

Virtual simulation of the heat exchanging process of a lithium-ion battery in a vehicle

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Abstract. The article describes a virtual (numerical) model of part of the temperature control system of a lithium-ion battery developed for subsequent modeling of the required operating conditions as part of a vehicle. This system lets to maintain a strictly defined temperature regime automatically. It is required for the safe operation of battery cells, protecting them from overheating and cooling during operation. The virtual model under consideration consists of a thermal model of the battery and a control system for it, while the control algorithm is specified in the form of a block diagram. The article is a continuation of work on the creation of a comprehensive functional 1D top-level model of the product to predict the operation of a typical battery pack depending on the type of vehicle and the battery management system (active or passive balancing).

1 Introduction

Eco-friendly, low-carbon transport and special equipment play an important role in reducing the negative impact on the environment and increasing the efficiency of agricultural production. Today in the transport engineering industry there is a tendency to gradually shift the interest of leading manufacturers and consumers from products with traditional gasoline and diesel engines to power plants using alternative energy sources, in particular, to installations powered by a lithium-ion battery (LIAB), which consists of lithium-nickel manganese cobalt oxide (NMC) batteries.

When developing LIAB, special attention is paid to the temperature control system, which allows maintaining a strictly defined temperature regime required for the safe operation of NMC battery cells, protecting them from overheating and cooling during operation.

The purpose of this work is to describe an approach using specialized 1D CAE software to develop a virtual (behavioral) model of a battery module, including a temperature control system heat exchanger, which allows you to calculate heat exchange processes between cells and coolant depending on the operating mode of the vehicle and environmental conditions.

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2 Thermal model of lithium-ion battery

2.1 Thermal model of LIAB as part of a vehicle

Figure 1 shows a complex 1D upper-level model of the vehicle for simulation of LIAB operation, developed in 1D application software, described in [1]. The virtual model is made in the form of a block diagram with the ability to configure; Model-based systems engineering (MBSE) technologies are used, described in [2-3].

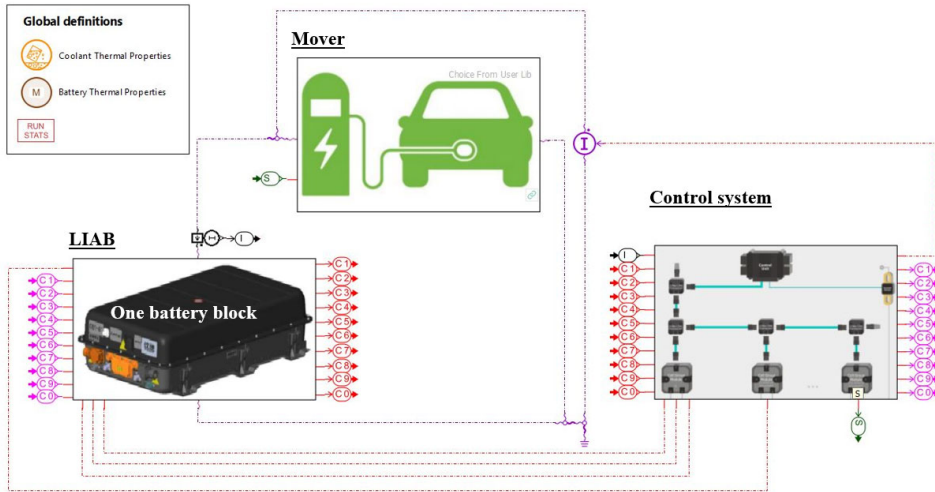


Fig. 1. General view of a complex 1D CAE model for reproducing the operation of LIAB as part of a vehicle.

The complex model of the upper-level level of the vehicle includes the following virtual models of the main systems:

- “Propulsionist” block of the complex model of the upper-level level (can be represented by an electric vehicle, railway transport, maritime transport, as well as a bench installation);
- “Battery block” of the complex model of the upper-level level;
- “Control System” block of the complex model of the upper-level level;
- “Dashboard” block of the complex model of the upper-level level.

The complex model of the upper-level level block “Battery block” simulates the operation of a rechargeable battery (Figure 2).

The upper part of the block elements imitates the electrical circuit of a battery pack. The lower part of the block elements reproduces the thermal processes occurring between the LIAB cells, between the aluminum heat exchanger and the LIAB cells, as well as between the aluminum heat exchanger and the coolant.

