Experimental studies of the thermal characteristics of electro-thermal storage

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Abstract. Based on the results of the performed experimental studies of thermal operation conditions and dynamic characteristics of electro-thermal storages (ETS), data on the behavior of the following thermal parameters of heat storage units made of magnesite and chamotte has been obtained: temperature change of heated air in channels of heat storage units and that in the outlet from ETS, temperature change in the bulk of thermal insulation and that on the surface of housing, 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 low heating rate of chamotte storage units by application of metal plates installed between adjacent storage units which 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.

1. Introduction
An urgent issue for agriculture, rural settlements, and farms is the use of efficient decentralized heat supply systems. One of the most effective solutions to this problem is the transition to electric-thermal storage heating systems [1-4]. 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 [5]. Nighttime dips in the load schedule of the power system lead to additional losses in the power grids, overconsumption of fuel at the thermal power plants (TPPs) and combined thermal and power plants (CTPPs) and reducing their efficiency associated with a decrease in the volume of electricity generation at TPPs and CTPPs. 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 [6-10].

In this work, dynamic-type electro-thermal storages (ETS) are selected as the object of research.

To increase the efficiency of ETS and their mass-scale implementation in rural areas, it is necessary to carry out theoretical and experimental studies of heat exchange processes occurring in the modes of charging and heat emission of ETS, followed by an assessment of the dynamics of temperature changes in heat storage units in the modes of charging and heat emission, and the calculation of heat
transfer coefficients in air channels and the surface of the ETS housing with free and forced convection, as well as the rate of heating and cooling of the heat storage units of the ETS and the choice of a rational heat storage material.

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 [11-15].

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 [16-19]. Thermophysical properties of heat storage materials were investigated and their heat accumulating capacity had been evaluated, in temperature range from 70 °C to 650 °C. The change of heat quantity accumulated in dynamic-type ETS during the charging and heat emission cycle was defined [20,21].

2. Objective
Experimental studies of thermal conditions and dynamic characteristics 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.

3. Materials and methods
ETS consists of several individual elements (blocks) assembled in a steel housing. 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. 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 0.19×0.02 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 and (CC) chromel-copel thermocouples. In zones with high temperatures, CA thermocouples were installed in jackets made of heat-resistant tissue. CC thermocouples were applied for measuring air temperature at the outlet of ETS, that on the surface of ETS housing and of thermal insulation. Where it was possible, thermocouple routes coincided with the isothermal lines of temperature field of heat storage unit in order to exclude the influence of heat flux on the hot junction of thermocouple, in temperature measurements. Functional-technological scheme of ETS with heat storage units made of magnesite (conventional design structure) and chamotte (newly-developed design structure) is presented in figure 1 where positions of thermocouples, in experimental studies, are indicated.
Figure 1. Positions of thermocouples in experiment for studying thermal operation conditions of heat storage units: (a) heat storage units made of magnesite (conventional design structure); (b) heat storage units made of chamotte (newly-developed design structure).

Positions of thermocouples installed in heat storage units of both types are shown in figure 2. Points for measuring temperature of walls of channels, for incoming and heated air, are designated as T1 and T2, respectively.

Figure 2. Positions of thermocouples installed in heat storage units made of magnesite, with slot-shaped channels, and of chamotte, with round-shaped channels.

In the process of experimental studies of thermal operation conditions, characteristics of ETS, temperature values where recorded in a number of test points:
- T1 – temperature of wall of incoming air channel of heat storage unit in lower and upper parts of ETS;
- T2 – temperature of heated air in lower and upper parts of ETS;
- T3 – temperature of heated air in the outlet of ETS;
- T4 – temperature of the surface of ETS housing;
- T5 – temperature in the bulk of heat storage unit of ETS;
- T6 – temperature in the bulk of thermal insulation in lower and upper parts of ETS.

4. Results and discussion
As a result of experimental studies were obtained: 1. Temperature change $T_{\text{wch}}$ wall of the air channels of the heat storage units with slit-shaped and round-shaped channels made of magnesite and chamotte in lower and upper parts in the modes of charging and heat emission of ETS (see figure 3a, 3b); 2. Temperature change of the heated air $T_{\text{air_wch}}$ in the channels of heat storage units with channels of slit-shaped and round-shaped channels made of magnesite and chamotte in lower and upper parts in the modes of charging and heat emission of ETS (see figure 3c, 3d); 3. Temperature change of the thermal...
... insulation \( T_{in} \) in lower and upper parts of ETS (see figure 3e); 4. Temperature change on the surface of the housing \( T_{sh} \) and the temperature change of the heated air at the outlet of ETS \( T_{outlet} \) (see figure 3f, 3g).

