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Research on Ways to Charge a Phase Change Heat Accumulator

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Abstract: the work is devoted to the study of methods for charging thermal accumulators of phase transition. The effectiveness of using such units is explained by the possibility of accumulating and further using large volumes of thermal energy compared to sensible energy batteries. The process of charging a heat accumulator depends on many factors, including the direction of supply of coolant through the heat exchange surface inside the heat accumulator structure. Increasing the rate of heat charge is an important task, since their application requires that energy storage and further transfer be carried out in less time while maintaining overall efficiency. The paper presents the main properties of the heat-storing material that was used in the design of the heat accumulator, describes the methodology for conducting the experimental part of the study, and provides a description of the experimental stand. Based on the data obtained, an analysis of the results was carried out, which presented a description of the heat exchange process inside the phase transition heat accumulator, and also highlighted the shortcomings of the used heat accumulator model. As a result, provisions were formed for modernizing the design of the thermal accumulator and conducting further research, and conclusions were drawn about the effectiveness of using various charging methods. The research was carried out under a state order with agreement number 075-03-2025-458 dated 17/01/2025.

1 INTRODUCTION

Currently, at facilities in the energy and industrial industries there is a certain number of problems associated with the requirement to reduce the consumption of consumed resources, as well as thermal accumulation as part of increasing energy efficiency.

To be able to accumulate thermal energy, it is necessary to use a large number of storage tanks. In turn, this increases capital costs for installation, further maintenance, and, accordingly, expansion of the construction space for their placement.

Phase change batteries, which are based on the accumulation of energy by changing the phase state of the working fluid, can replace traditional water thermal batteries.

This kind of units have high competitive advantages, such as: (a) accumulation of large volumes of thermal energy due to the latent heat of the working fluid; (b) have smaller overall dimensions, which will reduce capital costs for their manufacture, installation, and further maintenance.

For low-temperature batteries, the most effective is the use of paraffin as a heat-storing material due to its properties. However, its use in phase change thermal batteries has a disadvantage, namely a low thermal conductivity coefficient (Musiał, 2022, 2023; Vrbanc, 2023).

2 MATERIALS AND METHODS

This section will consider the materials required for the manufacture of a phase change accumulator (PCA) structure, as well as consider an experimental stand for conducting research to identify the dependence of the charging time of a heat accumulator on the direction of coolant supply through the heat accumulator (Wang, 2022; Levitskij, 1996; Bai, 2023).

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2.1 Heat storage materials

Conservation, or accumulation of thermal energy (TE), is carried out with the purpose of its accumulation during periods of time when there is an excess of production, and its further transfer during periods of time when there is a shortage.

TE accumulation is possible by heating water, solids, and other materials or using phase, chemical transformations, which include the processes of crystallization of a substance, its melting, direct and reverse reactions (Osterman, 2023; Makhmudov, 2024).

A phase transition accumulator allows you to concentrate a large amount of TE in a small volume of material, which accumulates during the transition of a heat-storing material (HSM) from one phase state to another (solid - liquid, liquid - solid). In this case, the transition process is accompanied by the absorption and release of latent heat.

In the process of developing an PCA, the following requirements must be met for HSM: (a) HSM must have a high enthalpy of phase transition, high thermal conductivity, and high density; (b) have a low coefficient of volumetric expansion; (c) absence of chemical interaction with the structural material; (d) stability of composition and thermophysical properties during operation, that is, resistance to multiple cycles of melting and solidification; (e) low cost and availability for industrial use; (f) safety for humans (Naplocha, 2016; Reyes, 2020).

Paraffin was chosen as HSM; the properties of the selected paraffin are presented in Table 1.

Table 1: Properties of paraffin grade P-2.

Parameter	Meaning
Substance	Parffin
Melting point, °C	50-54
Latent heat, KJ/kg	210
Thermal conductivity, W/m·°C	0,24

2.2 Experimental stand

An experimental stand was developed and constructed (see Fig. 1,2) to study the processes of charging thermal accumulators of phase transition.

In the electric water heater 1, water is heated, which flows through the supply pipe 2 into the rotameter 3, which is designed to measure and visually record the coolant flow. Depending on the selected direction of supply (“top-down” or “bottom-up”) through the heat accumulator 5, by closing/opening the corresponding taps 4 the direction of movement of the coolant is adjusted (Lichołai, 2020).

