An Experimental Investigation of Electrical and Thermal Performance of Battery Pack for Zero Emission Vehicle

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Abstract. A motor transport is a leading cause of the negative ecological situation and the excessive use of non-renewable resources. Increasing the volume of emissions from the operation of internal combustion engines and increasing consumption of hydrocarbon fuel are factors that stimulate the development of electric vehicles which are environmentally friendly and energy efficient. However, today electric vehicles are difficult to counter conventional cars in terms of cost and performance, determined mainly by characteristics and operating modes of traction battery packs. This article considers some topical issues related to the practical implementation of traction battery packs based on lithium-ion cells. The electric and thermal characteristics of the battery pack are considered by the authors in conditions of a discharge mode simulation. This is believed to be a technical solution for the implementation of a modular battery pack. The present experimental investigations give qualitative and quantitative evaluation of the heat release of lithium nickel manganese cobalt oxide (NMC) cells and demonstrate the efficiency of the realized passive air cooling. This article partly fills the gap existing with regard to real (experimental) data on temperature conditions and heat release of NMC-cells in battery packs of electric vehicles.

1. Introduction

The transport complex is currently the main consumer of hydrocarbon energy sources. It accounts for more than 60% of the total oil production [1]. Over the past two decades, the rate of consumption of oil resources by the transport complex has increased by more than 40%. The increasing consumption of hydrocarbon fuel in transport is mainly due to the following factors:

- high level and rates of motorization;
- operation of motor vehicles (MV) with low fuel efficiency;
- a large proportion of traffic patterns, characterised by the low energy efficiency of the vehicle power unit operation.

The economic growth and the population desire for mobility entail an increase in the number of vehicles. At the same time, the discrepancy between the existing transport infrastructure and the pace of motorization aggravate the problem of fuel consumption. It also has a negative impact on the ecological situation. The traffic pattern in large cities is characterized by a highway overload which causes traffic pattern a large number of stops at a low average speed, this, in turn, results in the internal combustion engine (ICE) of the conventional vehicle operating in extremely inefficient modes – the idling mode and the low load ICE operation mode, thus reducing the fuel economy of the MV.
Given all this, there remains the problem of having a high number of the MVs with a long service life, which negatively affects the fuel economy.

The increase in the combustible fuel use is associated with an aggravation of the environmental situation. The transport complex (road, water, air, and rail) is one of the main polluters of the environment among the economic spheres, with more than 90% of the harmful emission volume of from the transport complex due to the road transport.

The increase in the amount of harmful emissions from the operation of automotive internal combustion engines and the growing consumption of hydrocarbon fuels are the factors that stimulate the development of environmentally friendly and energy efficient vehicles. The latter can rightly be attributed as electro mobile transport, which open up opportunities for a significant improvement of the ecological situation that has developed over the past decades. The usage of zero electric vehicles (EV) can be the way of ensuring the implementation of promising environmental safety standards in transport, including reducing emissions of toxic substances into the atmosphere and transport noise.

However, it should be remembered that the process of producing electric energy necessary for the operation of electric vehicles is associated with the processing and burning of fossil resources at thermal power plants (TPPs). The TPP electric power accounts for a significant share in the total amount of all generated energy. When fuel is burned at TPPs toxic substances are released into the atmosphere, including the carbon dioxide, which negatively affects the atmosphere and the terrestrial climate. Nevertheless, these disadvantages do not cancel out the positive role of the operation of electric vehicles due to the following facts:

- recently, the technology of electricity production has significantly improved in terms of the efficiency of primary fuel conversion, fuel, economic and environmental figures;
- a power plant is a concentrated source of emissions of harmful substances into the atmosphere, in relation to which a complex of environmental measures can be implemented more effectively;
- a power plant is located and operated, as a rule, outside the people everyday life zones, as opposed to road transport;
- the power plant of an electric vehicle, unlike one of a conventional car, is not a source of toxic emissions at the immediate place of vehicle exploitation;
- the electricity conversion efficiency of an electric vehicle is significantly higher than the fuel consumption efficiency of an ICE vehicle;
- the charging infrastructure of electric transport can be considered as a way of correcting the uneven load schedule for the existing power system;
- along with improving the effectiveness of power plants for electric vehicles, it is possible to improve the energy and environmental efficiency by optimizing and improving the process of electricity production, as well as using environmentally friendly renewable energy sources.