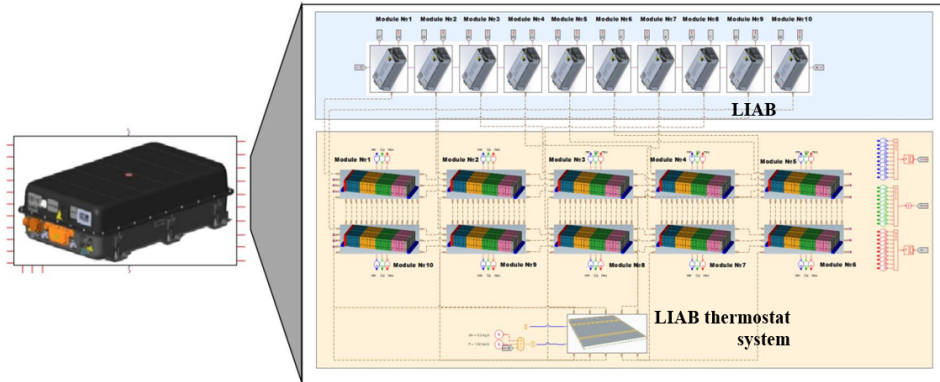


Fig. 2. Sketch of a 1D model of the “Battery block” of the complex model of the upper-level level.

Let us consider in more detail the description of the numerical model of the heat exchange processes of the battery pack.

2.2 Description of the LIAB thermal model

A schematic diagram of the design of part of the thermostating system as part of the LIAB is shown in Figure 3.

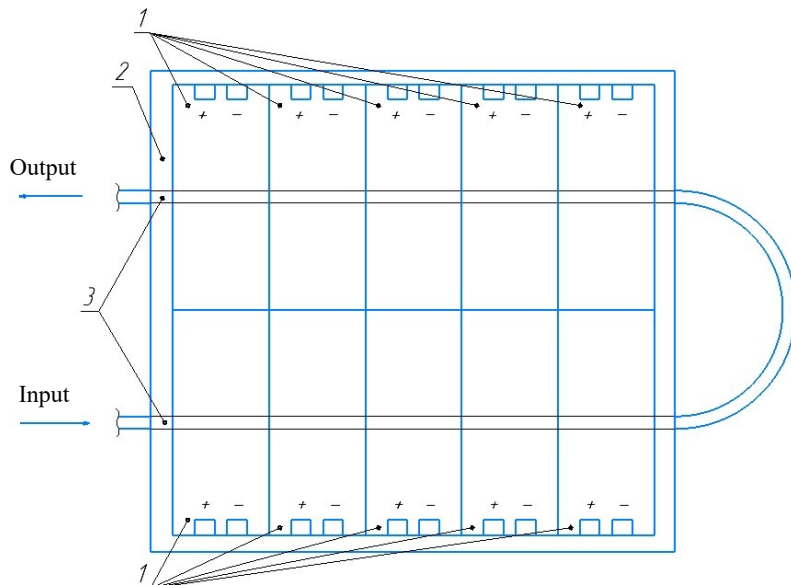


Fig. 3. Schematic diagram of the LIAB THERMOSTATING SYSTEM: 1 – LIAB modules; 2 – aluminum plate; 3 – channels with liquid.

Let us consider the principle of operation of the device (see Figure 3). LIAB blocks (position 1) are installed on an aluminum plate (position 2) with channels for liquid (position 3). Cooling and heating of the LIAB is carried out through heat exchange between blocks of cells and the plate. Liquid (ethylene glycol 40%, water 60%) is supplied through channels in the aluminum plate. Cooling and heating of the aluminum plate is carried out through heat exchange between the plate and the liquid.

To describe the design of the thermostating system part of the battery pack, the following behavioral thermal 1D model was developed (see Figure 2, lower part). The model is described using sources of heat flow supplied (or removed) to the LIAB cells, providing a given operating temperature of the LIAB cells. The 1D model of the thermal part consists of supercomponents, which determine the thermodynamics of each module and plate with liquid. Models of LIAB modules are connected to each other and to the plate model by thermal ports, with the help of which heat exchange is carried out between the corresponding elements. The heat release for heating during operation of the battery of each module cell is set from the supercomponents (SC) of the electrical part of each module, respectively, while the detailed structure of the thermostating system and the principle of heat supply or removal are not modeled. When developing numerical models, materials presented in sources [4-5] were used, as well as additional data from sources [6-7].

