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THERMAL PERFORMANCE OF ENERGY STORAGE VESSEL

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1. Introduction

World demands for thermal energy are constantly increasing. The technology, which can contribute to increasing the efficiency of energy consumption, is thermal energy storage. The main role of such energy storage systems is to accumulate heat and to achieve the most effective use of the collected energy.

Thermal energy storage is a preservation of thermal energy in the form of some substances with high or low temperatures for later use, e.g. to keep the thermal energy in summer and to use it for heating buildings or water heating in winter. This type of energy storage systems is called seasonal thermal energy storage system.

2. Sensible thermal energy storage systems

The selection of this system for a specific use depends mainly on: duration of storage, storage capacity, costs, supply and utilization temperature requirements, heat losses and available space [1]. There are two possible media for sensible heat storage: liquid and solid materials. Sensible thermal energy storages are usually designed to accumulate thermal energy during summer and to use it in winter, when it is needed. However this application requires large storage volumes and the best place could be underground space [2].

3. Design of water heat storage

The heat accumulation device according to [4] consists of two concentric cylindrical containers made of concrete. Between these two layers there is a thermal insulation layer – the gap with thin air (the vacuum-like one). A construction of the model storage tank is shown in Fig. 1. The air from the gap between both containers should be sucked out in order to obtain the residual air pressure equal to 10^{-3} [Pa]. The inner container is filled by water intended to operate as a heat accumulation medium. The temperature of the water is 90^{o}C. Finally, the accumulator device should be placed in the surroundings (e.g. basement) providing stable conditions on the external boundary with the air temperature of 12°C.

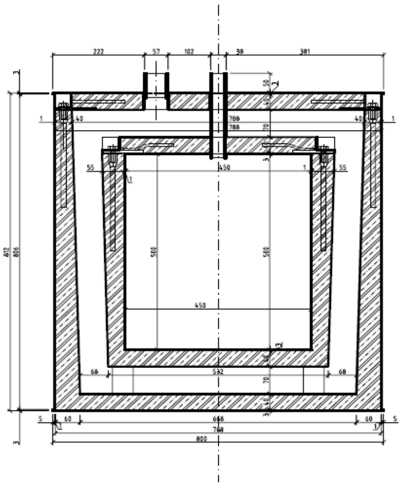

Fig. 1. A schematic cross-section of the thermal energy storage tank.

4. Heat transfer within the accumulator device – physical and mathematical model

An initial point of our model investigations is the instant when the hot water is poured to the container and closed hermetically. Accordingly, the temperature of the container of heat accumulation medium increases gradually and it is equal almost to the temperature of the medium during a sufficiently long time interval. Our investigations are focused on the cooling process of the accumulation medium enclosed in such an insulated device.

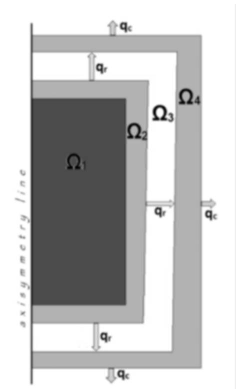

Fig. 2. Domain of the heat transfer calculation – 2D section of axisymmetric body.

In order to evaluate the process the authors created a nonlinear complex heat transfer model of the heat exchange between the accumulator device and the ambient cold air taking into account a conduction, convection and radiation type, as well. The investigated domain Ω included the accumulator device consisting of two containers (Ω_2 and Ω_4), accumulation medium (Ω_1) and vacuum-like layer (Ω_3) ($\Omega=\Omega_1\cup\Omega_2\cup\Omega_3\cup\Omega_4$). The heat conduction was assumed for both solid components of the device – two concrete containers – and for the water, where a continuous homogenization was supposed and convection was neglected.

A strongly dominant type of heat transfer in the insulating vacuum-like layer Ω_3 was radiation and conduction influenced the total heat transfer minimally.

The corresponding governing equation for the considered heat conduction problem is of the form:

$$c(\mathbf{X},t)\,\rho(\mathbf{X},t)\,\frac{\partial T(\mathbf{X},t)}{\partial t} = \nabla \cdot \big(\lambda(\mathbf{X},t)\;\nabla T(\mathbf{X},t)\big), \tag{1}$$

where: $\mathbf{X}=(x,y,z)\in\Omega$ – an arbitrary point of domain Ω, t – time, T – temperature, c – specific heat, ρ – mass density, λ – heat conduction coefficient.

