Theoretical studies of the thermal state of heat storage elements of the electric thermal storage in the modes of charging and heat output

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Abstract. Theoretical studies of the thermal state of heat storage elements with air channels of various shapes in the modes of charging and heat output of the electric thermal storage (ETS) are carried out. The mathematical model of heat exchange processes adapted to the operating modes of the ETS is presented. The change in the average heat transfer coefficient in the air channels in the conditions of natural and forced convection in the modes of charging and heat output ETS, and the heat flux density in the mode of charging of the ETS from a tubular electric heating element (TEH) for heat storage elements with channels of a slit and round shape are shown. The temperature distribution in heat storage elements made of chamotte and magnesite with slit-shaped (standard design) and round shape channels is obtained. As a result of the studies carried out, the temperature change and the dynamics of heat transfer in the air channels of heat storage elements made of various types of thermal storage material (TSM) in the modes of charging and heat output of the ETS were analyzed. The conclusion is made about the efficiency of using heat storage elements made of chamotte with round-shaped channels in the ETS.

1 Introduction

The main sources of heat supply for rural areas are usually small boiler houses, as well as individual heat generators using various types of organic fuel. In most cases, these heat-generating installations have quite low efficiency, the actual value of which is less than that stated in the boiler's passport data. This is often due to the use of local types of low-grade and substandard fuel (coal, peat, wood), unsatisfactory technical condition, and also the conditions and modes of operation of boilers. The use of such heat-generating installations will certainly entail a significant excessive consumption of fuel [1, 2].

In this regard, improving the energy efficiency of heat supply systems and the rational use of organic fuels in rural areas, and also energy saving in farms and livestock farms, remains an urgent issue [3, 4].

With the commissioning of new nuclear power units' nuclear power plants (NPPs) and the development of hydropower in Russia, the irregularity of the load schedule of the power

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system during the day is observed. It is possible to align the load schedule of the power system at night when switching to decentralized electric heating systems in agriculture and rural areas. With the large-scale introduction of electric heat storage heating systems in agriculture and rural settlements with a sufficiently large total capacity and the possibility of their remote dispatch control, these systems will be able to act as load regulators of the Unified Energy System of Russia, and, thereby, will reduce the requirements for the flexibility of the power generating capacities of the thermal power plants (TPPs) and NPPs. The mass introduction of ETS in rural areas and farms will not require the introduction of additional power generating capacities, will reduce the consumption of organic fuel at TPPs and combined thermal and power plants (CTPPs) (gas, coal) by replacing it with nuclear energy and reduce electricity losses in the power grid, and will also eliminate the need in maneuvering the capacities of power plants of TPPs and CTPPs at night, which leads to a decrease in their efficiency and excessive consumption of fuel.

ETS electricity consumption occurs at night (charging mode) and therefore it is advisable to use them as electric heat storage heating systems in combination with a two-rate or multi-rate metering device for consumed electricity using tariffs differentiated by zones of the day (night zone from 23.00 to 07.00).

2 Materials and methods

The heat storage by solid heat storage material (TSM) in ETS occurs due to its heating by tubular electric heating elements (TEH) during the period of the minimum load of the power system-at night, when rates for electricity consumption, differentiated by zones of the day, are applied. In the daytime, the air in the room is heated by passing it through the air channels of the heat storage elements of the ETS, and also due to convective heat exchange and radiation from the surface of the ETS housing.

To increase the energy and economic efficiency of ETS operation with their mass introduction in rural areas and farms, it is necessary to carry out theoretical and experimental studies of heat exchange processes occurring in the modes of charging and heat output of ETS, the thermophysical properties of TSM used in ETS, and also the thermal mode of premises when using ETS as electric heat storage heating systems.

ETS is referred to as thermal storage (TS) of the heat capacity type. TS of this type are used in various heat supply systems for household and commercial consumers, in agriculture [5, 6], various industries, and also in solar heat supply systems [7]. The widespread use of TS with solid TSM was obtained due to the use of relatively cheap TSM and the simplicity of designs.

In [8], the study of the efficiency of heat storage by electric heat storages was carried out. In [9...11], studies of the efficiency of heat output by ETS are carried out. Studies of the thermal mode of the room when using ETS as a heating system were also carried out [12]. In [10], ways of intensification heat transfer processes in ETS air channels by using metal inserts of different configurations are also considered.

The purpose of this work is theoretical studies of the thermal state of solid heat storage elements of ETS with different shapes and configurations of air channels, and also when using different TSMs.

