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Evaluation of the efficiency of heat storage by a solid-state electric thermal storage

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Abstract. Calculated and experimental studies of thermal processes and the efficiency of heat storage of solid thermal storage materials in an electric thermal storage (ETS) were carried out. Changes in the thermo physical properties of selected thermal storage materials depending on temperature are analyzed. The specific heat storage capacity in the temperature range from 50 °C to 650 °C of such materials as magnesite, chamotte, dinas, corundum was estimated. The research was carried out on an electric thermal storage with an electric power of 2.4 kW with heat storage elements made of magnesite. The temperature distribution is obtained in the heat storage element, as well as in the wall of the air channels of the heat storage elements. Measurements of the temperature of the heated air in the channels of heat storage elements and at the exit from the ETS were carried out. Temperature measurements were carried out with chromel-alumel thermocouples in a ceramic shell and chromel-kopel in a heat-resistant fabric cover. As a result of experimental studies, the temperature distribution in the heat storage elements of ETS is obtained. Based on these data it was calculated the amount of stored heat by heat storage elements of ETS for the complete cycle of its operation.

1. Introdaction

For the widespread introduction of electric heating systems with electrothermal storage (ETS), a comprehensive assessment of the performance of such heating systems is required, namely: a study of the thermophysical properties of solid heat-accumulating materials and thermal processes that occur in the ETS in the mode of charge and heat transfer. Such studies are necessary to assess the factors affecting heat transfer processes and heat storage processes in the ETS in the charge and heat transfer mode.

In previous studies, the study of the effectiveness of the use of solid heat storage materials for ETS [1] was started. Mathematical modeling of heat transfer processes in the heat-accumulating elements of ETS from magnesite, pheolite and chamotte is carried out. The temperature distribution in the wall of the air channels of the heat storage elements in the charge and heat transfer mode ETS is obtained. Based on these data, the heat transfer from the channel walls to the flow of heated air was calculated.

The aim of this investigation were to evaluate and analyze the dynamic characteristics of the ETS heat storage elements and their storage capacity based on theoretical and experimental studies.

2. Theoretical investigation

The change in the thermophysical properties of solid heat-accumulating materials depending on temperature were analyzed. The formulas for calculating the coefficients of thermal conductivity and heat capacity [2] are given in Table 1. For the pheolite, the averaged values of the thermophysical properties are given [3].



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Material	$c_p, \text{kJ/(kg^{\circ}C)}$	λ , W/(m·°C)	$\rho_{av}, kg/m^3$
Magnesite	$1,05 + 0,29 \cdot 10^{-3} T_{TSM}$	4,7 - 1,7 \cdot 10 ⁻³ T_{TSM}	3000
Chamotte	$0,88 + 0,23 \cdot 10^{-3} T_{TSM}$	$0,84 + 0,58 \cdot 10^{-3} T_{TSM}$	2200
Corundum	$0,79 + 0,42 \cdot 10^{-3} T_{TSM}$	$2,1+1,9\cdot 10^{-3}T_{TSM}$	3300
Dinas	$0,837 + 0,25 \cdot 10^{-3} T_{TSM}$	$0,93 + 0,69 \cdot 10^{-3} T_{TSM}$	2200
Feolite	2,1	0,92	3900

Table 1. Thermo physical properties of solid thermal storage materials

The coefficients of thermal conductivity and heat capacity shown in Figure 1, Figure 2 for the temperature range 650-50 ° C. These are the maximum and minimum temperatures according to which the ETS heat storage elements are heated in the charge mode and cool in the heat transfer mode.



Figure 1. Change in thermal conductivity coefficient as a function of temperature T_{TSM}



Figure 2. Change in heat capacity coefficient as a function of temperature T_{TSM}

After analyzing the results, it can be noted that chamotte, corundum and dinas have a direct dependence of the change in the coefficient of thermal conductivity on temperature (Figure 1). In the

process of heating and cooling, magnesite has the highest values of the coefficients of thermal conductivity and heat capacity among the studied materials (Figure 1, Figure 2). It should also be noted that the coefficient of thermal conductivity of magnesite is inversely proportional to the increase in temperature.

The next step was the thermal diffusivity coefficient of the selected heat-accumulating materials (Figure 3).



Figure 3. Change in thermal diffusivity as a function of temperature T_{TSM}

Figure 3 shows that magnesite again has the highest thermal diffusivity, and chamotte has the lowest value.

In a previous study, mathematical modeling of thermal processes occurring in a heat storage element from fireclay with circular air channels in the charge and heat transfer mode ETS was performed [4]. Based on the obtained temperature distribution in the wall of the air channels of the heat storage elements, the heat transfer coefficients from the channel walls to the heated air flow were calculated. The values of heat transfer coefficients α_{κ} were calculated with the air channel length of 0.3 m and air speed w = 3 m/s. The heat transfer coefficient anat in the charge mode for natural convection is in the range 13-14 W/(m^{2.o}C, and in the heat transfer mode the heat transfer coefficient α_{ch} for forced convection is 18.5-19.5 W/(m^{2.o}C).

The specific heat storage capacity of the studied TSM was also calculated by the formula

$$q_{st} = \frac{Q_{st}}{m_{TSM}} = c_1 \cdot (T_2 - T_1)$$
(1)

The calculated values of the specific heat storage capacity in the range of 650-50°C with an average heat capacity coefficient of materials are given in Table 2.