The radiation in subdomain Ω_3 obeyed the Stefan-Boltzmann law expressing radiative heat flux between two (radiating and irradiated) surfaces of temperatures T_1 and T_2:

$$q_r = \sigma\varepsilon AF\left(T_1^4 - T_2^4\right), \tag{2}$$

where: σ – Stefan-Boltzmann constant equal to 5.6704×10^{-8} [W/(m^{2}K^4)], ε – emissivity of the surface, A – the receiving surface magnitude, F – dimensionless viewing factor, T_1/T_2 – temperature of hot/cold surface. The conductive part of heat transfer was also taken into account in subdomain Ω_3 despite of the fact the air was thin in the gap. Finally, the convective heat transfer boundary conditions were applied on the outer boundary of domain in the following form:

$$q_c = h_c\left(T - T_e\right). \tag{3}$$

The computations based on Eqs. 1-3 were realized by using the multiphysical finite element software. The overall time interval was divided into subintervals. The time interval of non-uniform division for the model was chosen with regard to the nonlinearity of radiative heat transfer employed in the analysis.

5. Simulation of case study

The task was solved by means of computer program ANSYS 14.5 [3]. As for every analysis conducted by means of software of such a type, it included three basic parts:

• Creation of a model – defining elements and materials, drawing geometry of the model: The accumulator device consisted of two concentric concrete containers separated by the thermal insulation vacuum-like layer as described in section 3. The height of the outer tank was 812 [mm] and its diameter was 800 [mm]. The parameters assumed for the simulation were: concrete – λ=1.43 [W/(m·K)] and ρ=2300 [kg/m^3]; vacuum-like layer – λ=0.0004 [W/(m·K)] (apparent (equivalent) value) and ρ=0.2 [kg/m^3]

• Definition of initial and boundary conditions and then starting the calculation: The initial temperature of water was assumed as 90^{o}C. The temperature of air in the surroundings of accumulator device was assumed as constant and equal to 12°C. A value of surface film coefficient for convective heat transfer was assumed as h_c=2,5 [W/(m^2·K)]. The cooling process was simulated for a period of 30 days.

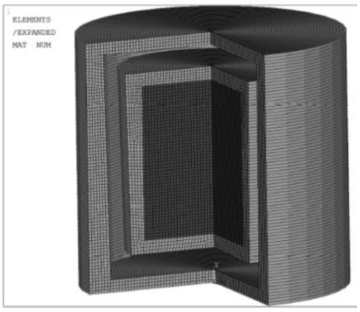

Fig. 3. A scheme of the model created in the ANSYS software environment.

• Analysis of results – graphical display of geometrical layout of required values.

6. Results

There were set three points in the model, which temperature was monitored at. The first one was situated in the middle of inner tank in the water, the second one was on the inner surface of the vacuum layer, and the third one was on the outer surface of external wall of the tank. The layout of these points is shown in Fig. 4.

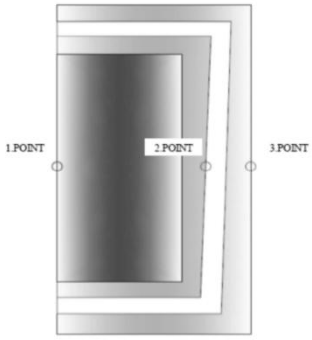

Fig. 4. A layout of the monitored points.

Figs. 5 and 6 show the change of the temperature during 30 days. Temperatures at the first and second monitored points were almost the same. The initial temperature was 90°C in both cases. After 30 days, water cooled down to 72.7°C and temperature at the second point was 72.4°C. So, there were only relatively small differences. In Fig. 8 the temperature change during 30 days at the third point is shown. The initial temperature at this point was 12°C, i.e. the same as the temperature of surrounding air T_e stated in the corresponding boundary condition. During the heating caused by the water in the tank of initial temperature 90°C, the temperature at the third point in the short time increased to 12.09°C and next it gradually decreased to 12.04°C.