Results of experimental studies of thermal and dynamic characteristics of heat storage units made of magnesite and chamotte are shown in figures 3.

\[ \begin{align*}
T_{wch\_mag}, \quad ^\circ \text{C} \\
T_{wch\_ch}, \quad ^\circ \text{C} \\
T_{air\_wch\_mag}, \quad ^\circ \text{C} \\
\end{align*}\]
\[ T_{\text{air\_wch\_1\_low}}, T_{\text{air\_wch\_1\_up}} \]
\[ T_{\text{air\_wch\_2\_low}}, T_{\text{air\_wch\_2\_up}} \]

\[ T_{\text{in\_low}}, T_{\text{in\_up}} \]

\[ T_{\text{mag}}, T_{\text{sh}} \]

\[ T_{\text{outlet}} \]
Figure 3. Results of experimental studies of thermal state and dynamic characteristics of heat storage units made of magnesite and chamotte: (a, b) Temperature change $T_{wch}$ wall of the air channels of the heat storage units with slit-shaped and round-shaped channels made of magnesite and chamotte in lower and upper parts; (c, d) Temperature change of the heated air $T_{air,wch}$ in the channels of heat storage units with channels of slit-shaped and round-shaped channels made of magnesite and chamotte in lower and upper parts; (e) Temperature change of the thermal insulation $T_{in}$ in lower and upper parts of ETS; (f, g) Temperature change on the surface of the housing $T_{sh}$ and the temperature change of the heated air at the outlet of ETS $T_{outlet}$.

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 figure 3c, 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 a more uniform heating and cooling of the heat storage units of their chamotte than from magnesite (see figure 3a, 3b).

3. It was found that the temperature of thermal insulation in the lower part $T_{in,low}$ in the charging mode is higher than in the upper part $T_{in,up}$. In the heat emission mode, after 3 hours, the rate of cooling of thermal insulation in the upper part becomes less intense than in the lower part and, as a result, the temperature of thermal insulation is higher already in the upper part (see figure 3e).

4. The air temperature at the outlet of the ETS $T_{outlet}$ rises sharply immediately after the end of the charging mode and the fan is turned on from 180 to 300 °C. In the future, in the heat emission mode, its uniform decrease is observed (see figure 3f, 3g).

5. The surface temperature of the housing of ETS $T_{sh}$ is almost constant in the heat emission mode, and in the charging mode it increases from 30 to 70 °C (see figure 3f, 3g).

6. The temperature of the heated air $T_{air,wch}$ 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, 3c), than chamotte units (see figure 3b, 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 (see figure 4, 3b).
Figure 4. Temperature change wall of the air channels $T_{\text{wch,0}}$ of the heat storage units with round-shaped channels made of chamotte without the use of metal plates in lower and upper parts in operation modes of charging and heat emission.

The average cooling rate of heat storage units calculated with the use of the received experimental data ($m_{\text{mag}} = 9.28 \times 10^{-5} \text{ s}^{-1}$ and $m_{\text{ch}} = 1.54 \times 10^{-4} \text{ s}^{-1}$) 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, heating rate of heat storage units changes from $3.39 \times 10^{-4} \text{ s}^{-1}$ to $1.94 \times 10^{-5} \text{ s}^{-1}$, and from $7.22 \times 10^{-4} \text{ s}^{-1}$ to $1.39 \times 10^{-5} \text{ s}^{-1}$, for ETS heat storage units made of magnesite and chamotte, respectively.

5. 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: temperature change of heated air in channels of heat storage units and that in the outlet from ETS, temperature change in the bulk of thermal insulation and that on the surface of housing, 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. This feature is explained by the inverse dependence of the change in the thermal conductivity coefficient of magnesite on temperature, whereas in chamotte, the change in the thermal conductivity coefficient is directly proportional to the increase in temperature. The noted features of the dynamics of heating and cooling of heat storage units are also traced in the results of theoretical studies, which are qualitatively consistent with the experimental data presented in this work, with a discrepancy of no more than 10%.

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