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Intensification of heat exchange with a modified coolant in phase transition heat accumulators

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Abstract. The article presents the results of experiments on intensifying heat transfer of a paraffin heat accumulator using nanomaterials. The purpose of the work is to create a laboratory stand to test the effectiveness of a heat accumulator using a nanomodified coolant. The paper presents information about phase transition heat accumulators, a description of the laboratory bench, and the results of experiments. During the study, results were obtained that allowed us to evaluate the positive effect of the introduction of nanomodifiers on the operating cycle of a heat accumulator.

1 Introduction

Increasing the efficiency of energy consumption is the main vector of development of modern energy. The main way to reduce the consumption of primary fuel and energy resources and increase the efficiency of thermal power plants and systems is the accumulation of thermal energy.

Currently, there are many designs of heat accumulators, but the greatest prospects for development are heat accumulators that use the latent heat of the phase transition of the heat-storing material [1, 2, 3].

When the phase state changes, for example, during a transition from a solid to a liquid or from a liquid to a gaseous state, a large amount of heat is absorbed; in the case of reverse processes, a large amount of heat is also released, called the latent heat of phase transition [4, 5, 6].

Low-temperature heat accumulators are widely used in hot water supply systems, in which paraffin is an effective heat-accumulating material due to its properties, such as thermal and chemical stability, safety, but this material has a significant drawback - a low thermal conductivity coefficient, which significantly increases the charging time of such an accumulator. Therefore, conducting research on intensifying heat exchange between the coolant and the phase-transition material to accelerate the process of charging (melting) and discharging (crystallization) is an urgent task.

One of the ways to intensify heat exchange is to modify heat carriers, i.e. add various additives to improve heat transfer, one of which is nanomaterials.

Nanofluids are colloidal suspensions in which nanometer-sized particles of solid matter are uniformly distributed in a specific base fluid.

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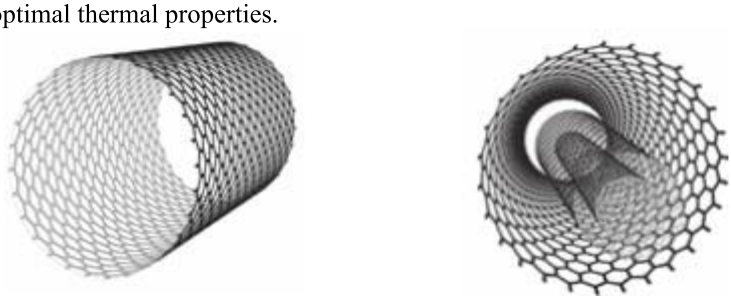
Substances that form nanofluids are called nanomaterials, the following elements can be nanomaterials:

- various metals such as aluminum, copper, iron, silver, gold;
- oxides, for example, sulfur dioxide, copper oxide, aluminum oxide, etc.;
- carbides and nitrides of metals and non-metals;
- carbon modifications (multi-layer, single-wall carbon nanotubes, graphene).

Among the various nanomaterials used to improve the properties of thermal fluids, the most common are carbon nanotubes (CNT), shown in Figure 1. This is due to several reasons, including their ease of production compared to other materials, their physicochemical stability, and optimal thermal properties.



a) b)

Fig. 1. Carbon nanotubes: a – single-walled; b – multi-walled

Figure 1 shows single-walled and multi-walled carbon nanotubes. Their advantages include high thermal conductivity, which exceeds those of metallic and non-metallic particles, reaching 3500 W/(mºC). Besides, they have a wide range of applications.

The main interest of modifying coolants with carbon nanotubes is the ability to increase the thermal conductivity of the base fluid, which will have a positive effect on the efficiency of heat exchange processes.

Studies of thermal conductivity of T-CNT (treated carbon nanotubes) in distilled water at 1 vol. % volume fractions in [4] showed an increase in thermal conductivity by 7%.

In [7], the authors investigated the effects of untreated carbon nanotubes and MWCNT-PEG using the Fischer esterification approach to show their dispersion in aqueous media with different concentrations of 0.01, 0.05 and 0.1 wt. % by weight without using any surfactants. The maximum improvements in thermal conductivity of 5.77% and 19% were recorded at 1 wt. % loading of pure CNT and functionalized MWCNT, respectively.

