Calculation and experimental research of liquid flow through a radiator of the electric car power battery thermal management system

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Abstract
The article presents current state of the development of the thermostatic control system for electric vehicle traction batteries. The results of calculation and experimental research of the fluid flow through the radiator of the electric car power battery thermal management system are described. Based on the data obtained, a pressure-flow characteristic of the radiator is constructed.

Keywords: CFD, coefficient of hydraulic resistance, liquid cooling system, electric vehicle battery

1. Introduction
Currently, in the automotive industry there is a steady trend towards the development and implementation of innovative technologies. A major area of development and research in the automotive industry is the transition to environmentally friendly energy sources, instead of the traditionally used carbon-based internal combustion engines. Recently, vehicles with an electric type of engine (electric vehicles) have become very popular. Structurally, the electric car is driven by one or more electric motors powered by an autonomous energy source, which is usually an electric battery. In addition, the battery system, in addition to batteries, also includes charge balancing systems, a battery management system and a battery temperature control system.

The thermal management system of the battery is designed to maintain acceptable temperature on the battery cells (battery cells, Figure 1) under various climatic conditions of car operation.

Figure 1. Battery cell

The presence of this system is primarily due to the fact that the battery is the most expensive component of the electric vehicle, and the battery cells are the most expensive component of the battery (Figure 2). It is also worth noting that the battery cells can not be repaired, so when they fail, they are replaced with new ones. The service life of the battery cells can be increased by maintaining a constant cell temperature in the range from 20 °C to 25 °C (for most types of battery cells).
Experimental research [1] show that at a temperature of 45 °C for 1500 charge-discharge cycles, the ability of a cell to hold a charge decreases by more than 30%, and the increase in internal resistance reaches 100%. However, while maintaining the temperature of the battery cell at 24 °C for 1500 charge-discharge cycles, the ability of the cell to hold a charge decreases by less than 15%, and the growth of internal resistance decreases to 30% (Figure 3).

Taking into account the above factors, it can be concluded that the presence of a battery thermal management system increases the life of the battery cells and reduces the cost of repair and maintenance of the electric vehicle’s traction battery.

2. Research subject
One of the main elements of the battery thermal management system is a liquid radiator (Figure 4), which serves to remove or supply thermal energy to the battery cells of the traction battery. These radiators are connected by a single pipe with a circulating coolant.

One of the main tasks in designing the pipeline of a thermal management system is to determine the hydraulic resistance coefficient (HRC) of the system (1). This value is necessary to select the operating point for the volumetric flow rate of the liquid in the system and select the necessary circulation pump. One of the main sources of hydraulic resistance in the pipeline of the thermal management system is the liquid radiator of the battery. Since the battery, depending on the configuration, consists of 10-20 radiators, it is necessary to evaluate the hydraulic resistance of this element with high accuracy. To determine the hydraulic resistance, methods of computational fluid dynamics (CFD-Computational Fluid Dynamics) can be used, which allow modeling the turbulent fluid flow generated inside the radiator channel with fairly high accuracy.

\[ \xi = \frac{2 \cdot \Delta P}{\rho \cdot v^2} \]  

where \( \xi \) is the hydraulic resistance coefficient (HRC), \( \Delta P \) is the pressure drop (Pa) created by the fluid flowing through the radiator, \( \rho \) is the fluid density (kg/m\(^3\)), and \( v \) is the fluid flow velocity in the calculated section (m/s) (in as the calculated one, the section of the pipeline supplying medium is taken).

3. Experimental Research

To confirm the calculation results using CFD analysis, an experimental research was conducted, the purpose of which was to determine the HRC of a liquid radiator.

Figure 5 shows the hydraulic circuit of the bench for hydraulic testing of the radiator. Liquid (water) enters the test radiator 6 from the pressure tank 1 by means of a circulation pump 2. Measurement of the flow rate and temperature of the liquid in the supply line takes place using a flow meter 4 and a temperature sensor 3. The pressure drop across the test radiator is measured by a differential pressure gauge 5. Tubing of the test bench (Figure 6) is made of polypropylene pipes reinforced with fiberglass.
Figure 6. General view of the test bench

According to the recommendations from [2] and [3], in order to obtain the correct values of the pressure drop ($\Delta P$) generated by the radiator, it is necessary to position the test radiator and the static withdrawals of the differential pressure gauge in areas with a stabilized flow. To fulfill this condition, the withdrawals and the inlet (fitting) of the test radiator are located at a distance $L_{\text{start}}$.

$$L_{\text{start}} = 15 \cdot d$$  \hspace{1cm} (2)

where $d$ is the inner diameter of the pipe of the hydraulic circuit.

