Experimental studies of the thermal state of heat storage units of electro thermal storage

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Abstract. Experimental data on the behavior of the following thermal parameters of heat storage units made of magnesite and chamotte of electro-thermal storages (ETS) has been obtained: wall temperature change of air channels of heat storage units, temperature change of heated air in channels of heat storage, temperature change in the bulk of thermal insulation, for one cycle of heat charging and heat emission of ETS. After analyzing the obtained temperature distribution in the wall of channels of the heat storage units, it can be concluded that the heating rate of the heat storage units made of chamotte is higher during almost the entire charging mode of ETS compared to the units made of magnesite. In the heat emission mode, the cooling rate is significantly higher for chamotte units compared to a lower cooling rate for magnesite heat storage units.

1. Introduction
One of the effective solutions to the problem of increasing the efficiency of heat supply systems in rural areas is the transition to decentralized electric heat storage heating systems [1,2]. The main advantage of such heating systems is that, with their mass-scale implementation, they can act as consumers-load regulators of power generating systems at night, when there is a significant decline in electricity consumption. The economic incentive for the implementation of thermal storage heating systems is the presence of reduced tariffs for electricity consumption in the period from 23.00 to 07.00 (night zone). Electric-thermal storage heating systems can also be effectively used in combination with photoelectric and wind power installations [3-6].

In this work, dynamic-type electro-thermal storages (ETS) are selected as the object of research. The results of field tests of ETS, in individual residential buildings, as well as those of their thermal operation conditions modeling, for heaters on the basis of ETS, and technical-economic analysis prove the effectiveness of these electric-thermal storage systems of heating, in residential buildings, compared to conventional electric heating systems [7-11].

Theoretical research of thermal conditions of heat storage central module of dynamic-type ETS, in operation modes of charging and heat emission, were carried out earlier. Calculations of non-stationary temperature field were carried out with the use of finite element analysis. Temperature distribution, in heat storage units of ETS, for the entire cycle of charging and heat emission, were defined, for air speed in the channels of charging units in the range 2 m/s to 3 m/s, in the heat emission operation mode of ETS [12-14]. Thermophysical properties of heat storage materials were investigated and their heat accumulating capacity had been evaluated in the temperature range from 70 °C to 650 °C.
During the charging and heat emission cycle, the change of heat quantity accumulated in dynamic-type ETS was defined [15,16].

The purpose of this work is to carry out experimental studies of thermal state of heat storage units made of magnesite and chamotte in operation modes of charging and heat emission of ETS, followed by the analysis of temperature change dynamics in heat storage units.

2. Materials and methods
ETS consists of several individual elements (blocks) assembled in a steel housing. The thermal-insulated heat storage unit, consisting of magnesite heat storage units with air channels for air circulation inside the ETS. The heating unit consists of U-shaped air tubular electric heating elements (TEH), placed in the grooves between the heat storage units. Ambient of air room air is carried out through the holes in the side panel of the ETS; the outlet of heated air is through the opening of the grate located on the front panel of the grate located on the front panel. A tangential fan is installed at the bottom of the side compartment, which is electrically connected to the room thermostat.

Experimental studies were carried out in two steps. At the first step, thermal operation conditions and dynamic characteristics of heat storage units made of magnesite, with two slot-shaped air channels, having size of $0.19 \times 0.02$ m and net weight of 62.5 kg, were studied. At the second step, heat storage units made of chamotte, with two round-shaped ($d_{ch} = 0.044$ m) tubular air channels, having net weight 58 kg, were tested. Temperatures were measured with the use of chromel-alumel (CA) thermocouples in ceramic mantle. Where it was possible, thermocouple routes coincided with the isothermal lines of temperature field of the heat storage unit in order to exclude the influence of heat flux on the hot junction of thermocouple in temperature measurements.

Positions of thermocouples installed in heat storage units of both types are shown in figure 1. Points for measuring wall temperature of air channels and heated air in channels are designated as $T_1$ and $T_2$, respectively.

Figure 1. Positions of thermocouples installed in heat storage units made of magnesite with slot-shaped channels, and of chamotte with round-shaped channels.

3. Results and discussion
There are results of experimental studies of thermal state and dynamic characteristics of heat storage units made of magnesite (see figure 2) and chamotte (see figure 3).

After carrying out experimental studies of the thermal state of heat storage units in the modes of charging and heat emission, the analysis of the obtained experimental data was carried out at several control points of the ETS.

1. There is a sharp drop in the temperature of the heated air in the $T_{air, wch1, low}$ channel in the heat emission mode in the lower part (see figures 2b and 3d). Thus, we observe an uneven temperature distribution in the area between the air channels of heat storage units made of magnesite in the lower part of ETS.

2. There is more uniform heating and cooling of the heat storage units of their chamotte than that from magnesite (see figures 3c and 2a).