In [8], the authors observed an increase in the thermal conductivity of CNT nanofluid with different volume fractions of CNT (0.22 – 1 vol. %) at (30–90 °C). A nonlinear increase in thermal conductivity from the volume fractions of CNT was also discovered.

2 Conducting experiments

To conduct experiments on the intensification of heat exchange in phase transition heat accumulators with a modified coolant, an experimental stand was designed, the diagram of which is shown in Figure 2.

The stand is a closed system consisting of 3 circuits: a heating circuit, a charging circuit and a discharging circuit. The stand is assembled from polypropylene pipes and fittings with a diameter of 25 and 20 mm.

The heating circuit shown in Figure 3 is a closed system consisting of a boiler 2 and a pump 1; an expansion tank 4 was also installed to compensate for the expansion of the coolant with increasing temperature. Filling the circuit with distilled water is carried out through the filling pipe 13; an air vent valve 7 is provided to remove air from the circuit. Since carbon nanotubes have a tendency to coagulate, large agglomerations collected on the electric heaters of the boiler can reduce its efficiency and subsequently cause it to fail. To prevent such situations, it was decided to make the heating circuit closed and heat the nanomodified liquid entering the heat accumulator through plate heat exchanger 6.

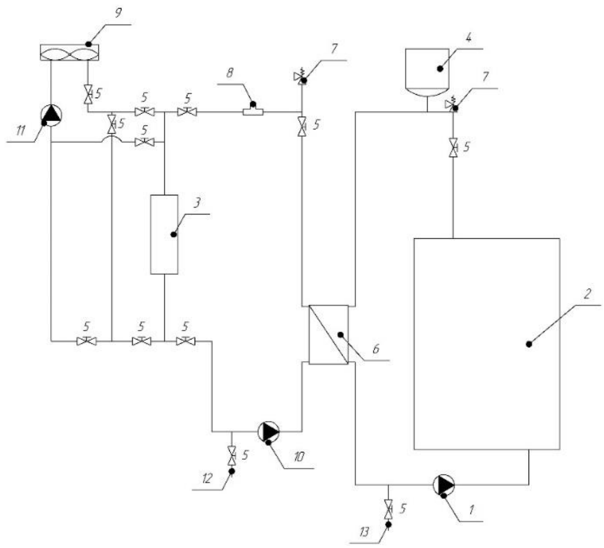
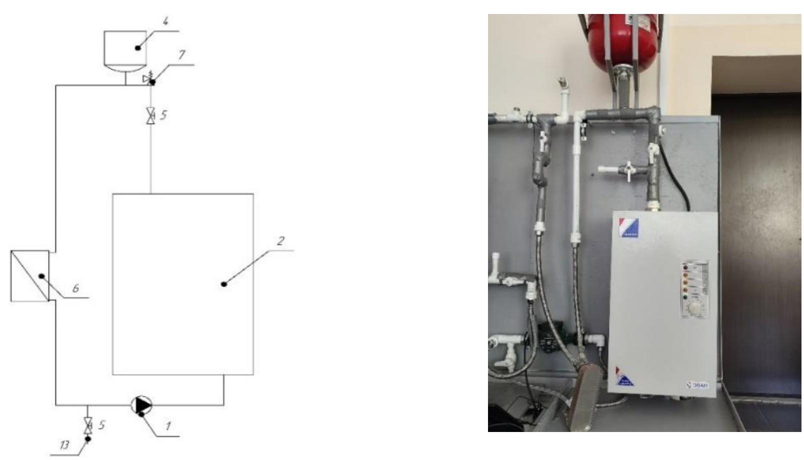