Thus, it is possible to position with confidence the large-scale operation of EVs in large cities and megacities as a way to improve the ecological situation and improve the quality of people's life.

However, a modern electric vehicle is still difficult to put in a row with a conventional car in terms of performance and affordability to the end user. The reason for this is a traction lithium-ion battery pack which is the most expensive component of a modern electric vehicle. The improving of the performance of electric vehicles, such as all-electric range, traction and dynamic performance, service life, reliable operation temperature and many others is inextricably linked with the temperature mode of battery cells in a traction battery (TB) optimization. The effective heat dissipation implementation in discharge and charging modes or maintaining optimum TB operating temperature in the cold season is an important issue that determines the characteristics of an EV in operation and the EV battery life.

There are many different technical solutions for the creating of the traction batteries temperature conditions, including using air and liquid thermal management systems, mathematical simulations for describing the temperature dynamics of cells. However, among the existing information sources it is difficult to find real (experimental) data on the temperature conditions and the heat release of lithium-ion cells in the traction battery of an electric vehicle. In this connection, the present article is aimed at
calculating the current loads of the traction battery of an electric vehicle in different traffic patterns and the experimental evaluating of the heat release associated with the indicated heat release modes.

2. Features and operating modes of the electric vehicle power system
One of the main problems of battery packs based on lithium-ion cells (LIC) is the change in the characteristics of the latter during operation. The loss of energy can be the result of an increase in internal resistance which, in turn, leads to a decrease in the capacity and operating voltage. There are additional energy losses which are caused by the conversion of active materials to inactive phases. Some mechanical changes in the structure of the active material take place during the cycling, including stratification of graphite, reduction of the active surface of the electrodes and a reduction in the nominal capacitance, directly related to these processes. The temperature increase in battery during the operation negatively affects the nominal capacity, which reduces in these conditions by 5 ... 10% and is aggravated along with the current load increase.

The battery cells operation in the battery pack of an EV includes a number of modes, such as a discharge with short-time maximum currents and long-time current loads. In this connection, the operation of the TB is accompanied by the release of thermal energy and the exothermic reactions taking place here can lead to an excessive increase in the temperature of the TB modules, which in turn can initiate the failure of the LIC. The operation of the LIC in conditions of negative temperatures is more advantageous, in comparison with inadmissible heating of the cells, which can lead to a decrease in the capacity and power of the TB, as well as the limitation of the charging currents.

Summarizing, it can be concluded that it is necessary to use a specialized system that provides an optimal temperature regime for the traction battery operation, aimed at ensuring the traction source of power operation safety, energy efficiency and an increase in the service life of an LIC.

One of the best methods for maintaining the optimal temperature regime for the traction battery among the existing ones, is heat rejection from battery cells to a device that conducts heat exchange with the environment. The following can be considered as the main qualitatively different solutions for cooling the electric vehicles TB of:

- Passive cooling of the traction battery. The main advantage of this scheme is simplicity and low cost. The main drawbacks include uneven heat dissipation from cells, lack of heating elements and heat-insulating materials which adversely affects the capacity of the battery during operation in low-temperature conditions.

- Forced air cooling of TB. The advantages of the air cooling systems include the even cooling of battery modules, relatively low cost and relatively small weight of the structure. The main disadvantage is the lower values of specific energy by volume (Wh/l).

- Cooling with a liquid coolant. Cooling of the cells in the TB with a coolant is the most effective technique of battery thermal management. The disadvantages of such systems include high complexity and cost of implementation.

