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DESIGN OF A COMPACT HIGH-TEMPERATURE THERMAL STOR-AGE UNIT WITH MULTI-LAYER INSULATION FOR LOW-RISE CONSTRUCTION

The energy transition in the heat supply sector for the private housing market, particularly in non-gasified regions of Russia, is a key objective within the context of import substitution and environmental policy. Federal programs, such as "Clean Air," incentivize the shift away from coal and fuel oil heating towards electric systems [1]. However, a widespread adoption of electric heating creates critical peak loads on the power grid during morning and evening hours. This not only necessitates infrastructure modernization but also diminishes economic benefits for consumers due to high daytime electricity tariffs. A clear example is the situation in the Krasnoyarsk Territory, where levels of harmful PM2.5 particles are double the WHO recommendations, and pilot projects for switching homes to electric heating are already being implemented [2].

An effective solution to this problem is the accumulation of thermal energy during the night for use throughout the day. Among existing energy storage technologies, thermal accumulators are the most suitable for domestic applications due to the direct conversion of electricity into heat, relatively low cost, and long service life [3-4]. The most common types are water-based buffer tanks and phase-change material accumulators. However, they have significant drawbacks: the former are excessively bulky and incapable of providing a full day of autonomy for a house during severe winters, while the latter are prohibitively expensive, have a limited lifespan, and are incompatible with high-temperature radiator heating systems.

To solve this problem, the author proposes a newly developed compact solid-state thermal accumulator with combined insulation (Fig.1). Structurally, it consists of a chamotte core 4, surrounded by combined insulation layers 2 and 3, all housed within a casing 1. The selection of materials is critical for achieving high energy density and long-term cyclability. The core utilizes chamotte, a refractory ceramic known for its high heat capacity and thermal stability. Its high maximum service temperature (up to 850°C) ensures a substantial safety margin and long-term reliability under actual operating conditions affecting the cyclic durability. This allows for a significantly greater energy storage density per unit volume compared to traditional water-based systems. The insulation strategy is equally deliberate: the inner tungsten foil layers act as radiation shields, reflecting infrared waves back to the core, while the outer mineral wool layer suppresses residual conductive and convective losses.

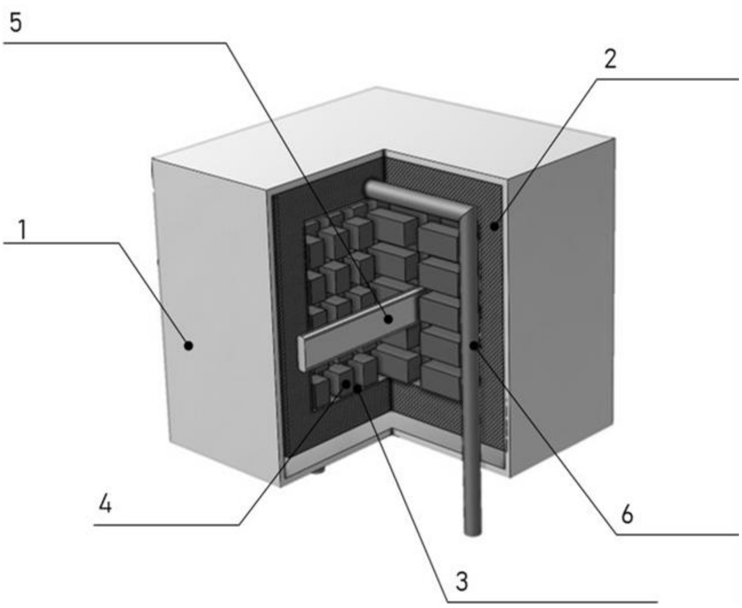

Fig.1. Model of the compact high-temperature thermal storage unit with multi-layer insulation: *1* – casing; *2* – second insulation layer; *3* – first insulation layer; *4* – core heat storage body; *5* – control unit; *6* – heat exchanger

The operating principle of the thermal accumulator is based on a cyclic process of storing and subsequently releasing thermal energy. During the night, when off-peak electricity tariffs are in effect, heating elements can heat the core *4* to a preset, technologically optimal temperature significantly lower than its maximum thermal limit, accumulating a significant heat reserve. Throughout the day, while the heat transfer fluid continuously circulates through the heating circuit, it passes through the steel heat exchanger *6* inside the accumulator. Here, the fluid is intensively heated by the incandescent chamotte, compensating for the building's heat losses. The internal insulation layer is formed by a series of tungsten radiation shields *3*, whose primary function is to efficiently reflect the radiant thermal energy from the core *4*, drastically reducing the most significant heat losses at such high operating temperatures. The outer layer is made of dense mineral wool *2*, which acts as a convective-conductive barrier, reliably retaining the heat already weakened by the shields and ensuring a safe temperature on the external surface of the casing *1*. Thus, the device does not function as an independent circuit but operates as a high-temperature buffer heater integrated into the main heating system.