Consider a magnesite heat storage element of square-section size 0.2×0.2 m, in the center of which are located: 1. Two parallel slit-shaped air channels with a size of 0.1×0.015 m; 2. Two round-shaped channels with a diameter of d_{ch} = 0.044 m. The length of each air channel is 0.5 m. The heat storage core is covered with high-temperature thermal insulation, the thickness of which is 0.05 m. The heat capacity coefficient of thermal insulation is practically independent of temperature and is assumed to be constant c_p = 1.047 kJ/(kg·°C). The density of thermal insulation is adopted ρ_{in} = 340 kg/m^3. The density of magnesite is adopted $\rho_{\text{mag}} = 3000$ kg/m^3, the density of chamotte $\rho_{\text{cham}} = 2200$ kg/m^3. TEH – nichrome thread in a steel shell ($\lambda_{TEH} = 45.4$ W/(m·°C); $c_{pTEH} = 0.462$ kJ/(kg·°C); $\rho_{TEH} = 7900$ kg/m^3).

The cross-sectional area of the round-shaped air channels was selected in such a way that its value was equivalent to the cross-sectional area of the two slit-shaped air channels of a standard heat storage element. The equality of the geometric parameters of the studied heat storage elements ensures the correct of the assessment of the impact of the shape and size of the air channel on the temperature distribution in the heat storage element.

The radiant component of the heat transfer coefficient α_{ch} from the wall of the air channel is not taken into account due to the fact that the temperature of the walls is assumed to be the same and the radiant heat exchange between them does not occur.

It should be noted that the heat exchange conditions change along the length of the air channel, which makes the problem of the thermal interaction of the air flow and the walls of the channel three-dimensional. Obviously, the three-dimensional problem can be reduced to a series of two-dimensional problems in the horizontal sections of the ETS, if the temperature of the air in each of the sections is set, taking into account its heating in the previous sections of the channel. Three cross-sections of the ETS element were considered (in the lower, middle and upper parts of the ETS heat storage core). Preliminary calculations showed that the difference between the obtained temperatures of the wall of the air channel of the heat storage element in the considered cross-sections in height is not more than 20 °C, that is the temperature fluctuations in height are insignificant. Therefore, it was decided to perform mathematical modeling of thermal processes in the heat storage element of the ETS in the modes of charging and heat output, using a two-dimensional model of the element [13].

Taking into account the difficulty of solving the conjugate problems of non-stationary heat transfer in a strict mathematical formulation, it was decided to carry out separate numerical simulation of heat exchange processes in the TSM and in the channels of heat storage elements.

We calculate the non-stationary temperature field of the heat storage element by solving a two-dimensional direct non-stationary heat conductivity problem by the finite element method [13].

The mathematical model of heat exchange processes during heating and cooling of a solid heat storage element ETS includes a two-dimensional non-stationary equation of thermal conductivity with specified initial and boundary conditions:

$$
\begin{gathered}
c\rho\frac{\partial T_i}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T_i}{\partial y}\right) + q_{V\,TEH}(\tau, x, y), \\
q_{V\,TEH} = \begin{cases} \dfrac{Q_{TEH}(\tau)}{V_{TEH}} & (x, y) \in \Omega_{TEH} \\ 0 & (x, y) \notin \Omega_{TEH}, \end{cases} \qquad (1) \\
Q_{TEH}(\tau) = \begin{cases} \text{const in the mode of charging} \\ 0 \text{ in the mode of heat output,} \end{cases}
\end{gathered}
$$

where $T_i\ (x, y, \tau)$ – the temperature in the i-th layer TSM, $i = 1...n$, °C; $q_{VTEH}\ (\tau, x, y)$ – specific volumetric density of heat dissipation of TEH, W/m^3; τ – time, sec.

The chamotte heat storage element with round-shaped channels is supplemented with a 2 mm thick metal plate in the simulation of thermal processes to increase the heating dynamics in the charging mode [14].

In Fig. 1 the change in the coefficients of heat transfer from the walls of the channels to the heated air flow for the first α_{ch1} and the second channel α_{ch2} (the mode of heat output), and also the heat flux from the TEH (the mode of charging) for the heat storage element with two slit-shaped channels made of magnesite, are shown.

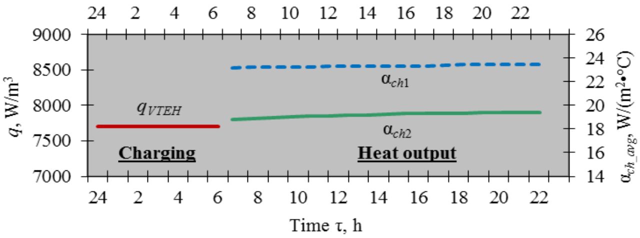


Fig. 1. Setting the boundary conditions of the II and III kind in time τ for a heat storage element made of magnesite with two slit-shaped channels

Change in the average heat transfer coefficient α_{ch_nat} and α_{ch} in the air channels with free and forced air movement in the modes of charging and heat output of the ETS, and also the heat flux in the mode of charging of the ETS from the TEH for a heat storage element made of chamotte with two round-shaped channels [14] (Fig. 2).