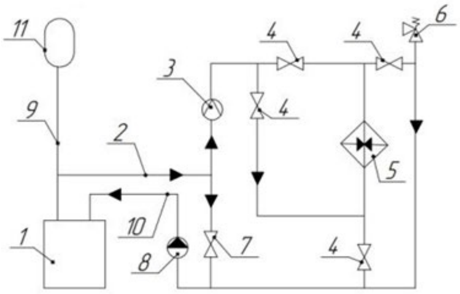

Figure 1: Scheme of the experimental setup: 1 – storage water heater; 2 – supply pipe; 3 – rotameter; 4 – tap; 5 – heat accumulator model; 6 – Mayevsky tap; 7 – bypass line with tap; 8 – circulation pump; 9 – vertical tube; 10 – return line; 11 – expansion tank.

Figure 2: View of the experimental setup.

The circulation of water through the system is carried out by the operation of a circulation pump 8 installed on the return line 10 to the water heater.

Compensation for thermal expansion in the system is carried out by expansion tank 11.

To maintain a constant flow of coolant, a bypass line with valve 7 is provided, which regulates the addition of supply coolant into the return line.

2.3 Design of a heat accumulator structure

To design and assemble a heat accumulator structure, it is necessary to take into account several factors: the amount of heat that needs to be stored, the shape of the heat exchange surface and its dimensions, and also select the heat storage substance that will be used as the working fluid of the PCA.

When calculating the accumulated heat, we use formula 1. This formula takes into account the accumulation of energy during melting of the solid working fluid (HSM), as well as the heat that can be stored due to the heat capacity of the liquid HSM, kJ.

$$Q=m\cdot(L+c''\cdot(T-T_C)) \qquad (1)$$

where, m – mass of the working fluid inside the PCA housing, kg; L – heat of phase transition, KJ/kg; c” – heat capacity of the working fluid in the liquid state, KJ/(kg·°C); T – the overheating temperature of the working fluid is higher than the crystallization temperature, °C; T_C – crystallization temperature of the PCA working fluid, °C.

Convective heat exchange promotes the removal of heat from the phase transition of the AFP working fluid. Let us express the area of heat exchange between dissimilar media from the Newton–Richmann law, m2:

$$F=Q/(\alpha_1\cdot\Delta T) \qquad (2)$$

where, α_1 – heat transfer coefficient from the coolant to the pipe, W/(m2·K); ΔT – average logarithmic temperature difference, °C.

During the operation of a phase transition accumulator, there is a constant change in the volumetric ratios of the liquid and solid phases of the storage material. Excess volume for HSM mass, m3:

$$\Delta V=(Q/L)\cdot((\rho'')^{-1}-1) \qquad (3)$$

where, ρ” – HSM density in liquid state, kg/m3.

The total volume of the AFP bunker is not less than, m3:

$$V=V_0+V_2+\Delta V \qquad (4)$$

where, V_0 – volume of heat exchange surface inside the heat accumulator structure, m3; V_2 – volume of solid HSM inside the heat accumulator structure, m3.

3 RESULTS

3.1 Progress of experimental research

To compare the results, experimental studies were carried out under the following conditions: 1) the mass of HSM loaded into the PCA is constant in all energy storage models; 2) the temperature of the coolant leaving the water heater in all experiments is 65 °C; 3) to prevent heat loss from the battery into the environment, thermal insulation made of an airgel composite 1 cm thick, covered with a layer of foil, was used to reflect heat flows; 4) temperature values inside the PCA working space were displayed on the OVEN UKT38 meter (see Fig. 3); 5) the time of heating and melting of paraffin was measured using a stopwatch from the moment the pump was turned on until the heat accumulator was fully charged; 6) during the experiments, photographs and thermal imaging recording of the state of the working fluid were taken every 5°C, after reaching a temperature of 57 °C - every 1°C.

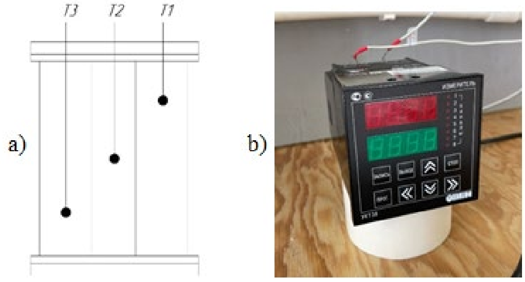

Figure 3: (a) location of thermocouples inside the PCA housing; (b) OVEN UKT38 meter. T1, T2, T3 – thermocouple for measuring the temperatures of the upper, middle and lower layers inside the working space of the PCA.