The differences were minimal, so the heat transfer form inner tank towards the outside did not influence considerably the temperature of outer tank, what indicates that the proposed type of insulation is effective.

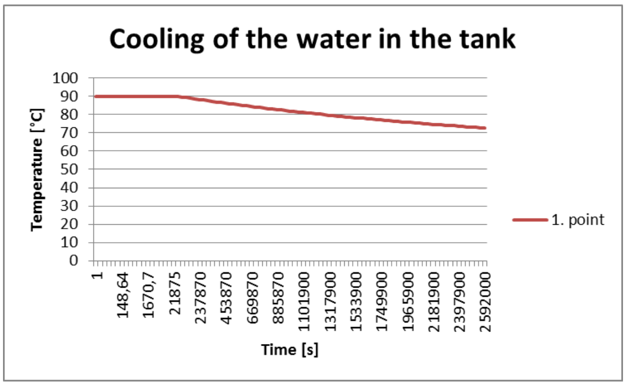

Fig. 5. Cooling of the water in the tank.

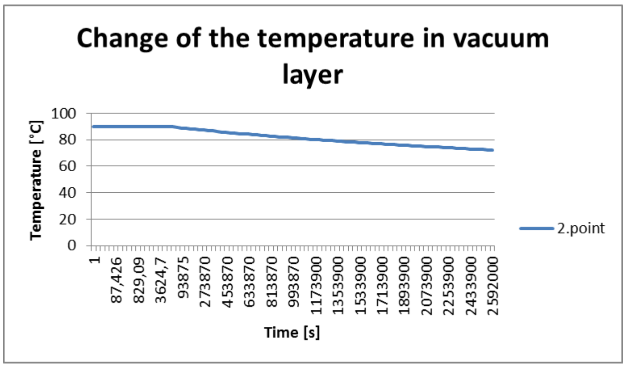

Fig. 6. Change of the temperature in the vacuum layer.

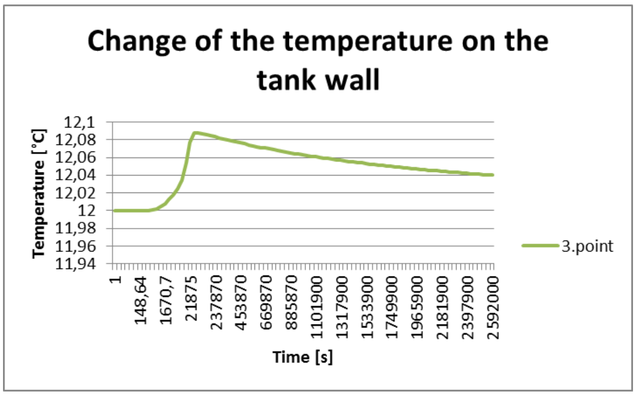

Fig. 7. Change of the temperature on the tank wall.

7. Conclusions

Using a 30-day simulation, the temperature decrease of the thermal energy storage was analyzed. The simulation showed that the temperature of water continuously decreased. The initial temperature was 90°C and after 30 days water cooled down to 72.7°C. This decrease of the temperature is not notable, but the further research is needed. Concluding on the basis of obtained results it can be stated that the right designed vacuum storage vessel is able to keep thermal energy in summer period for efficient using it for heating in winter.

Acknowledgements

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Denotations of symbols

c – specific heat, [J/(K·kg)],
t – time, [s],
A – receiving surface magnitude, [m^2],
F – viewing factor, [-],
T – temperature, [K],
ε – emissivity of the material surface, [-],
λ – heat conduction coefficient, [W/(K·m)],
ρ – mass density, [kg/m^3],
σ – Stefan-Boltzmann constant equal to 5.6704×10^{-8}, [W/(m^{2}K^4)].

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Summary

This paper is focused on an analysis of thermal energy performance of storage vessel [4]. This storage system consists of two concentric cylindrical containers made of concrete, between these two layers there is a thermal insulation layer – the vacuum-like one. The inner container is filled by water intended to operate as a heat accumulation medium and temperature of the water is assumed as 90^{o}C. The cooling process was simulated for a period of 30 days in the ANSYS software environment. The simulation showed that the analyzed type of heat storage vessel is able to keep the thermal energy relatively efficiently.