A numerical 1D model of the thermal part of one cell module is presented in Figure 4. The signal part of the 1D model determines the minimum, average and maximum temperature of the cells of each module.

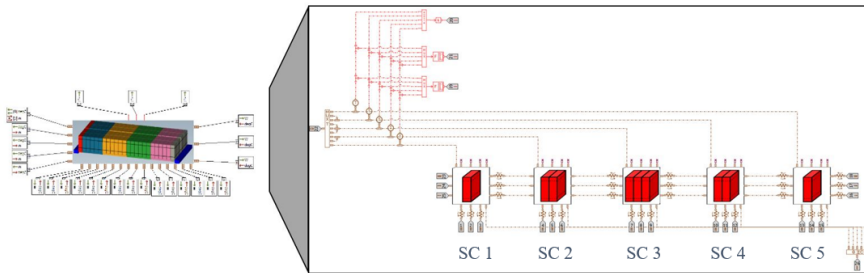


Fig. 4. Sketch of a 1D model of the thermal part of one block of cells.

The SC of the thermal part of each block of cells, in turn, consists of 5 SC (combining several cells into one SC is justified by accelerating the calculation time and simplifying the model):

- 1st and 5th include one cell each;
- 2nd and 4th include two cells each;
- 3rd includes three cells.

An SC consisting of three cells is shown in Figure 5.

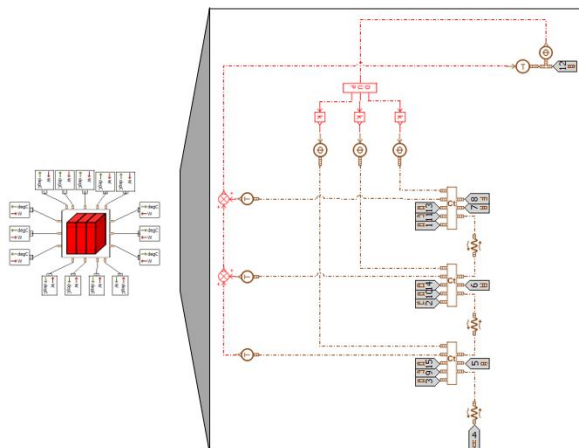


Fig. 5. Sketch of a 1D model of a set of cells in the SC thermal part of one cell module.

The supecomponent (Figure 5) consists of the following elements:
 - submodel of conductor heat exchange between the corresponding thermal masses;
 - a submodel of thermal mass that determines thermodynamic processes in the cell element.

The following parameters are specified: material type (electrolyte); heat exchange area; distances between temperature determination points; mass of material.

A numerical 1D model of a plate with a liquid block of the complex upper-level model “Battery block” (one section) is presented in Figure 6.

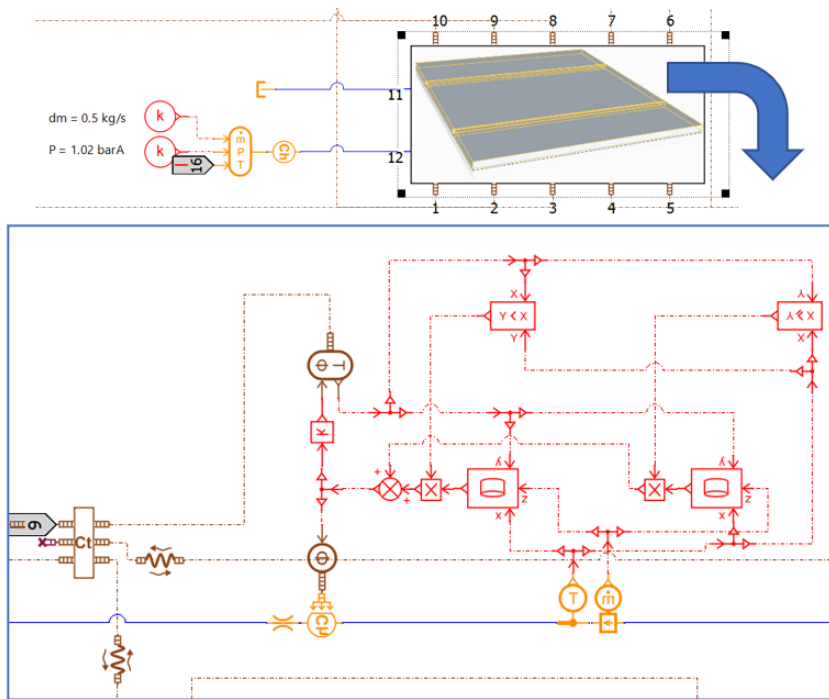


Fig. 6. Sketch of one section of the 1D plate model “Battery Pack” of the complex upper-level model.