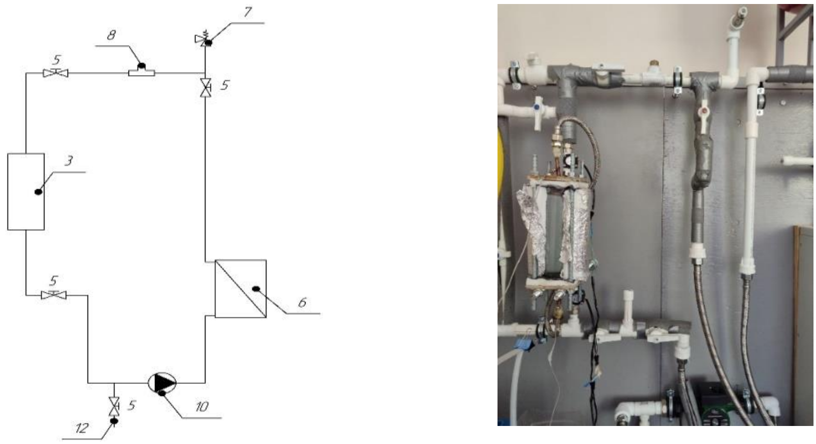
Fig. 2. Experimental stand diagram: 1 – heating circuit pump, 2 – boiler, 3– heat accumulator, 4 – expansion tank, 5 – crane, 6 – plate heat exchanger, 7 – Mayevsky tap, 8 – tee for adding nanotubes,9 – air cooler, 10 – charging circuit pump, 11 – discharge circuit pump, 12,13 – filler pipes

The charging circuit in Figure 4 is represented by the following elements: a soldered plate heat exchanger 6 is installed to heat the coolant before supplying it to the heat accumulator 3, the circulation of the nanomodified coolant is carried out by a pump 10, and the addition of carbon nanotubes is carried out through a tee 8.



a) b)

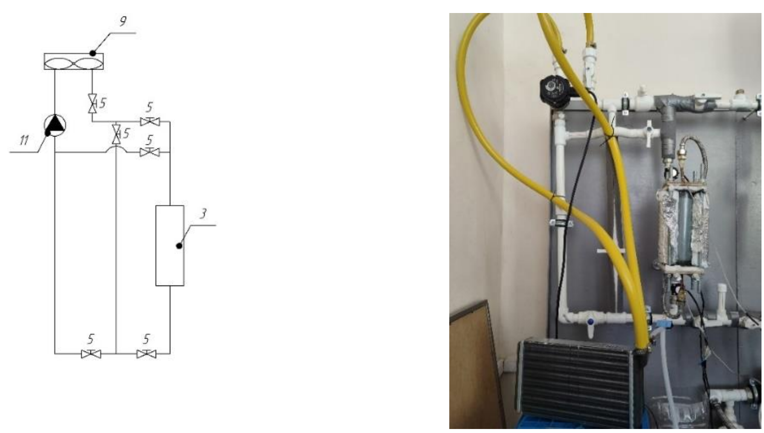
Fig. 3. a) heating circuit diagram; b) heating circuit



a) b)

Fig. 4. a) charging circuit diagram; b) charging circuit

The discharge circuit (Figure 5) is necessary for conducting studies of the paraffin crystallization process, but in this work it performs an auxiliary function and was used to accelerate the process of paraffin hardening and its complete cooling. By opening and closing the corresponding taps 5 in the circuit, the supply of cooling water to the heat accumulator is realized both from top to bottom and from bottom to top. Cooling is carried out by air cooler 9, the circulation of the cooling liquid is carried out by pump 11.



a) b)

Fig. 5. a) discharge circuit diagram; b) discharge circuit

To determine the coolant flow rate and the temperature at the inlet and outlet of the accumulator, a measuring complex was assembled (Figure 6). The device includes two thermocouples of type K [9], two flow meters. Arduino UNO is used as an analog-to-digital converter. Table 1 shows the module specification.

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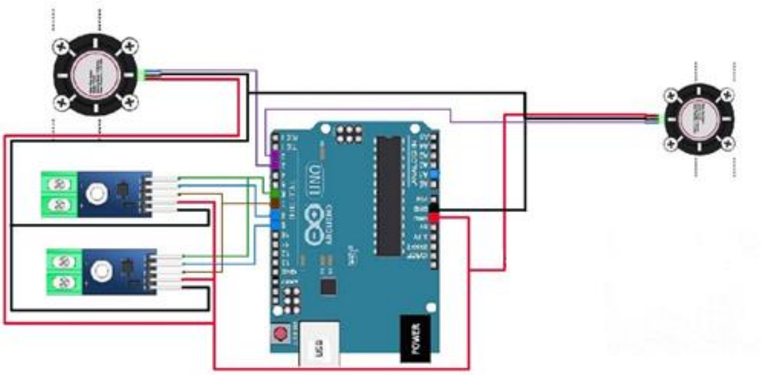
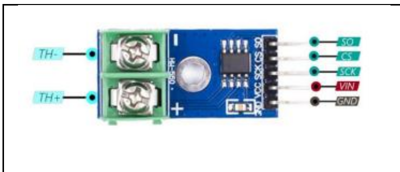
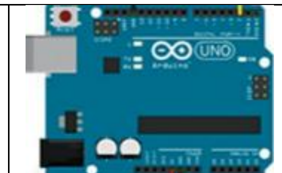