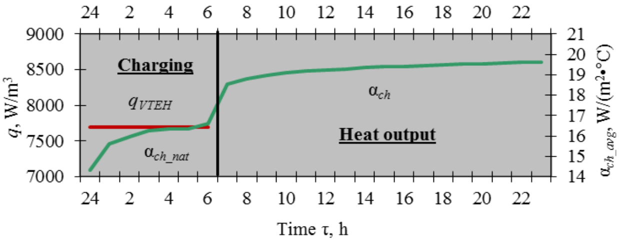


Fig. 2. Setting the boundary conditions of the II and III kind in time τ for a heat storage element made of chamotte with two round-shaped channels

Important factors in the numerical simulation of heat exchange processes in the heat storage elements of the ETS are the influence of natural convection and the change in the air temperature in the air channels of the heat storage elements in the charging mode of the ETS.

The change in the average heat transfer coefficient α_{ex_avg} from the outer surface of the ETS housing during the period of charging and heat output is presented in Fig. 3.

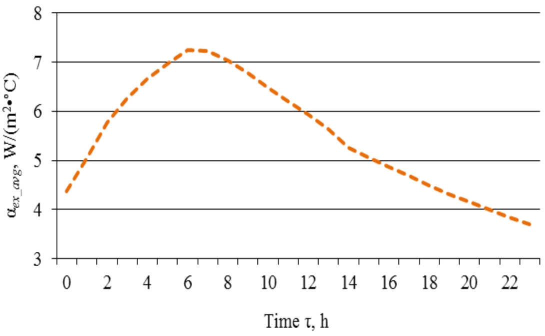


Fig. 3. Setting the boundary conditions of the III kind in time τ for a heat storage elements made of magnesite and chamotte

3 Results and discussion

The results of numerical simulation of thermal processes in heat storage elements made of magnesite with slit-shaped and round-shaped channels are presented in Fig. 4.

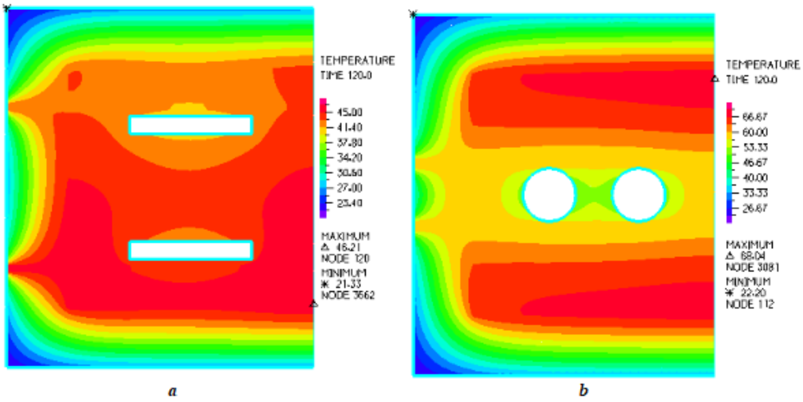
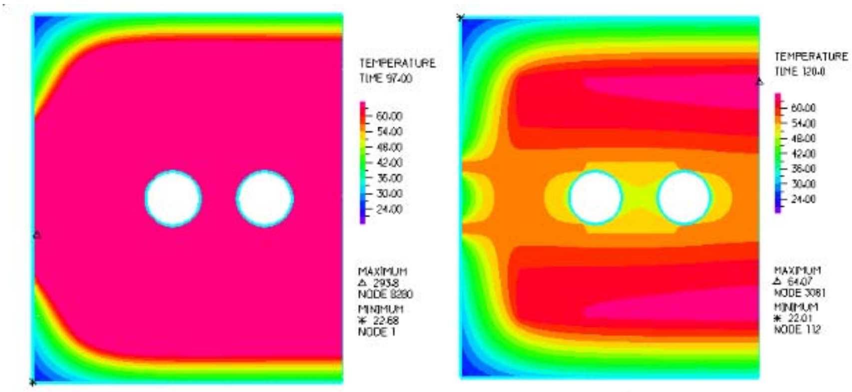


Fig. 4. Temperature distribution in the magnesite heat storage element at the end in the mode of heat output of the ETS: a - diagram of the heat storage element with two slit-shaped channels (standard design); b - the same with two round-shaped channels

As a result of numerical simulation of thermal processes, the temperature distribution in the heat storage element made of chamotte with round-shaped channels in the modes of charging and heat output of the ETS was obtained (Fig. 5).