The plate consists of 10 elements (sections) in contact with the corresponding module. A liquid with a given mass flow rate and pressure is supplied to the plate inlet. The temperature of the liquid at the plate inlet is determined by the thermostating system control system. Each section of the plate includes a thermal part of the plate element, a thermal-hydraulic part of the liquid, and a signal part that sets the heat exchange process between the plate and the liquid.

The SC (see Figure 6) consists of the following elements:

- submodels of thermal masses that determine thermodynamic processes in the plate element; the type of plate material (aluminum alloy) and the mass of the material are specified as parameters;
- submodels of conductive heat exchange between the corresponding elements, the type of material, heat exchange area, distances between temperature determination points are specified as parameters;
- submodels simulating thermodynamic processes in the volume of liquid;
- submodels simulating hydraulic losses; the geometric characteristics of the channel flow section are determined as parameters.

The heat exchange process between the plate and the liquid is specified using a set of 3D tables. These tables were generated based on the results of a CFD thermal-hydraulic calculation of fluid flow in a cooling plate in specialized 3D CAE software in order to simplify the 1D model and reduce the calculation time.

The input data for the 3D calculation are fluid temperature, plate temperature and fluid mass flow. The object of calculation is a plate with channels for liquid. The 3D CAD model selected a fluid channel element corresponding to one block of the LIAB module (Figure 7).

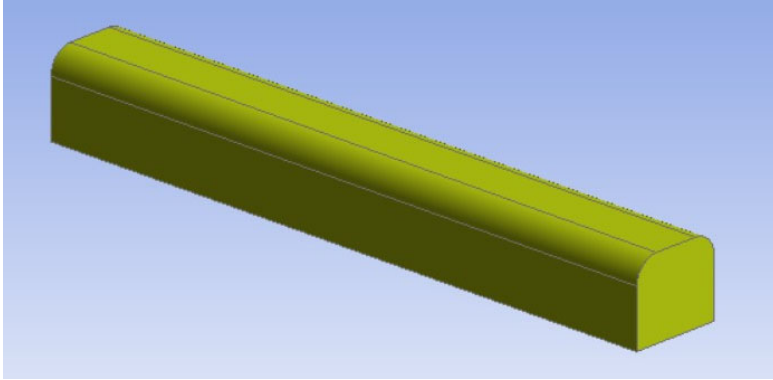


Fig. 7. 3D CAD model of a fluid channel for CFD calculations.

To carry out 3D CAE calculations, a finite element model of the fluid flow body was built (Figure 8), which contains 308,512 elements with the following parameters:

- average element size: 1 mm;
- average element bevel: 0.22;
- average element orthogonality: 0.77.

The model has 12 boundary layers caused by heat exchange between the liquid and the plate.

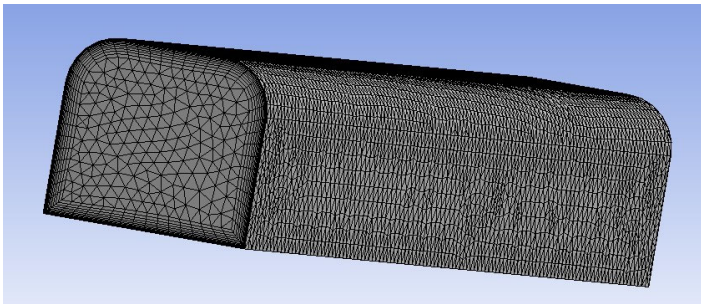


Fig. 8. Finite element model of a fluid flow body.

The following process conditions for CFD calculations are considered:

- liquid flow: 10-35 l/min in increments of 5 l/min;
- liquid temperature: 5°C-20°C in increments of 5°C;
- plate temperature: 30°C-55°C in 5°C increments.