In this article, the authors propose a solution for the implementation of the traction battery of the electric vehicle, which makes it possible to realize the combination of two thermal management cell techniques - highly effective natural convection and air forced ventilation.

3. Description of the electric vehicle traction battery design
Technical design of the TB is based on the principle of modularity of design and unification aimed at forming the system of accumulation and storage of electric power with specified characteristics on the basis of one functionally complete and autonomous module. The basis of the unified battery module (UBM) is a prefabricated structure made of composite frames of the patented configuration. The physical configuration of UBM is shown in figure 1. Two interfaced frames (1) form a section containing two prismatic lithium-ion battery cells (2) with electrodes of a determined shape. The type of cells used in this solution is Lithium Nickel Manganese Cobalt Oxide with Lithium Manganese Oxide (NMC + LMO). The section with cells is limited by aluminum plates on both sides (3), the
plates serve as a heat sink. The functioning of this heat sink is ensured by the air gap (4) formed between the adjacent sections.

![Figure 1. Physical configuration of UBM: a) a detailed diagram; b) model; c) photo of the manufactured module](image)

Several sections are combined into one unit - a battery module, fastened by aluminum end walls (5) and tie rods (6). The electrical connection of the battery cells in the module is provided by the special conductive plates (7, 8) which provide electrical contact between the electrodes. In this example, the module contains 24 cells, included in the 12s2p scheme. The electrodes of the first and last battery section in the module are connected to the power insulated terminal (9), which forms the positive and negative pole of UBM for the subsequent connection of power cables (10). The connecting cable is then fixed in the module using a sealed cable entry (11). The battery module contains a battery management system (BMS) board (12) that provides status monitoring and balancing of cell voltages in the module.

The BMS heat sink is fixed to the aluminum cover (13) of the UBM casing. In addition to measuring the temperature of the module by temperature sensors (14) in the BMS, each battery section additionally contains a thermal switch (15), which provides direct indication of exceeding the permissible operating temperature of the cells. The power and communication circuits of UBM are connected to the multipoint connectors (16). The BMS compartment of the module is divided into two parts by a cover-insulator (17), also performing the screening function.

A battery pack of almost any configuration with any specified characteristics can be formed on the basis of a unified battery module. Along with the transport purpose, the presented technical solution can be successfully used in power engineering, including autonomous power plants designing, for the formation of energy accumulation and storage systems.

4. Definition of traction battery operation modes as part of the electric vehicle power system

Within the framework of the research carried out in this article an assessment is made of electrical and related thermal characteristics applicable to the technical solution for the execution of the EV traction battery presented above. The ultimate goal of this study is the experimental evaluation of the battery modules heat release and the efficiency of realized convection cooling. The solution of this problem can be arbitrarily divided into the following stages:

1. Calculation of discharge and charge power of the electric vehicle battery pack under various conditions of vehicle movement.
2. Calculation of the current load of the TB in the driving cycle of the EV.
3. Calculation the equivalent discharge current of the battery pack.
4. Experimental reproduction of the calculated load currents during bench tests.
5. Measurement of heat release during the experimental realization of the TB loading regimes.

The operating modes of an electric vehicle TB depend on many factors, which are determined by the characteristics of a vehicle (vehicle weight, frontal projection area, aerodynamic resistance, wheel
radius, etc., as well as traffic patterns (driving cycle, type and profile of the road and etc.). These parameters determine the necessary traction and power characteristics of the electric propulsion system and TB operation modes. The characteristics of a vehicle are constants, while the traffic patterns are functions of many variables. So, for example, the characteristic aspects of the city and the suburb traffic vary according to an average traffic speed, a number of acceleration and deceleration sections, and a number of stops in the total travel time. Given such a difference in the traffic pattern and chaotic character of the traffic itself, a standardized driving cycle of vehicle, which would be as close as possible to the most loaded conditions for the movement of EV, should be distinguished for an objective analysis of the TB operation modes [2].