The definition of HRC radiator is carried out in two stages. Since withdrawals are located at some distance from the test radiator, sections of the supply pipes create additional hydraulic resistance. Based on the fact that the purpose of the tests is to determine the hydraulic resistance of the radiator ($\xi_{\text{rad}}$), it is necessary to measure the pressure drop created by the friction of the flow against the pipe walls ($\Delta P_{\text{pipe}}$) and subtract the calculated hydraulic resistance coefficient ($\xi_{\text{rad}}$) from the total coefficient of hydraulic resistance of the radiator and pipes sections ($\xi_{\text{total}}$).

$$\xi_{\text{rad}} = \xi_{\text{total}} - \xi_{\text{pipe}}$$  \hspace{1cm} (3)

$$\frac{2 \cdot \Delta P_{\text{rad}}}{\rho q^2} = \frac{2 \cdot \Delta P_{\text{total}}}{\rho q^2} - \frac{2 \cdot \Delta P_{\text{pipe}}}{\rho q^2}$$  \hspace{1cm} (4)

where $\Delta P_{\text{rad}}$ - the desired pressure drop on the radiator; $\Delta P_{\text{total}}$ - pressure drop measured with a radiator connected to the circuit; $\Delta P_{\text{pipe}}$ - pressure drop measured when connecting the supply pipes.

At the first stage, the pressure drop is measured ($\Delta P_{\text{total}}$) in the hydraulic circuit system consisting of the tested radiator and supply pipes (Figure 7). The flow meter, temperature sensor and pressure transducer (manometer) are taken.

At the second stage, the pressure drop is measured ($\Delta P_{\text{pipe}}$) in the hydraulic circuit system without a radiator. For this, the radiator is excluded from the pipeline, and the supply pipes are interconnected, forming a new closed loop (Figure 7). The fluid flow rate is set equal to the flow rate measured in the first test stage. The flow meter, temperature sensor and pressure transducer (manometer) are taken. The measurement results of the volumetric flow rate of the liquid ($q$, [m$^3$/s]), pressure drop ($\Delta P_{\text{pipe}}$ [Pa]), temperature of the liquid in the circuit (T [°C]) are recorded in the table of the test report.

After the experiment, the results are processed and the radiator HRC is calculated ($\xi_{\text{rad}}$). Provided that the results of measuring the pressure drop ($\Delta P_{\text{total}}$) and ($\Delta P_{\text{pipe}}$) are obtained at the same fluid flow rate ($q$), we can calculate the value of the hydraulic resistance coefficient of the radiator ($\xi_{\text{rad}}$) based on the ratio:
4. Processing experimental data

Table 1 - the results of the calculation of the radiator hydraulic resistance

| №  | Q \cdot 10^{-3} (m³/s) | ΔP_{rad} (Pa) | ξ_{rad} | ξ_{ave} |
|----|-------------------------|----------------|---------|---------|
| 1  | 0.169                   | 13041          | 3.08    | 3.06    |
| 2  | 0.188                   | 16041          | 3.08    |         |
| 3  | 0.200                   | 18437          | 3.04    |         |
| 4  | 0.224                   | 22578          | 3.04    |         |

After calculating the hydraulic resistance coefficient of the radiator, it is necessary to determine the measurement errors [4].

Calculation of the systematic measurement errors in determining the HRC of the radiator:

$$\delta \xi_{syst} = \delta \xi_{rad} + \delta \xi_{pipe}$$  \hspace{1cm} (6)

Where $\delta \xi_{syst}$ is the systematic error of measurements in the system of supply pipes and the radiator, $\delta \xi_{rad}$ is the systematic error of measurements of the radiator, $\delta \xi_{pipe}$ is the systematic measurement error of the supply pipes.

$$\delta \xi_{i} = \frac{C}{q_i^2} \cdot \varepsilon_{diff} + \frac{2 \cdot \Delta P_i}{q_i} \cdot \varepsilon_{low, met}$$  \hspace{1cm} (7)

$$C = \frac{2 \cdot f^2}{\rho}$$

where $\varepsilon_{diff}$ is the relative error of the differential pressure gauge, $\varepsilon_{low, met}$ is the relative error of the flowmeter, and $\varepsilon_i$ is the systematic measurement error.

The calculation results are presented in Table 2

Table 2 - The calculation results

| ε_{diff} | ε_{low, met} | δξ_{rad} | δξ_{pipe} | δξ_{syst} |
|----------|-------------|-----------|------------|-----------|
| 0.005    | 0.01        | 0.124     | 0.032      | 0.092     |

Calculation of random measurement error:

We take the sample size of the measurements $N = 4$, then:

$$\sigma_{ave} = \sqrt{\frac{\sum (\xi_{calc} - \xi_{ave})^2}{N(N-1)}} = 0.017$$  \hspace{1cm} (8)

Student's coefficient $K_0 = 2.353$ for $n = 1$ degrees of freedom and 95% of the two-way confidence interval.