3. The temperature of the heated air $T_{air, wch3}$ in the channels of heat storage units from magnesite in the charging mode is higher than the same parameter for chamotte units, thus the temperature
difference between the air channels wall and the heated air in channels of heat storage units from magnesite is lower (see figure 3a, 3b), than chamotte units (see figure 3c, 3d).

To increase the heating rate of heat storage units made of chamotte, at the second step of the experiment, metal inserts in the form of steel plates 2 mm thick were used, which were placed between the heat storage units. As a result, the values of the air channels wall temperature $T_{wch}$ at the end of the charging mode of ETS increased by an average of 50 °C compared to the option when steel plates were not used.

**Figure 2.** Results of experimental studies of thermal state and dynamic characteristics of heat storage units made of magnesite: (a) Temperature change $T_{wch}$ wall of the air channels of the heat storage units with slit-shaped channels in lower and upper parts; (b) Temperature change of the heated air $T_{air, wch}$ in the channels of heat storage units with slit-shaped channels in lower and upper parts.
Figure 3. Results of experimental studies of thermal state and dynamic characteristics of heat storage units made of chamotte: (c) temperature change $T_{wch}$ wall of the air channels of the heat storage units with round-shaped channels in lower and upper parts; (d) temperature change of the heated air $T_{air\_wch}$ in the channels of heat storage units with round-shaped channels in lower and upper parts.

The estimation of the maximum absolute and root-mean-square error of measurements of the software and hardware complex consisting of the secondary temperature converter UKT38.Sch4. TP is carried out including primary temperature converters of thermocouples CA. It is concluded that it is advisable to measure temperatures in the range of 350-650 °C with the CA thermocouple. The error is for CA thermocouple (from 7 to 0.8 %) in the range from 50 to 650 °C.

With the purpose of analysis of the dynamics and efficiency of heat emission in ETS, let us define the average cooling rate of heat storage units made of magnesite and chamotte from the following dependence (first theorem by Kondratiev), with the use of values average surface heat exchange coefficient $\alpha_{ch\_ave}$ for forced convection:

$$m = \psi \frac{\alpha_{ch\_ave}F_{ch}}{c_p\rho_lV_{hsw}},$$

(1)
where $F_{ch}$ is the surface of air channel (m$^2$), $c_{p1}$ is specific heat capacity of HSU material (kJ/(kg·°C)), $\rho_1$ is volumetric density of HSU material (kg/m$^3$), $V_{hsu}$ is volume of heat storage unit (m$^3$), $\psi$ is non-uniformity coefficient of temperature field, in heat storage unit (value 0.7 was selected).

The heating rate is defined as the relation of the difference of natural logarithms of excessive temperatures $\vartheta_{hsu}$ to the interval between the corresponding time moments $\tau$ [17]:

$$m = \frac{\ln \vartheta_2 - \ln \vartheta_1}{\tau_2 - \tau_1},$$  

where $\ln \vartheta_1$ and $\ln \vartheta_2$ are natural logarithms of excessive temperature $\vartheta$ of heat storage unit, for two time moments $\tau_1$ and $\tau_2$.

The average cooling rate of heat storage units calculated with the use of the received experimental data ($m_{mag} = 9.28 \cdot 10^{-5}$ s$^{-1}$ and $m_{ch} = 1.54 \cdot 10^{-4}$ s$^{-1}$) supports the model of dynamics of temperature change in heat storage units made of magnesite and chamotte, in heat emission operation mode of ETS in the process of experimental studies. During the charging cycle, the heating rate of heat storage units changes from $3.39 \cdot 10^{-4}$ s$^{-1}$ to $1.94 \cdot 10^{-5}$ s$^{-1}$, and from $7.22 \cdot 10^{-4}$ s$^{-1}$ to $1.39 \cdot 10^{-5}$ s$^{-1}$ – for ETS heat storage units made of magnesite and chamotte, respectively.

4. Conclusions

Based on the results of the performed experimental studies of thermal operation conditions and dynamic characteristics of ETS, data on the behavior of the following thermal parameters of heat storage units made of magnesite and chamotte has been obtained. These are wall temperature change of air channels of heat storage units, temperature change of heated air in channels of heat storage units, temperature change in the bulk of thermal insulation, for one cycle of heat charging and heat emission of ETS. Information obtained in the course of experiments has been analyzed. The suggestion has been made to compensate relatively a low heating rate of chamotte storage units by application of metal plates installed between adjacent storage units that made it possible to improve the dynamics of ETS heat charging. Growth of wall temperature of air channels of chamotte heat storage units, in the end of ETS charging cycle, amounted to approx. 10% (50 °C) compared to the design option without metal plates. It has to be noted that, in the heat emission mode of ETS, cooling rate of chamotte heat storage units is substantially higher than that of magnesite units.

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