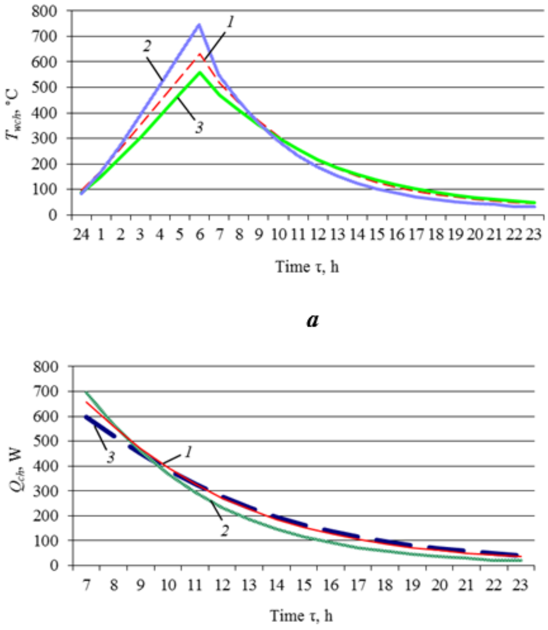
a *b*

Fig. 5. a – temperature distribution in the heat storage element from the chamotte after the 1st hour of the ETS charging mode; b - temperature distribution in the heat storage element from the chamotte at the end of the ETS heat output mode

It should be noted that the cooling rate of a heat storage element with two round-shaped channels is higher than that of a heat storage element with two slit-shaped channels (Fig. 4), which provides a higher heat output of the ETS.

In the scheme of a heat storage element with two round-shaped channels, a more uniform temperature distribution is also observed in its central part and in the area where the air channels are located, in contrast to the standard scheme of a heat storage element (Fig. 4 and Fig. 5), which leads to lower temperature stresses in the heat storage elements and an increase in their service life.

Studies of the thermal state of heat storage elements from various types of TSM in the modes of charging and heat output of the ETS are carried out. The standard scheme of a heat storage element with two slit-shaped channels was considered. The change in the temperature of the wall of the air channels of heat storage elements during the period of charging and heat output, and also the dynamics of heat transfer in the air channels of the heat storage elements of the ETS are analyzed. The results are presented in Fig. 6.



a

b

Fig. 6. Change in the temperature T_{wch} of the wall of the air channel of heat storage element in the modes of charging and heat output of the ETS during 1 day (a) and heat output Q_{ch} in the air channel of heat storage element (b): 1 – magnesite; 2 – chamotte; 3 – pheolite

Analyzing the results of theoretical studies of the thermal state of heat storage elements using various TSM, the following can be noted: 1. The rate of heating and cooling of the heat storage element made of chamotte is higher than that of similar elements made of magnesite and pheolite. This parameter is important in the processes of heat storage and heat output in the ETS. This will allow to get a higher temperature TSM at the end of the ETS charging mode, and also to provide a higher heat output when the ETS fan is running for the first 3 hours. The cooling dynamics of heat storage elements made of magnesite and pheolite is almost identical, with the exception of the first 2 hours in the heat output mode due to the higher temperature of magnesite at the end of the charging mode. In the following hours, uniform cooling of the considered TSMs is observed and the temperature values T_{wch} are almost the same in all three variants (Fig. 6 ***a***); 2. The heat transfer in the channel of the heat storage elements Q_{ch} is slightly higher in the case of using magnesite and pheolite, than in the variant with chamotte (Fig. 6 ***b***). This is due to the higher value of the thermal conductivity coefficient of magnesite and pheolite.

It can be concluded that the use of chamotte heat storage elements with round channels in the ETS is more rational in terms of energy and economics.

4 Conclusion

1. Theoretical studies of the thermal state of heat storage elements with air channels in the modes of charging and heat output of the ETS are carried out.

2. The temperature distribution in heat storage elements with air channels of various shapes in the modes of charging and heat output of the ETS has been obtained.

3. The round shape of the air channels of heat storage elements allows to increase the dynamics of their heating, which reflects the temperature T_{wch} at the end of the ETS

charging mode, and the dynamics of heat output in the channels of heat storage elements in comparison with standard heat storage elements with slit-shaped channels.

4. The efficiency of heat storage and heat output by heat storage elements using various heat storage materials has been evaluated. The conclusion is made about the advisability of using chamotte as a TSM for ETS.

5. Electric thermal storage with controlled heat output can be used as electric thermal storage heating systems in agriculture and rural settlements as an alternative to small boiler houses and individual heat generators using various types of low-grade and substandard local fuel.

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