Chapter 9
Solar System with Seasonal Thermal Energy Storage

V. M. Pakhaluev, S. Ye. Shcheklein, and A. V. Matveev

Difference in time of arrival and consumption of thermal energy for hot water supply and space heating of residential buildings and industrial premises is a characteristic feature of systems using solar energy. In summer, solar systems produce a significant amount of unclaimed thermal energy, while in winter there is a heat deficit. Therefore, such systems need energy storage devices. A large number of works performed to date confirm this argument [1–3].

The utility of seasonal thermal energy storage (STES) devices is determined by their ability to collect and store the necessary amount of thermal energy for a long time. The time of thermal energy accumulation in summer and its storage to be used in winter is the key indicator of the storage systems [4–6]. A STES with heat insulation along the boundaries of the thermal storage is up to the task.

The design of seasonal thermal energy storage can be of various types [7–9]. One of such types is an underground thermal energy storage represented by a heat-insulated body of soil receiving and giving off heat, where the soil body itself serves as a storage medium. An underground energy storage without thermal insulation exhibits significant energy losses as a thermal storage. The use of modern thermal insulation materials helps maintain the required temperature level in the absence of heating load [10–12].

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9.1 Operation of Seasonal Thermal Energy Storage During the Period of Charging

A mathematical model to study STES performance includes a dual-circuit solar system with a solar collector, water tank to collect the day's worth of heat, and a ground-coupled storage with an insulated body of soil (Fig. 9.1), similar to the one described in [13]. The period of heat accumulation is characterized by an increase in the volume-average temperature of the storage and depends on thermal energy coming from the water heating plant (WHP), with account of thermal losses through the insulation.

$$\left(c_p \rho V_s\right) \cdot \frac{d\Theta}{d\tau} = Q_{\text{WHP}} - Q_{\text{los}} = F_{\text{sc}} \cdot q(\tau) \cdot \eta_{\text{WHP}} - k \cdot \Theta \cdot S_s, \tag{9.1}$$

$$\eta_{\text{WHP}} = \eta_{\text{sc}}(\tau) \cdot \eta_{\text{st}} \cdot \eta_{\text{pipe}}, \tag{9.2}$$

where $(c_p \rho V_s)$ is thermal capacity, density, and volume of the ground-coupled storage; $\Theta(\tau)$ is the difference between the volume-average temperature of the storage and that of the surrounding soil; $q(\tau)$ is solar intensity on the solar collector surface; F_{sc} is the surface area of the collector; η_{WHP} is the efficiency of the water-heated plant which is a combination of the efficiencies of the solar collector, storage tank, and connecting pipelines; k is insulation heat transfer coefficient; and S_s is the outer surface area of the storage.

Using the "mean value" theorem to calculate the integral of the product of functions depending on time τ, the change in the storage temperature is given by

$$\theta(\tau) = BA \int_0^{\tau} Q_{\text{WHP}}(\tau) d\tau, \tag{9.3}$$

where

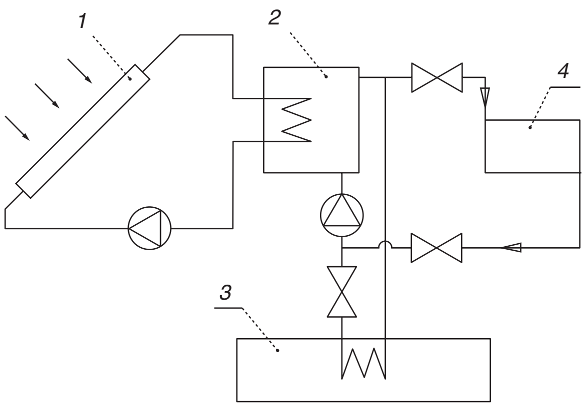

Fig. 9.1 Schematic diagram of the solar system with a seasonal thermal energy storage: *1*–solar collector, *2*—intermediate storage tank, *3*—seasonal thermal energy storage, and *4*–consumer

$$B = F_{\mathrm{sc}} \cdot \left(c_p \rho V_s\right), \tag{9.4}$$

$$A = \exp\left[-\frac{0.5 \cdot k \cdot S_s}{\left(c_p \rho V_s\right)} \cdot \tau\right] \tag{9.5}$$

$$Q_{\mathrm{WHP}}\left(\tau\right) = q\left(\tau\right) \cdot \eta_{\mathrm{WHP}}\left(\tau\right) \tag{9.6}$$

where $Q_{\mathrm{WHP}}(\tau)$ is the change in specific thermal output of WHP during the daylight hours.

Storage tank and connecting pipelines are assumed to be well insulated, which allows the heating capacity of a water heating plant in the summer period to be expressed as

$$Q_{\mathrm{WHP}}^{N} = \sum_{1}^{N} \left(Q_i \cdot \eta_i\right)^{\mathrm{month}} \tag{9.7}$$

where Q_i and η_i are the monthly values of solar intensity and the corresponding values of collector efficiency for that period, respectively.