Fig. 6. Schematic diagram of the measuring complex

Table 1. Measuring complex modules

		
MAX 6675	Sea YF-S 201	Arduino UNO

Chromel Copel thermocouples of type K are used as temperature gauges at the input and output of the accumulator. The MAX 6675 module was selected to amplify the signal from the thermocouples. A Sea YF-S 201 water flow sensor is installed to determine the flow rate at the input of the heat accumulator. The sensor operates in the range of 1 to 30 liters per minute, the maximum pressure is 1.75 MPa, the operating temperature range is from 1 to 100 °C. The Arduino UNO board was used for data processing. The platform uses an ATmega328P microcontroller with a clock frequency of 16 MHz.

To conduct research on the processes of charging and discharging phase transition heat accumulators, as well as to determine the influence of the nanomodified coolant on the intensification of heat exchange processes, a model of a heat accumulator was developed and assembled (Figure 7).

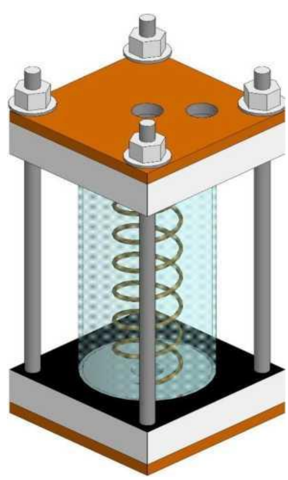


Fig.7. Heat accumulator model

The body is made of a polycarbonate pipe 20 cm high and 8 cm in external diameter. To create a tightness condition, a layer of plywood is laid on both sides as a solid base, an aerogel composite, a rubber gasket is provided to achieve tightness, and an aerogel composite 1 cm thick is laid between the gasket and the base to reduce heat loss. The integrity of the structure is supported by 4 rods tightened with bolts and washers.

Mwcnts Nano condensing multi-walled carbon nanotubes were used to conduct experiments on modifying the coolant.

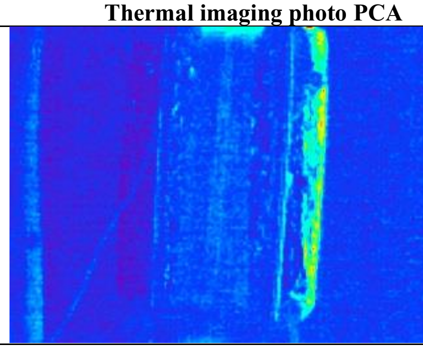
To compare the effect of the modified coolant on the efficiency of heat exchange, experiments were conducted on charging the accumulator with pure distilled water. During the experiment, the difference in coolant temperatures at the input and output of the phase-change accumulator was measured. Measurements were carried out with a time step of 10 minutes. The coolant was supplied from top to bottom, since according to [10-11], this method of supplying the coolant was more efficient.

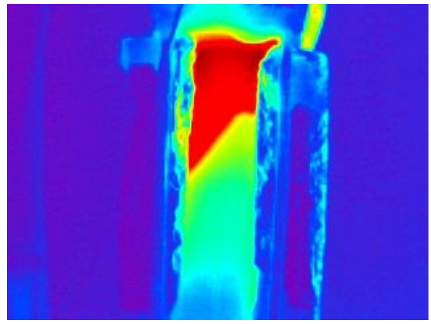
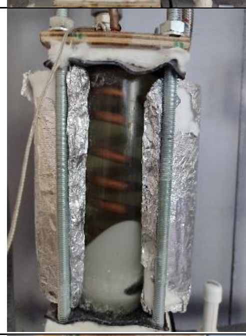
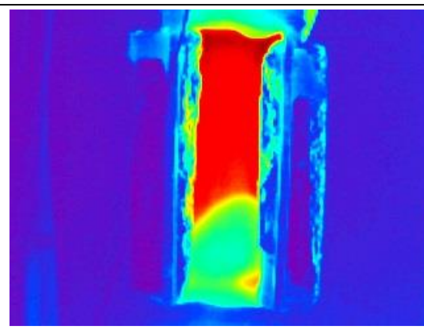
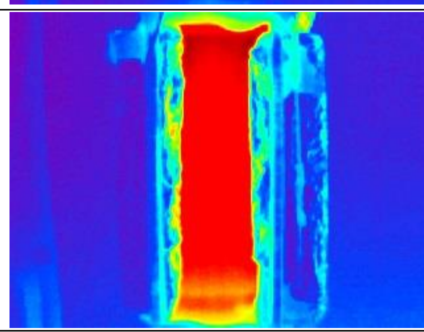
3 The results of the experiment