3.2 Results obtained

The design of the experimental stand (see Fig. 1) provides for the supply of heating coolant through the heat exchange surface of the PCA in two ways: (a) top-down, (b) bottom-up.

For case (a) and case (b), a series of experiments were carried out with different types of heat transfer surfaces. The experimental results for both cases of coolant flow are presented in Table 2 and Table 3.

Table 2: Results of PCA charging processes using the “top-down” coolant flow method.

Heat transfer surface type	Time to fully charge PCA, h:min
Smooth cylindrical	08:12
With spherical recesses with diameter of 4 mm	06:15
With spherical recesses with diameter of 4 mm	06:09

With spherical recesses with diameter of 4 mm	05:59

Table 3: Results of PCA charging processes using the “bottom-up” coolant flow method.

Heat transfer surface type	Time to fully charge PCA, h:min
Smooth cylindrical	09:15
With spherical recesses with diameter of 4 mm	07:46
With spherical recesses with diameter of 4 mm	06:38
With spherical recesses with diameter of 4 mm	06:24

The tables show that for all the heat exchange surfaces under study, the “top-down” coolant supply method is on average 13% more effective than the “bottom-up” method. It is also worth noting that the charging time of the heat accumulator is affected not only by the method of supplying the coolant, but also by the shape of the heat exchange surface.

Having analyzed a separate experimental study of the movement of the coolant through the heat transfer surface from top to bottom, we can note the fact that the phase transition line, or rather its movement during the experiment, indicates a complex mechanism of heat transfer from the heating surface to the working fluid (see Fig. 4).

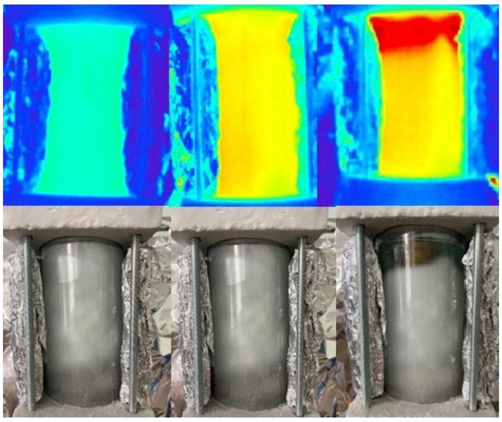

Figure 4: The nature of the advance of the phase transition front during the experiment.

In Fig. 3, it can be observed that at the initial stage there are no external changes in the working fluid, since heat transfer occurs by heat conduction from the heated wall of the heat exchange surface to the working fluid. In this case, melting of HSM occurs in the shape of a cylinder. Over time, the molten HSM begins to deviate from a cylindrical shape, especially in the upper part of the PCA body. This phenomenon indicates a change in the nature of heat transfer, namely the occurrence of natural convection inside the PCA, which leads to a change in the cylindrical shape of the molten HSM.

3.3 Estimation of the error of the experimental results

The experimental error was assessed according to the method specified in GOST R 8.736-2011 “Multiple direct measurements. Methods for processing results. Basic provisions".

For the measurements obtained in the study, Δ=2.75 °C is taken, with a confidence level of P=0.95.

3.4 Analysis of experimental research results

First of all, it is worth noting that the longer charging time of the PCA when the coolant flows from bottom to top is explained by the fact that the largest amount of heat during the experiment is transferred from the coolant to the paraffin in the lower part of the heat accumulator body, and then, under the influence of temperatures, a phase transition process occurs and liquid paraffin, having a lower density, begins its movement to the upper part of the PCA body. As it moves upward, the liquid phase interacts with solid paraffin, which has a temperature an order of magnitude lower, therefore, part of the heat of the liquid phase is transferred to the unmelted paraffin, but this thermal effect is not enough to complete the phase transition (Zhu, 2022; Turski, 2019; Kurpaska, 2020).

In contrast to the top-down method of coolant flow, during the further course of the experiment, heat transfer from the coolant passing bottom-up through the heat exchange surface simultaneously occurs to the lower part of the molten paraffin, the solid phase and the liquid phase, which, due to the difference in density, was raised to the upper part of the body and performed heat exchange during its movement.

This process is reflected in graphs of temperature versus time, namely by the intersection of temperatures of different layers of the heat accumulator (see Fig. 5). This intersection occurs in all cases of bottom-up coolant supply in experimental studies with various heat exchange surfaces. This intersection is absent in the temperature graphs of the battery charging process “from top to bottom” (see Fig. 6).