The efficiency of solar collector can be determined using the expression

$$\eta_i^{\mathrm{month}} = \eta_0 - 1.33 \frac{\Delta T_i}{I} - 0.007 \frac{\Delta T_i^2}{I} \tag{9.8}$$

where I is solar intensity per square meter of collector surface, η_0 is the optical efficiency of the collector, and ΔT_i is the monthly average difference between the heat carrier temperature in the collector and the ambient temperature.

Figure 9.2 shows the calculated values of heating capacity of a water heating plant with a south-facing vacuum tube collector ($\eta_o = 0.7$) arranged at an angle of 56° N to the horizontal. Climatic data used in the calculation were supplied by meteorological station of Yekaterinburg.

To assess the storage heat loss, its shape is assumed to be a rectangular parallelepiped with equal side dimension and height equal to half of it. In this case, the relationship between the surface area S_s and volume V_s is defined by a simple ratio:

$$S_s = 6.35 \cdot V_s^{0.67}. \tag{9.9}$$

Conductive heat losses from the storage to the surrounding soil depend on thermal resistance of insulation itself k_{insul} and that of its boundaries with the soil R_{soil} [14]:

$$k = \left(R_{\mathrm{insul}} + 2R_{\mathrm{soil}}\right)^{-1} = \left[\frac{\delta_{\mathrm{insul}}}{\lambda_{\mathrm{insul}}} + 0.75\left(\pi \lambda_{\mathrm{soil}} V_s^{0.33}\right)^{-1}\right]^{-1}, \tag{9.10}$$

where δ_{insul} is the thickness of insulation layer and λ_{insul} and λ_{soil} are the heat-conduction coefficients of the insulations and soil, respectively (0.04 W/(m·K) and 0.8 W/(m·K)) [14].

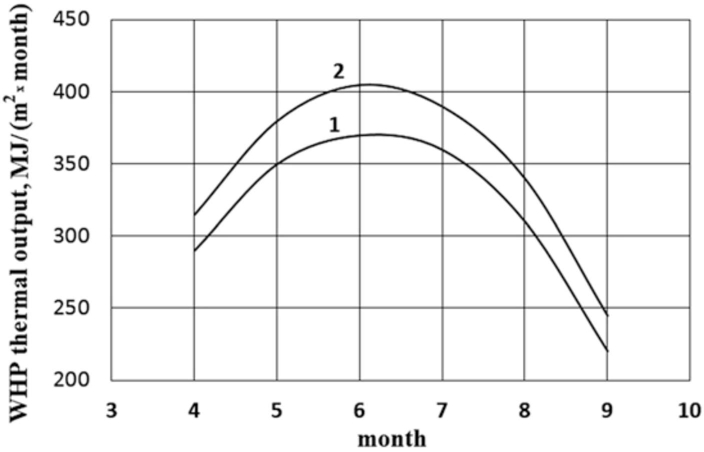

Fig. 9.2 Specific heating capacity of the STES water heating plant equipped with a vacuum collector during the summer months in Yekaterinburg. Lines 1 and 2 at an average temperature of the heat carrier T_κ of 75 °C and 50 °C, respectively

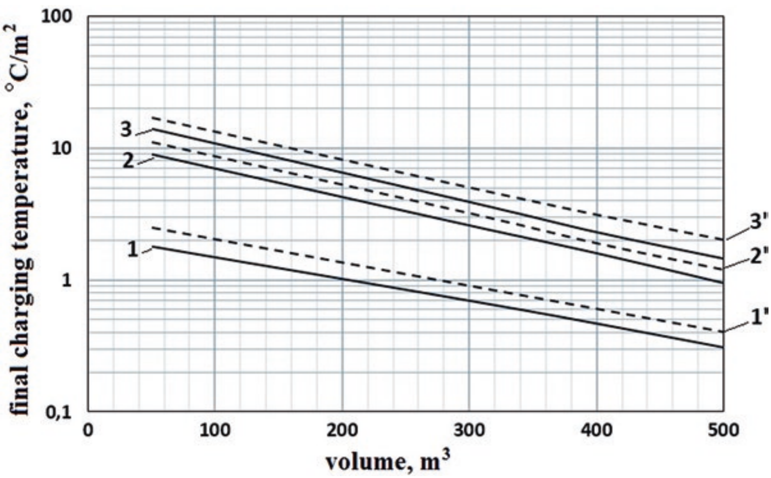

Fig. 9.3 The final temperature of STES charging per square meter of solar collector area (in Yekaterinburg): 1, 2, 3 and 1′, 2′, 3′ are the charging time during 1, 3, and 6 summer months at T_κ of 75 °C and 50 °C, respectively

With insulation thickness δ_{insul} of 0.5 m, the k factor equal to 0.08 W/(m^2·K) remains virtually unchanged at V_s of 50–500 m^3.