Respectively, the required current loads of TB, realized during the movement of an electric vehicle in typical driving cycles were calculated within the framework of this study, including: ECE15, EUDC, NYCC, HFEDS, NEDC, FTP72, US06. An experimental sample of a passenger electric vehicle with a curb weight of 1.4 tons was considered as an object of study [3]. The traction battery pack of this electric vehicle consists of eight UBMs with a nominal voltage of 45 Vdc and a capacity of 80 Ah. The nominal voltage of the TB with a serial connection of a UBM is 360 Vdc with a maximum energy reserve of 32 kWh.

For the indicated driving cycles, characterized by the duration D, the dependence of the speed V and the acceleration (deceleration) a, on the time t, for the passenger electric vehicle, as the required performance of the traction motor (TM) is calculated: the required shaft torque \( T_m \) and the rotor speed of TM \( n_m \) in the time function t. Here are the basic calculated dependencies:

\[
T_m = \frac{1}{i \cdot \eta} \left[ m \cdot f \cdot g \cdot \cos \alpha + g \cdot \sin \alpha + a \cdot \sigma + 0.5 \cdot \rho \cdot c_s \cdot S \cdot V^2 \right] \cdot r_w, \text{Nm} \tag{1}
\]

\[
n_m = \frac{30 \cdot V \cdot i}{\pi \cdot r_w}, \text{rpm}; \tag{2}
\]

where \( m \) is electric vehicle weight, kg; \( g \) is acceleration of gravity, m/s²; \( \alpha \) is road grade, deg; \( a \) is acceleration (deceleration) of an EV, m/s²; \( \sigma \) is rotational inertia coefficient, p.u.; \( \rho \) is air density, kg/m³; \( c_s \) is aerodynamic coefficient, p.u.; \( S \) is frontal projection area of EV, m²; \( V \) is the speed of the EV in the driving cycle, m/s; \( r_w \) is dynamic wheel radius, m; \( i \) is transmission ratio, p.u.; \( \eta \) is the mechanical transmission efficiency, p.u.

The values of \( T_m \) and \( n_m \) allow to determine the discharge / charge power \( P_b \) of the traction battery and the load current \( I_b \):

\[
P_b = \frac{T_m \cdot n_m}{9550 \cdot \eta_m \cdot \eta_i}, \text{kW}; \tag{3}
\]

\[
I_b = \frac{P_b}{U_b}, \text{A}; \tag{4}
\]

where \( \eta_m \) is the TM efficiency, p.u.; \( \eta_i \) is traction inverter efficiency, p.u.; \( U_b \) is the nominal voltage of the TB, Vdc. In the calculation, it is assumed that the voltage of the TB during the discharge and charge does not change and corresponds to the nominal value. The TB current in the EV movement mode varies in a wide range and takes different values. Therefore, for a comparative evaluation of the considered driving cycles from the point of view of the energy intensity the concept of an equivalent (thermal) current should be introduced, which is defined according to the following expression:

\[
I_{eq} = \left( \frac{1}{D} \int_0^D I_b^2 \, dt \right)^{1/2}, \text{A}. \tag{5}
\]

The value \( I_{eq} \) reflects the TB current load in the discharge and charge modes. This value is equivalent to the constant current of the discharge. The common sense of the equivalent current consists in substantially simplifying the experimental investigations of the temperature conditions, which in this case can be realized with a constant current load of the TB.
The characteristics of the considered driving cycles, as well as the results of calculating the performance of the light electric vehicle TB for these driving conditions, are presented in table 1.