Random measurement error:

$$\delta \xi_{rand} = K_0 \cdot \sigma_{ave} = 0.039$$  \hspace{1cm} (9)

The total measurement error during testing:

$$\delta \xi_{total} = \sqrt{\delta \xi_{rand}^2 + \delta \xi_{syst}^2} = 0.13$$  \hspace{1cm} (10)

5. Calculation research

For the correct description of the calculated geometry by the finite volume method used in computational fluid dynamics (CFD), a number of operations are necessary [6].
To simulate fluid flow through the radiator channel, the region of the fluid flow is generated from the initial three-dimensional radiator model (Figure 8), then the resulting geometry is edited to simplify the construction of the computational grid. The finished computational grid (Figure 8) consists of finite volumes of various types: the regions suitable for constructing the computational grid using the extrusion algorithm are constructed from triangular prisms, the remaining parts of the geometry are constructed from tetrahedral elements, the wall regions were crushed by prismatic elements. This action is necessary for the correct resolution of the wall layer of the fluid flow, in which a high velocity gradient occurs, caused by energy loss due to overcoming the friction forces against the wall of the radiator channel. The total number of finite elements of the primary mesh is approximately 1.6 million. This size was established based on preliminary tests grid convergence of solutions.

To correctly describe the fluid flow, a two-parameter model of turbulence "k-e Realizable" with standard model parameters was used. The boundary conditions for the calculation are: the volumetric flow rate \( q, \text{ m}^3/\text{s} \) of the liquid at the inlet section, the atmospheric pressure at the outlet section \( P_{\text{atm}}, \text{ Pa} \), and the no-slip wall conditions for all remaining external faces. The water under 20°C is selected for fluid domain.

6. Calculation results

According to the data obtained during the calculation research, it is possible to calculate the radiator hydraulic resistance coefficient. For a correct assessment of the pressure drop created by the fluid flowing through the radiator, it is necessary to take the result from the inlet and outlet sections of the radiator, i.e., do not take into account the stabilization sections (Figure 8). The difference in the static pressure values at the inlet and outlet sections of the fluid flow region of the radiator will be the total loss of pressure of the radiator. The calculation results are shown in table 3.

\[
\Delta P_{\text{rad}} = P_{\text{in}} - P_{\text{out}}
\]  

Table 3 - Numerical simulation results

| №  | Turbulence model | Input speed, \( v \) (m/s) | \( \Delta P \) (Pa) | \( \xi_{\text{rad}} \) | \( \xi_{\text{ave}} \) |
|----|------------------|-----------------------------|---------------------|----------------------|---------------------|
| 1  | k-e realizable    | 4,01                        | 25125,5             | 3,131                |                      |
| 2  | k-e realizable    | 3,6                         | 20421,6             | 3,158                |                      |
| 3  | k-e realizable    | 3,37                        | 17919,3             | 3,162                | 3,150                |
Figure 6 shows the pressure distribution on the surfaces of the radiator fluid flow region. The greatest hydraulic resistance to the flow is exerted by the zones near the inlet sections formed by the intersection of the fittings and the radiator body. In these areas, the high velocity of the fluid flow relative to the main channel of the radiator, and there is a change in the direction of fluid flow due to the geometric shape of the channel. The distribution of the streamlines of the fluid flow velocity (v, m/s) through the radiator is shown in Figure 7.

Figure 9. The distribution of static pressure

Figure 10. Distribution of streamlines

One of the main hydraulic characteristics of the pipeline elements, in this case the radiator, is the pressure-flow characteristic. The pressure-flow characteristic of the radiator is a graph of the pressure drop (ΔH, m) created by the radiator versus the volumetric flow rate of the liquid (Q, l/s) flowing through the radiator.
Figure 11. The graph of the pressure-flow characteristics of the radiator

7. Analysis of the of calculation and experimental research results

1. During the experimental research, the value of the radiator hydraulic resistance coefficient \( \xi = (3.06 \pm 0.13) \) was obtained; \( \delta \xi = 2\% \). This result satisfies the accuracy criteria (\( \delta \xi = 5\% \)).
2. When comparing the results of calculating the radiator using CFD codes with the results of the experiment, it was possible to find out that the calculation model and the proposed calculation procedure are correct, since \( \xi_{\text{ave}} = 3.15 \) falls within the confidence interval of the experimentally obtained value.

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