Using the specific output of water heating plant (Fig. 9.2) and applicable expressions (9.3), (9.7), and (9.10), it was possible to calculate the final heating temperature of STES as a function of its volume and its charging time for 1, 3, and 6 summer months in the climatic conditions of Yekaterinburg (Fig. 9.3).

As follows from Fig. 9.3, with V_s of 300 m^3, storage side dimension of 8.4 m, and height of 4.2 m, the solar collector area needed to heat STES to a temperature Θ of 65 °C in summer (6 months) would be F_{sc} = 32 m^2, while with V_s of 500 m^3, the required area would be 72 m^2.

In calculations, the temperature of the soil surrounding the storage was assumed to be constant and equal to 10 °C.

9.2 Operation of Seasonal Thermal Energy Storage During the Period of Heating

The amount of thermal energy that can be stored in STES and then used for space heating is determined by the final temperature of storage as a result of its charging and by the minimum storage temperature, which is usually assumed equal to the surrounding soil temperature of 8–12 °C. Heat losses during this period are due to conductive heat exchange of the storage through the layer of insulation.

STES operation in the discharge period under the fixed heating load corresponds to

$$\left(c_p \rho V_{\mathrm{STES}}\right) \cdot \frac{d\Theta}{d\tau} + k\Theta S_{\mathrm{STES}} = -Q_{\mathrm{hl}}, \tag{9.11}$$

where $\Theta(\tau)$ is the excess temperature of the storage body as a function of the surrounding soil temperature and Q_{hl} is the value of heating load in winter.

The time of STES operation with the selected heating load in direct heating mode (without a heat pump) is defined by

$$\tau = \left(c_p \rho\right)_{\mathrm{STES}} \cdot k^{-1} \left(\frac{S_{\mathrm{STES}}}{V}\right)^{-1} \cdot \ln \frac{(1+a)}{\left(\frac{\Theta}{\Theta_0} + a\right)} \tag{9.12}$$

$$a = \frac{Q_{\mathrm{hl}}}{\Theta_0} \cdot \left(k \cdot S_{\mathrm{STES}}\right)^{-1} \tag{9.13}$$

where Θ is the final cooling temperature of STES during discharge and Θ_0 is the maximum temperature of the storage during charging period.

For the analysis of Eq. (9.12), the temperature regime of STES operation was selected for the underfloor heating conditions ("warm floor"). A special feature of the system is a reduced temperature of supplied coolant (not more than 45 °C). The required temperature is attained by adding the reverse water into the heating system.

Optionally, a minimum cooling temperature of the storage up to 35 °C was considered for the case when a floor is directly heated by the circulating heat carrier and cooling to the surrounding soil temperature of 10 °C with a backup heat source or a heat pump.

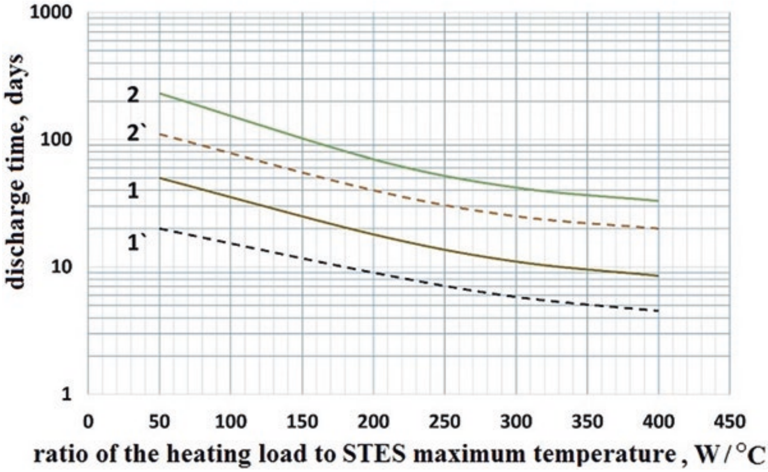

Fig. 9.4 STES discharge time in the modes of complete discharge (1, 2) and discharge to 35 °C (1′, 2′) with the storage capacity of 100 and 500 m³

In Fig. 9.4, the calculated values of STES operating time depending on the heating load are shown against the maximum charging temperature for the two modes of storage discharge. An example would be an individual house with the underfloor heating, total area of 800 m² and a heated area of 70 m², requiring a thermal output of 8.4 kW. The maximum operation time would be 120 days for a charging temperature of 90 °C in summer and for the volume of 500 m³; in the mode of complete discharge to 10 °C, operating time would be 220 days. Operating time is significantly reduced with a rise in heating load when maximum heating temperature of STES is limited to 60–90 °C.

The proposed method for calculating the solar system with seasonal thermal energy storage allows us to estimate the required solar collector area and the STES charging and discharging temperature regimes along with the main geometric parameters of the system.

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