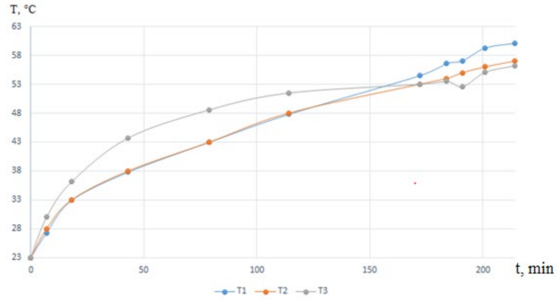

Figure 5: Graph of the temperature inside the PCA case when charging the heat accumulator “bottom-up”. T1, T2, T3 – temperature values of the upper, middle and lower layers inside the PCA working space.

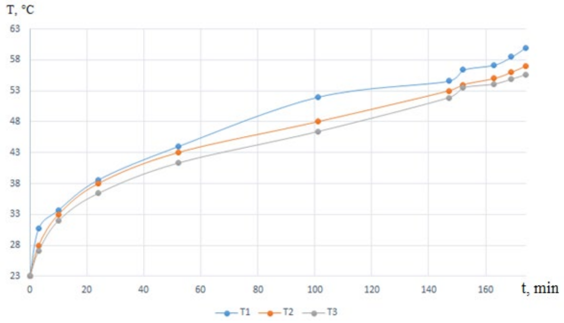

Figure 6: Graph of the temperature inside the PCA case when charging the heat accumulator from top to bottom. T1, T2, T3 – temperature values of the upper, middle and lower layers inside the PCA working space.

It is also worth noting that during the experiment, the disadvantage of using a straight cylindrical PCA body when charging the battery under the current temperature conditions of the coolant was revealed. When the coolant was supplied, regardless of the method, a zone of unmelted part of the paraffin formed in the working space of the heat accumulator (see Fig. 7).

Figure 7: Unmelted paraffin layer during PCA charging.

Over time, this layer slightly changed its geometric shape under the influence of internal convection. From this it follows that it is possible to conduct research with a modified shape of the heat accumulator body, which should increase the speed and efficiency of the battery charging process (Constantin, 2015).

As an alternative housing shape, the following types of housings can be proposed: a housing with a truncation of the lower part to a diameter equal to the diameter of the heat exchange surface, as well as a rounded bottom, where the radius of the rounding will be equal to the radius of the housing of the PCA design (see Fig. 8).

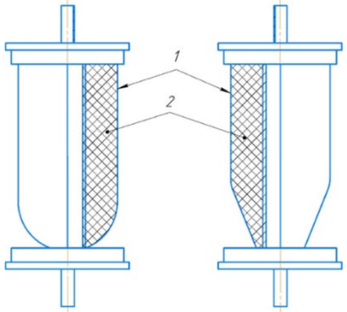

Figure 8: An alternative view of PCA models: on the left – with a spherical body bottom, on the right – with a truncated body bottom. 1 – PCA body, 2 – heat-storing material.

4 CONCLUSIONS

The problem of increasing energy efficiency poses challenges for researchers in solving specific issues, one of which is thermal storage and its optimization. That is why there is currently a large number of scientific works aimed at studying the properties and behavior of heat-storing substances, battery designs at phase transition and their modernization in order to increase operating efficiency.

The research was carried out by upgrading the design of the thermal storage model using a smooth cylindrical structure and a cylindrical structure with spherical recesses of 4, 6 and 8 mm in diameter.

The results showed that the top-down battery charging method is more efficient in all tested PCA samples, which is explained by the internal distribution of heat flows inside the PCA body.

Thus we get that:

(a) the charging time of the heat accumulator when the coolant is supplied “from top to bottom” is on average 13-15% faster than when the coolant is supplied “from bottom to top”;

(b) with different variations of the heat exchange surface and methods of supplying coolant, the average temperature inside the PCA remains unchanged, only the time to reach it changes;

(c) increasing the charge efficiency at low coolant temperatures is possible by changing the shape of the PCA body, which will avoid the formation of a zone of unmelted part of the working fluid;

(d) the melting zone of the working fluid in the process of charging the PCA at the initial stages is formed in a cylindrical shape and over time, due to internal natural convection, we begin to deviate from the cylindrical shape with the condition that the movement of the upper boundary of the phase transition is an order of magnitude higher than the lower one.

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