Based on the size of the flow path and the mass flow rate at the inlet, it was concluded that the flow is turbulent. The energy equation is included in the calculation, and the standard k-e turbulence model is selected. Current body: standard ethylene glycol. The entire volume

is assigned the selected liquid. The plate temperature is assumed to be constant throughout the entire volume of the calculation element. The heat exchange between the plate and the liquid is determined by the parameters of the channel walls.

The results of the CFD calculation are the magnitude of heat transfer between the liquid and the plate in all design modes. These values of the calculation results are entered into 3D tables for further use in the 1D model. An example of part of the calculation results is given in Table 1, where:

- Mass_flow_rate – mass flow rate of liquid at the plate inlet;
- Temperature_fluid – liquid temperature at the plate inlet;
- Temperature_wall – plate temperature;
- Total_heat_transfer_rate – heat flow through the contact surface of the liquid and the plate.

Table 1. Part of the CFD calculation results.

Mass flow rate	Temperature fluid	Temperature wall	Total heat transfer rate
<i>l/min</i>	°C	°C	W
10	5	30	891.28149
10	5	35	538.62545
10	5	40	1618.0713
10	5	45	1160.2388
10	5	50	2404.1451
10	5	55	1873.9036
10	10	30	1461.719
10	10	35	883.70114
10	10	40	2181.9401
10	10	45	1566.1312
10	10	50	2938.1187
10	10	55	2292.6372

2.3 Description of the control system for the LIAB thermostating system

The LIAB thermostating control system provides optimal operating modes for the thermostating system under all possible environmental conditions and operating modes of the LIAB. The required operation logic of the thermostating system is presented in Table 2.

Table 2. Operating modes of the thermostating system.

LIAB operating mode	Conditions for turning on	Shutdown conditions	Liquid temperature at the plate inlet, °C
Battery discharge + heating	$T_{min} \leq 5\text{ °C}$ and $T_{av} \leq 8\text{ °C}$	$T_{min} \geq 10\text{ °C}$ or $T_{av} \geq 13\text{ °C}$	55
Battery discharge + cooling	$T_{max} \geq 30\text{ °C}$ and $T_{av} \geq 26\text{ °C}$	$T_{max} \leq 26\text{ °C}$ or $T_{av} \leq 24\text{ °C}$	12
Battery charging + heating	$T_{min} \leq 12\text{ °C}$ and $T_{av} \leq 15\text{ °C}$	$T_{min} \geq 30\text{ °C}$ or $T_{av} \geq 26\text{ °C}$	55
Battery charging + cooling	$T_{max} \geq 17\text{ °C}$ and $T_{av} \geq 20\text{ °C}$	$T_{max} \leq 26\text{ °C}$ or $T_{av} \leq 24\text{ °C}$	7

where:

- T_{min} – minimum cell temperature;
- T_{av} – average cell temperature;
- T_{max} – maximum cell temperature.

The implemented numerical 1D model of the control system for the LIAB battery pack thermostating system, which describes the required control logic, is presented in Figure 9.