Table 2. Temperature readings of the coolant (distilled water) at the inlet and outlet of the PCA

№	Time	Coolant inlet temperature, °C	Coolant outlet temperature, °C	Temperature difference, °C
1	00:00:00	65.3	64.1	1.2
2	00:10:00	63.4	62.6	0.8
3	0:20:00	67.2	65.5	1.7
4	0:30:00	63.1	62.1	1
5	0:40:00	65.3	64.2	1.1
6	0:50:00	66.4	65.2	1.2
7	1:00:00	64.2	63.2	1
8	1:10:00	62.5	61.3	1.2
9	1:20:00	63.4	62.3	1.1
10	1:30:00	66.2	64.7	1.5
11	1:40:00	67.1	66.4	0.7
12	1:50:00	66.2	65.8	0.4
13	2:00:00	66.7	66.4	0.3
14	2:10:40	67.3	67.2	0.1

Table 3. Results of thermal imaging of accumulator charging with distilled water

№	Time	Photo PCA	Thermal imaging photo PCA
1	0:00:00		

2	1:00:00		
3	1:30:00		
4	2:10:00		

The results of the experiments show that using distilled water is not the most effective solution, especially at the final stages of charging, starting from 1:30 it is clear that minor paraffin residues are melting (table 3), and the temperature difference is sharply reduced (table 2). The main mass of paraffin begins to melt 20 minutes after the start of the experiment and continues for 1 hour and 10 minutes.

Then experiments were conducted on charging the PCA with a nanomodified coolant. It was decided to study coolants with 0.05%, 0.1%, 0.15% addition of nanotubes from the mass volume of the coolant. Intermediate thermal imaging images of the experiments are presented in Table 5. The results of these readings of the temperatures of the nanomodified coolant at the inlet and outlet of the PCA are presented in Table 4.

After analyzing the data obtained, we can conclude that the introduction of 0.05% carbon nanotubes created a positive effect and had a positive effect on both the charging time (the gain relative to plain water was 13 minutes 37 seconds) and on the temperature difference. The melting time of paraffin in the near-wall zones was reduced, and judging by the frames from the thermal imager, a more uniform distribution of temperature fields was achieved throughout the entire volume of paraffin.

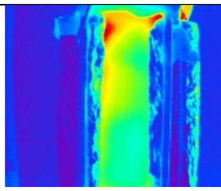
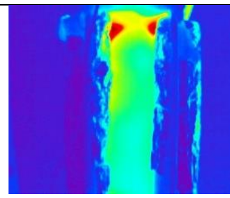
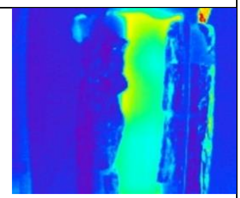
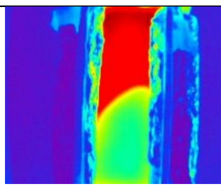
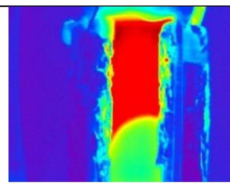
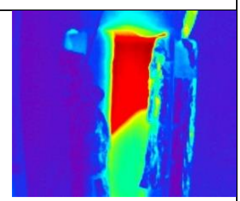
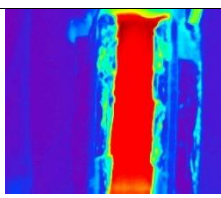
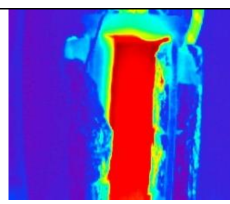
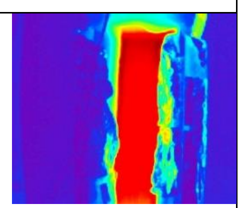
Charging the accumulator with a coolant with a concentration of 0.15% is smoother and more uniform, however, this advantage and the small gain in charging speed compared to a modified coolant with a concentration of 0.05% does not cover the economic inexpediency of using such a concentration.

