diagram)

**Figure 4.** Schemes of the active and passive air cooling system and heating of HVB.

Note that the scheme of the air system provides the functions of heating, cooling and ventilation, and the exhaust air is not returned again. In some cases, a heat recovery system is used, which provides additional potential for energy savings. The forced scheme of the air cooling system with heat recovery is shown in figure 5.

![ Forced scheme with heat recovery](Forced_scheme_diagram)

**Figure 5.** Forced scheme of the air cooling system with heat recovery.
3.2. Liquid cooling and heating

There are two groups of liquids used for thermal control of systems. The first is dielectric liquid that can directly contact battery cells, such as mineral oil. The second is conductive liquid that transfers heat through walls indirectly connected to battery cells, such as a mixture of ethylene glycol and water.

Figure 6 shows the circulating scheme of the passive liquid system. Coolant is circulated by a pump in a closed loop. The circulating fluid absorbs heat from the HVB and releases it through the radiator. Cooling capacity is strongly dependent on the difference in ambient temperature and HVB. Fans behind the radiator can improve cooling performance, but if the ambient temperature is higher than the temperature of the HVB or the difference between them is too small, then the system becomes ineffective.

![Figure 6. Circulating scheme of a passive liquid system.](image)

In the following scheme, (see figure 7) there are two circuits. Upper circuit - primary, lower circuit - secondary. In the upper circuit of the passive liquid system, the coolant circulates by means of a pump. The lower circuit is from the microclimate system of the cabin. The upper radiator operates as an evaporator for cooling and connects both circuits. When operating in heating mode, the 4-way valve switches and the upper radiator operates as a condenser, and the lower radiator operates as an evaporator.

![Figure 7. Scheme of the active liquid system.](image)

3.3. Cooling with refrigerant

The principle of cooling with refrigerant is similar to that with cooling fluid. The refrigerant acts as a cooling fluid and circulates through a HVB (see figure 8).
As a result, the following advantages and disadvantages of the considered methods of cooling and heating of electrical components (for example, HVB) can be noted:

- the scheme of the forced air cooling system has a simple structure, high reliability and low cost, as well as ease of maintenance. But not in all cases, the system provides the desired temperature and takes up more space compared to liquid analogues;

- the scheme of the passive cooling system depends on the ambient temperature. Heat from the heat exchanger is dissipated into the environment. In this case, heat dissipation depends on the temperature difference between the liquid and the ambient temperature. At medium temperatures, this scheme operates efficiently, but at high ambient temperatures, it does not. The scheme of the active cooling system has good thermal characteristics, allowing to maintain the battery within the operating temperature, but due to the large number of auxiliary elements, the structure of such a scheme is complex, poorly regulated and has a probability of leaks;

- the scheme of the cooling system using a refrigerant is more efficient, since it uses the refrigerant directly to cool the system, rather than to cool the coolant, which in turn would cool the system. The disadvantages of this cooling system scheme are in the complexity of the structure and maintenance, as well as in the probability of leaks. [5, 2].

4. Experience in developing a thermal management system

The engineers of FSUE “NAMI” carried out research and development of various types of designs of the temperature control system for high-voltage batteries. According to the basic requirements for the system, the design must be efficient, compact, lightweight and meet the safety requirements.

From the point of view of design, layout, manufacturability, pouch cells are the most suitable for heat removal. Their shape allows maximum use of the external surface of the cell case for heat transfer. In addition, we used heat-conducting material, which also provides electrical insulation between the cell case and the cooling system, which can contact other electronic devices of the vehicle through the fluid.

Figure 9 shows the design of the module of 12 pouch cells, between which there are six heat-conducting plates. A cylindrical tube is fixed to each plate through which the coolant flows. The tubes are connected to the collectors of the module.
The developed high-voltage battery with the capacity of 6.2 kW*h with the voltage of 340 V, has eight modules that are interconnected by common collectors. The model of the developed design of the thermal management system is shown in figure 10.

To determine the effectiveness of the thermal management system, hydraulic calculations were carried out.

Design conditions:

- water is selected as the coolant;
- coolant temperature plus 40°C;
- absolute coolant pressure at the outlet of the battery 1.0 atm.
Figure 11 shows the results of the design simulation of the thermal management system for the coolant flow rate of 5 l/min.

![Streamlines and local velocity of coolant flow](image1)

**Figure 11.** The streamlines and the local velocity of the coolant flow for the design model.

The colors of the streamlines show the velocity of the coolant flow, and also allow you to see the formation of turbulence and the uniform distribution of flow in different parts of the system design. In some sections of the module collectors, which are displayed in blue, it is possible to note a low flow rate of the coolant. To improve the uniformity of flow in these areas, it is enough to change the shape of the collectors.

Figure 12 shows the calculated curve of the loss of total pressure as a function of coolant flow. The graph shows that with an increase in coolant flow rate, the hydraulic resistance increases significantly. This dependence is quadratic.

![Total pressure loss](image2)

**Figure 12.** Total pressure loss in the thermal management system of a high-voltage battery.

Figure 13 shows the values of coolant flow rate by modules of HVB. In the presented design of the thermal management system, for its effective operation, the coolant flow must be the same for each
module. Based on this, the optimal value of the distribution of coolant flow rates for eight modules will be 12.5% of the total flow. The graph shows that there is unevenness in the distribution of the coolant relative to the optimal value of 12.5% for the version №1. This indicator can be improved by making adjustments to the design of the thermal management system. In version №2, one of the common collectors was changed. Namely, one of the collectors was turned 180 degrees, after which more optimal values of the distribution of the coolant by module were obtained.

![Figure 13. Distribution of coolant flow rates by high-voltage battery modules.](image)

Figure 13. Distribution of coolant flow rates by high-voltage battery modules.

![Figure 14. Distribution of coolant flow within the 1-st battery module.](image)

Figure 14. Distribution of coolant flow within the 1-st battery module.

Figure 14 shows the values of coolant flow within the 1-st battery module. For the thermal management system of the module consisting of 6 cylindrical tubes, the uniform distribution of the coolant is 16.6% of the total flow. On the graph, we see that the coolant is uniform distributed along the cylindrical tubes of the module, which indicates the efficiency of the design of the thermal management system of the module.
After the optimization modeling, the design documentation for the high-voltage battery was developed; its appearance and dimensions are shown in figure 15.

Figure 15. The appearance and dimensions of the high-voltage battery.

The developed design of the high-voltage battery is intended for operation in the HEV at ambient temperatures from minus 40ºC to plus 50ºC.

5. Conclusion

Thus, when developing a thermal management system, it is necessary to apply the most rational form of collector channels, ensuring minimum turbulence of discharge zones, the smoothest fluid flow without interruptions, which will ensure a more optimal distribution of coolant and the lowest hydraulic resistance and, as a consequence, higher energy efficiency of the heat exchanger.

When developing its own HVB design, the experience of global automakers of batteries for hybrid electric vehicles has been taken into account. The design of the thermal management system of the HVB has good efficiency, since provides quick removal of heat from the battery cells. The efficiency of the design allows you to get an increased power reserve and resource using the required number of cells that are distributed across the modules. The number of modules may be different and depends on the required technical parameters. Improvement of HVBs will allow the use of HEVs in different climatic conditions.

6. References

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