**Table 1. Parameters of driving cycles and current load of the electric vehicle traction battery.**

|                     | Urban driving cycles | Highway driving cycles | Mixed driving cycles |
|---------------------|----------------------|------------------------|----------------------|
|                     | ECE15                | NYCC                   | HFEDS | US06  | NEDC  | FTP72 |
| Duration, sec       | 195                  | 598                    | 400    | 765   | 600    | 1181  | 1368 |
| Distance, km        | 1.013                | 1.898                  | 6.955  | 16.512 | 12.8  | 11.007 | 12.1 |
| Maximum speed, km/h | 50                   | 44.6                   | 120    | 96.4  | 129.2  | 120   | 91.2 |
| Average speed, km/h | 19                   | 11.4                   | 62.6   | 77.7  | 77.3   | 33.4  | 31.5 |
| Maximum battery current I₀, A | 50.2 | 105.7 | 130.7 | 96.7 | 298.3 | 130.7 | 117.6 |
| Equivalent battery current Iₑq, A | 14.4 | 17.3 | 44.5 | 40.6 | 78.2 | 28.2 | 25.2 |

The analysis of the obtained results allows to conclude that the most energy intensity driving cycle among the considered is US06 cycle, describing the motorway traffic. The cycle is characterized by the high values of the average and maximum speed, intensive acceleration and deceleration. The operation of the electric vehicle TB in this case is accompanied by a significant current load: the maximum value of the discharge current reaches 298 A, and the equivalent of load current, taking into account its own consumption by the on-board systems, is 78 A.

The presented results made it possible to formulate the TB operation conditions for experimental investigations of the battery module thermal conditions.

5. An experimental simulation of the calculated load currents and thermal conditions of the electric vehicle traction battery

For the purpose of experimental research of electric and thermal modes of the proposed technical solution for the execution of the EV traction battery modules a complex test bench (CTB) for the traction and power electrical equipment system was formed. The CTB includes the following equipment: Inverter (I), Motor (M), Load Device (LD), Power Switching Unit (PSU), Remote Control (RC), Auxiliary Power Supply (APS), Analog-to-Digital Converter (ADC), Personal Computer (PC), Current Sensor (CS), Voltage Sensor (VS). The structural diagram of the stand with the connected TB is shown in figure 2.

![Figure 2. Structural diagram of the complex test bench with the connected traction battery](image)

The principle of operation of the test bench is based on setting the required discharge current of the TB by means of an alternating current electric drive operating on the load device. The required operating mode of the LD and the electric drive is set from the remote control. The CS and VS sensors measure the load current and the TB voltage with subsequent display and registration on a personal computer. During the investigation of the TB, the status of the cells in the battery pack is also monitored via the BMS included in its structure.
Within the framework of this study, an experimental evaluation of the electrical characteristics of the TB based on NMC-cells was carried out. The experiment included the following steps of the TB tests:

1. The discharge of the TB with the maximum current realized in the US06 driving cycle (Step 1).
2. The discharge of the TB with a constant current which is an equivalent to the current load in the US06 driving cycle (Step 2).
3. Repeat the equivalent current mode according to the previous stage after a short pause (Step 3).

The implementation of the maximum currents was carried out in a short-time mode with alternating phases of the TB discharge and relaxation. The purpose of the first stage of the tests is the experimental estimation of the battery pack performance in modes close to the maximum permissible, as well as the evaluation of the efficiency of the implementation of internal electrical connections in the battery module. The results of measuring the current and the voltage of the TB during a discharge with a maximum current are shown in figure 3. The presented graphs show changing characteristics of the TB voltage at a linear increase of the discharge current (see figure 3, a) and when sustaining the maximum current during 20 s (see figure 3, b).

![Figure 3](image-url)

**Figure 3.** The traction battery current and voltage in the maximum load mode

The above modes of the electric vehicle TB take place, mainly, when intense acceleration to high speeds is performed, and can also be observed when driving on up-grade. In typical driving conditions, such loads are short, they constitute a small part of the total cycle and, as a rule, alternate with lower load modes. Despite the high values of discharge current, these modes (with reference to typical cycles) change in a minor way the overall steady-state thermal operation of the TB.

In order to determine the overall picture of the TB modules thermal condition, in the second stage of the tests the TB was being operated in the long-term discharge mode with a constant current $I_{eq}=78.2$ A. This current value corresponds to the TB operation mode which is an equivalent to the EV movement in the mixed US06 driving cycle, including sections of low speed and highway traffic.