The coolant with a concentration of 0.1% is the best option compared to those considered earlier. The coolant with this concentration charges the heat accumulator faster by 7 minutes 51 seconds faster than the modified coolant with a concentration of 0.05% and by 21 minutes 28 seconds compared to distilled water.

Table 4. Temperature readings of the coolant, with different concentrations of nanotubes, at the inlet and outlet of the PCA

№	Time	Coolant inlet temperature, °C	Coolant outlet temperature, °C	Temperature difference, °C
0.05%				
1	00:00:00	64.1	62.2	1.9
2	00:10:00	67.4	64.8	2.6
3	0:20:00	66.5	64.1	2.4
4	0:30:00	66.2	64.5	1.7
5	0:40:00	67	65.1	1.9
6	0:50:00	68.5	67	1.5
7	1:00:00	64.4	62.3	2.1
8	1:10:00	65	63.1	1.9
9	1:20:00	66.3	64.5	1.8
10	1:30:00	64.3	63	1.3
11	1:40:00	65.5	64.4	1.1
12	1:50:00	65.2	64.6	0.6
13	1:57:03	63.8	63.3	0.5
0.1%				
1	00:00:00	65.5	63.8	1.7
2	00:10:00	65.2	63.3	1.9
3	0:20:00	67.7	65.5	2.2
4	0:30:00	67.2	65.4	1.8
5	0:40:00	66.1	64.5	1.6
6	0:50:00	68.1	64.3	3.8
7	1:00:00	67.4	65.2	2.2
8	1:10:00	64.5	63	1.5
9	1:20:00	66	63.8	2.2
10	1:30:00	64.8	63.2	1.6
11	1:40:00	66.8	65.7	1.1
12	1:49:12	66.9	66.2	0.7
0.15%				
1	00:00:00	65.1	63.8	1.3
2	00:10:00	64.2	62.8	1.4
3	0:20:00	65.3	63.7	1.6
4	0:30:00	64.4	62.4	2
5	0:40:00	65.3	63	2.3
6	0:50:00	67.1	64.9	2.2
7	1:00:00	66.6	64.2	2.4
8	1:10:00	65.2	63.3	1.9
9	1:20:00	65.4	63.7	1.7
10	1:30:00	66.4	64.5	1.9
11	1:40:00	67.7	66.1	1.6
12	1:50:00	66.2	64.5	1.7
13	1:55:43	65.4	64.9	0.5

Table 5. Thermal imaging images of the process of charging the PCA with nanomodified coolant of different concentrations

0.05%		**0.1%**		**0.15%**	
Time		**Time**		**Time**	
0:40:00		0:40:00		0:40:00	
1:10:00		1:10:00		1:10:00	
1:57:03		1:49:12		1:55:43	

4 Conclusions

The paper examined the issue of intensifying heat exchange in heat accumulators with a phase transition through the use of nanomodified coolants. To study this issue, an experimental stand was assembled, a model of a shell-and-tube heat accumulator with a coil heat exchange surface. Heat exchange was intensified by introducing multi-walled carbon nanotubes of a certain concentration into the base liquid (distilled water): 0,05%, 0,1% and 0,15%. Modification with carbon nanotubes proved to be effective, since in the case of using a modified coolant, the difference in coolant temperatures at the inlet and outlet of the PCHA increased (Table 4), and the charging process accelerated; in comparison with simple distilled water, the increase in speed was 10,43% at a concentration of 0,05%, 16,43% at a concentration of 0,1% and 11,45% at a concentration of 0,15%.

Intensification of heat exchange by adding multiwalled nanotubes to the coolant showed the best effect at a concentration of 0.1%. With a further increase in concentration, no strong increase in the effect was observed.

Also, during the experiment, it was noticed that when the PCA was charged with a nanomodified coolant, the phase transition process of the paraffin proceeded more uniformly. During the analysis of thermal imaging images of an experiment with distilled water, melting of paraffin was recorded in the second half of the experiment in the lower part of the battery.

The main savings in charging time for a battery with a nanomodified coolant occurred in the second half of the experiment.

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