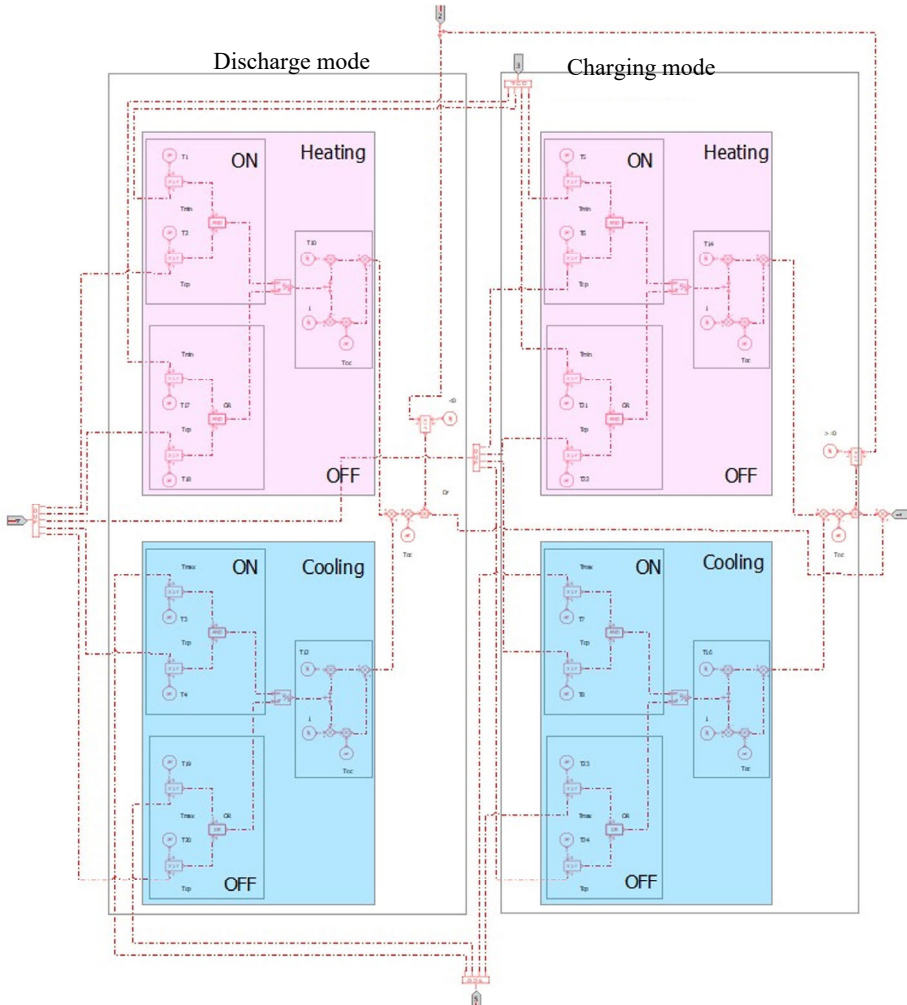


Fig. 9. Sketch of a 1D model of the control system for the LIAB battery pack thermostating system.

The implemented numerical model determines the values of the parameters of the liquid supplied to the input of the plate depending on the discharge/charging mode of the LIAB.

The numerical model of the control system for the thermostating system is located in the “Control System” block of the complex upper-level model in the form of a control system.

3 Results and discussion

As an illustrative example, below there are the results of virtual modeling using a complex upper-level model when operating a LIAB (with active balancing) as part of an electric vehicle (vehicle category M1, number of LIAB battery units - 2 pcs.) during straight-line movement along the WLTC driving cycle for 1800 sec followed by stopping and charging the battery. The vehicle traveled more than 23 km, during which time an average of 12% of the maximum possible stored energy in the LIAB was spent. For an ambient temperature set

at 25 degrees Celsius, the maximum heating of the cell does not exceed 30 degrees Celsius (Figure 10), which indicates adequate operation of the thermal control system in these environmental conditions and in this vehicle driving mode.

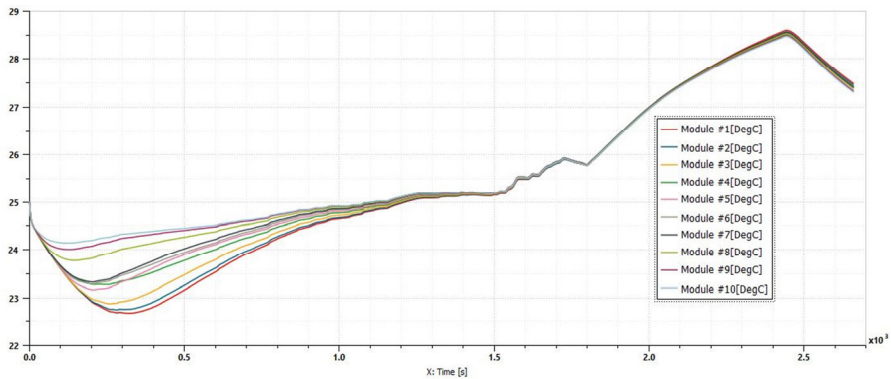


Fig. 10. Results of virtual modeling during operation of LIAB as part of an electric vehicle. Changing the maximum temperature value in the modules of one LIAB battery pack.

4 Conclusion

The virtual 1D model of the part of the thermostating system as part of the LIAB presented in this work was developed as part of the general 1D model of the vehicle. At the same time, it is an independent tool for conducting virtual tests in various operating modes. Analysis of data obtained in this way saves resources for carrying out full-scale tests, allows you to determine modes with high energy efficiency, and also test the system in emergency modes without risks for vehicles and personnel. The developed virtual model can be used as part of a complex upper-level model of a vehicle with LIAB.

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