The implementation of TB load modes with the help of the complex test bench was accompanied by the monitoring and recording the temperature of each battery module at the completion of the each stage of testing. The general aspect of UBM and TB as a whole in the infrared spectrum with the temperature on the surfaces is shown in figure 4.

The results of TB temperature measurements are summarized in table 2.

6. The analysis of the results

The obtained data show that the proposed technical solution for the implementation of TB modules provides an acceptable thermal mode of battery cells operation in the energy intensity mode which is an equivalent to the movement of a light electric vehicle in the US06 driving cycle.
During the test the maximum temperature recorded in the air gap between the UBM sections at an ambient temperature of 18 °C, was 24.3 °C, but on the heat sink surface it reached 28.9 °C. Taking into account the maximum permissible operating temperature of 55 °C it can be concluded that the UBM convection cooling, which was suggested, is effective without active air cooling. It should be noted, that forced air ventilation of battery cells was not used but, available in the shown solution, increases the potential to maintain the normal temperature conditions of each lithium-ion cell in the UBM and extends the environment operating temperature range.

### Table 2. The results of thermal mode estimation of the EV traction battery at the maximum current (Step 1) and two consecutive US06 cycles (Step 2, Step 3).

|                         | Step 1 | Step 2 | Step 3 |
|-------------------------|--------|--------|--------|
| Average temperature of UBM, °C | 18.9   | 20.9   | 21.6   |
| Maximum temperature of UBM, °C | 20.7   | 22.7   | 24.3   |
| Minimum temperature of UBM, °C | 18.0   | 19.8   | 20.1   |
| Maximum temperature of UBM electric connectors, °C | 20.7   | 23.0   | 24.9   |

**Figure 4.** The infrared images of UBMs in the process of traction battery thermal conditions investigation:
- (a) UBM after two cycles of maximum load of 300 A according to Fig. 3;
- (b) UBM at the end of the first discharge cycle with the equivalent current of US06;
- (c) UBM and (d) UBM internal electrical connectors at the end of the second discharge cycle with an equivalent current of US06

Since UBM contains a sufficiently large number of interconnected cells, the issue of the quality of internal electrical connections is relevant. In connection with this, in the course of experimental studies, temperature control was carried out at the places where the electrodes were connected. The maximum temperature did not exceed 24.9 °C, at that, the temperature spread of all connectors in the module was about 0.5 °C, which confirms the reliability of the realized split bolted connection.

### 7. Conclusion

Environmentally friendly and energy efficient vehicles are the basis of the future motor transport complex, which closely interacts with the electric power industry based on the same principles. Lithium-ion cells are the most expensive and complex part of the transport complex. The mentioned cells require special operating conditions aimed at increasing the service life and efficiency of available battery power indicators. In this regard, the issue of ensuring optimal operating conditions for cells in traction battery packs is relevant, including new technologies in chemical current sources.

The proposed variant of the execution of the electric vehicle modular battery is aimed at solving the indicated issues. The analysis of the obtained results allows concluding that the implementing of the
technical solutions for battery cooling in the unified battery module of an electric vehicle is efficient. The realized heat dissipation in UBM, the arrangement of the batteries, as well as the solutions for connecting the electrodes, can provide the high discharge powers required for the realization of intensive driving modes of the electric vehicle.

The approach to the determination of the equivalent current load, presented in this paper, makes it possible to evaluate the operating cell modes as part of traction batteries. At the same time, the equivalent current load causes the heat release in the TB which proves to be comparable with the heat release both in the case of a discharge in the traction mode and in the regenerative braking of the electric vehicle mode. This approach makes it possible to substantially simplify the reproduction of TB thermal conditions in the course of experimental studies to evaluate the effectiveness of various technical solutions for battery thermal management, which is vital for electric vehicles.

8. References

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