Although chamotte can withstand temperatures up to 850°C, in a residential installation the core is maintained at a lower, controlled temperature level. This ensures that, in combination with the multi-layer insulation (radiation shields and mineral wool), the external casing remains at a safe temperature, comparable to conventional heating radiators, eliminating any risk to occupants and allowing for compact placement within the living space.

The primary economic benefit stems from leveraging differential electricity tariffs. By charging the accumulator at night using low-cost power and discharging it during expensive daytime hours, the system can achieve substantial savings on annual heating costs. Preliminary calculations for a typical low-rise building in a cold climate suggest the potential for payback periods competitive with other capital-intensive energy upgrades. This financial incentive, coupled with the reduction in peak-load demand charges for utility providers, creates a compelling value proposition for both homeowners and grid operators.

The daily heat requirement was calculated by (1):

$$Q = V \cdot q \cdot \Delta T \cdot k_1 \cdot k_2 \cdot k_3, \tag{1}$$

where V – the volume of the room, m^3; q – the specific thermal characteristic of the building, $W/(m^3 \cdot K)$; ΔT – the temperature difference between outdoors and indoors, K; k_1, k_2, k_3 – a coefficient that takes into account glazing, infiltration and a margin for abnormal frosts.

For a house with an area of 100 m^2 and a ceiling height of 2,7 m located in the northern region of the Russian Federation, where the outdoor temperature reaches -40 °C and the indoor temperature should be +22°C with a glazing degree of 20%, where k_1, k_2, k_3 are equal to 1,1; 1,05; 1,15 respectively, according to (1) Q = 204 kWh, for confidence in the calculations, we will take a margin of 25%, then the daily heat requirement is 255 kWh.

The heat storage material is chamotte, and its required mass to maintain a given temperature can be calculated by (2):

$$m = \frac{Q}{c_ш \cdot \Delta T}, \tag{2}$$

where Q – the daily heat demand, J; $c_ш$ – the heat capacity of the fireclay brick, J/kg·K; ΔT – the temperature change of the fireclay brick, K.

To convert the daily requirement from kWh to Joule, multiply the number by $3{,}6 \cdot 10^6$. The heat capacity of a fireclay brick is assumed to be equal to 833 J/kg·K. We also assume that chamotte will be heated from room temperature, 293 K, to 1073 K. Then the weight of chamotte will be 1413 kg.

The volume of the chamotte core will be about 0,74 m^3 with a density of 1900 kg/m^3.

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References:

1. Federal Project "Clean Air" [Электронный ресурс] // Ministry of Natural Resources and Environment of the Russian Federation. – URL: https://www.mnr.gov.ru/activity/environmental_well-being/federalnyy-proekt-chistyy-vozdukh/ (дата обращения: 21.10.2025).

2. TVK Krasnoyarsk [Электронный ресурс] // News. – URL: https://tvknews.ru/publications/news/87485/ (дата обращения: 21.10.2025).

3. Algorithm for calculating a multilayer thermal insulation system for a high-temperature thermal energy storage unit / A. N. Chadayev, A. V. Dmitriev, V. E. Zinurov [et al.] // Power engineering: research, equipment, technology. – 2024. – Vol. 26, No. 6. – P. 166-179. – DOI 10.30724/1998-9903-2024-26-6-166-179. – EDN JNGEHY.

4. Numerical Modeling of Thermal Energy Storage Unit Heating for Greenhouse Farming / A. V. Dmitriev, V. E. Zinurov, M. O. Utkin [et al.] // Vestnik of Kazan State Agrarian University. – 2025. – Vol. 20, No. 1(77). – P. 47-53. – DOI 10.12737/2073-0462-2025-1-47-53. – EDN PCSCQF

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