Table 2. Specific heat storage capacity and average heat capacity coefficient of the studied materials

Material	Magnesite	Chamotte	Corundum	Dinas	Feolite
c_{pav}	1,14	0,94	0,92	0,90	0,92
q_{sp}	685	563	554	539	532

Using the temperature dependences of the thermal conductivity and heat capacity of TSM shown in Figure 1 and Figure 2 and the obtained experimental data [5], we can calculate the amount of

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accumulated heat Q_{st} ETS taking into account the storage capacity of thermal insulation using the formula

$$Q_{st} = c_{pav} \rho_{av} V_{TSM} (T_{TSM2} - T_{TSM1}) + c_{pins} \rho_{ins} V_{ins} (T_{ins2} - T_{ins1}),$$
(2)

Where T_{TSM1} – initial temperature TSM, °C;

 T_{TSM2} – TSM temperature at a specific point in time τ , °C;

 T_{ins1} , T_{ins2} – the initial and current temperatures of thermal insulation ETS, °C;

 V_{TSM} , V_{ins} – TSM and thermal insulation volume ETS, m³.

ETS usually uses 2 types of thermal insulation - MKRP-340 [6] and Microtherm Panel [7]. The MKRP-340 plate is made of refractory fiber of a mullite-siliceous composition and is used in Ukrainianmade ETS [8]. Microtherm Panel high-temperature microporous thermal insulation is made in the form of panels in an outer shell of fiberglass. The composition of thermal insulation includes a damped mixture of fibers reinforced with fumed silica (SiO₂).

The change in the thermal conductivity coefficient λ of the indicated high-temperature heatinsulating materials depending on the temperature is shown in Figure 4.



Figure 4. Change in thermal conductivity coefficient λ of high-temperature thermal insulation materials: I – Microtherm Panel 1000R; 2 – MKRP-340

It can be noted that the thermal insulation of the Microtherm Panel 1000R has a lower coefficient of thermal conductivity in contrast to the MKRP-340. But the cost of the Microtherm Panel 1000R is several times higher than that of the Russian-made MKRP-340, which will affect the final cost of ETS for consumers.

The heat capacity coefficient of these heat-insulating materials is practically independent of temperature. For MKRP-340 $c_{pins} = 1,047 \text{ kJ}(\text{kg} \cdot ^{\circ}\text{C})$ [6], and for Microtherm Panel 1000R c_{pins} changes in the range of 0,92-1,08 kJ/(kg $\cdot ^{\circ}$ C) [7]. Insulation density for MKRP-340 is 340 kg/m³, but for Microtherm Panel 1000R – 240 kg/m³.

3. Experimental research

Experimental studies of the dynamic characteristics of solid heat storage elements from magnesite and chamotte in the mode of charge and heat transfer ETS were carried out. Measurements were taken in the upper and lower zones of the ETS heat storage unit. The temperature was recorded in the channel wall of the heat storage elements and in the thermal insulation of ETS. Heated air temperatures were

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also measured in the channels of the heat storage elements and at the outlet of the ETS. The primary temperature transducers were chromel-alumel thermocouples in a ceramic shell and chromel-copel (ChC) in a case made of heat-resistant fabric. A universal 8-channel temperature controller was used as a secondary converter UKT-38.SH4.TP. Via interface adapter AC-2 data entered the computer and processed in a software package Owen Process Manager v1.2. Detailed results of experimental studies are given in [5].

On Figure 5 and Figure 6 show photographs of the heat storage elements from chamotte and magnesite.



Figure 5. Magnesite thermal storage elements of ETS.



Figure 6. Chamotte thermal storage elements of ETS.

The indicated features of changes in the thermophysical properties depending on temperature are reflected in the dynamics of heating and cooling of the heat-accumulating elements from magnesite and chamotte. Note that in both cases the heat flux from TEH is the same and constant ($q_{\text{TEH}} = 7700 \text{ W/m}^3$), and also cooling occurs at a constant speed of air flow in the channel (w = 3 m/s).

Based on the obtained experimental data, the amount of accumulated heat was calculated by ETS elements from magnesite and chamotte (Figure 7) [5].



Figure 7. The amount of stored heat in absolute values in the charge and the heat output mode of ETS: m-magnesite, ch-chamotte

4. Discussion

Theoretical and experimental studies of the dynamic characteristics of heat-accumulating elements from chamotte and magnesite in the charge and heat transfer mode ETS. It is shown how the thermophysical characteristics of the selected heat-accumulating materials change upon heating from 50 $^{\circ}$ C to 650 $^{\circ}$ C and subsequent cooling during the period of charge and heat transfer ETS. More effective material in the ETS charge mode is magnesite. In the ETS heat transfer mode, the use of chamotte heataccumulating elements with circular channels is more efficient, which provide a higher heat transfer in the channels of ETS heat-accumulating elements compared to magnesite heat-accumulating elements with slit channels, which is confirmed by the obtained experimental data. This is explained by a more uniform temperature distribution in the heat storage elements from chamotte, the shape of the air channels, a more intensive cooling rate and a higher temperature pressure between the channel wall and the heated air in the channel than in the air channels of the heat storage elements from magnesite. The specific heat-storage ability and the amount of accumulated heat of the studied materials were calculated. The amount of accumulated heat depends on the heat capacity of the material, its mass and the operating temperature range. Thermal insulation, which has a certain storage capacity, also affects the efficiency of heat storage in ETS. It is also advisable to use ETS as electrothermal storage systems in high-tech closed-type agricultural and aquaculture facilities (greenhouse complexes, hatchery hatcheries, animal complexes) to maintain the required temperature regime in accordance with technological requirements. It should also take into account the possibility of generating additional volumes of electricity through the use of the heat of secondary energy resources generated as a result of technological processes at these enterprises, which will contribute to an increase in the volume of output and a reduction in its cost.

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