Title: Energy consumption determination of the heat storage device based on the phase change material depending on the temperature ranges

Author: Vladyslav Bondarenko, Abdessamad Faik, Yaroslav Grosu, Victor Stoudenets

Citation style: Bondarenko Vladyslav, Faik Abdessamad, Grosu Yaroslav, Stoudenets Victor. (2020). Energy consumption determination of the heat storage device based on the phase change material depending on the temperature ranges. "Rocznik Ochrony Środowiska" (Vol. 22 (2020), s. 144-155).

MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

Rocznik Ochrona Środowiska

Volume 22. Year 2020 ISSN 1506-218X 144-155

Energy Consumption Determination of the Heat Storage Device Based on the Phase Change Material Depending on the Temperature Ranges

Vladyslav Bondarenko[1], Abdessamad Faik[2,3],
*Yaroslav Grosu[2,4], Victor Stoudenets[1]**
[1]National Technical University of Ukraine
Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine
[2]Centre for Cooperative Research on Alternative Energies (CIC energiGUNE),
Basque Research and Technology Alliance (BRTA), Vitoria-Gasteiz, Spain
[3]Materials Science, Energy and Nano-engineering,
Mohammed VI Polytechnic University, Ben Guerir, Morocco
[4]University of Silesia, Katowice, Poland
**corresponding author's e-mail: v.stoudenets@kpi.ua*

1. Introduction

The work deals with the peculiarities of the thermal energy storage in the concentrating solar unit based on Stirling engine, which is an ecological engineering system that includes the elements of material engineering. Thermal energy storage is one of the key functions in the concentration solar systems operation (Liu et al. 2016, Zhang et al. 2016), in particular, solar dish Stirling units (Andraka et al. 2015).

The purpose of the work is to study the operation of the heat storage device (HSD) based on the phase change material (PCM), Mg-51%Zn eutectic metal alloy (Blanco-Rodríguez et al. 2014a,b), and to determine its basic energy characteristics.

The battery consists of two concentric steel cylinders with the bottom space filled with the alloy. The design of the heat storage device is determined by its purpose. It is used for the continuous operation of the solar dish Stirling UDS-1 (Stoudenets el al. 2019, Stoudenets & Dudarchuk 2019).

The previous work (Bondarenko 2018a) described the process of creating the heat storage from the alloy Mg-51%Zn with the next parameters:
PCM phase transition specific heat – 155 kJ/kg; PCM specific heat – 0,73 kJ/(kg K); PCM mass – 143 g; HSD net weight – 197 g.

In the course of the experimental studies, the heat storage device was heated to a predetermined temperature (higher than the melting temperature of the alloy) and cooled independently. The melting temperature is 337°C. During the cooling the heat storage device temperature was measured at four points. The work (Bondarenko 2018b) describes the conduct of experimental studies measuring the basic characteristics of the solar unit and the obtained experimental data are presented.

2. Investigation of the heat storage when cooled on the outdoor air

Using thermograms obtained by the heat storage cooled independently on the air, the thermogram of the heat recovery process averaged over the heat storage was obtained (Fig. 1). In this case, we consider that thermocouple sensors mounted on the heat storage surface on the insulation side indicate the temperature of the storage substance, considering that the steel wall of the heat storage shell has a thickness of 0.5 mm and a thermal conductivity of 26.1 W/m·K. The average temperature of the accumulating substance is defined as the arithmetic mean between the statements of the four temperature sensors.

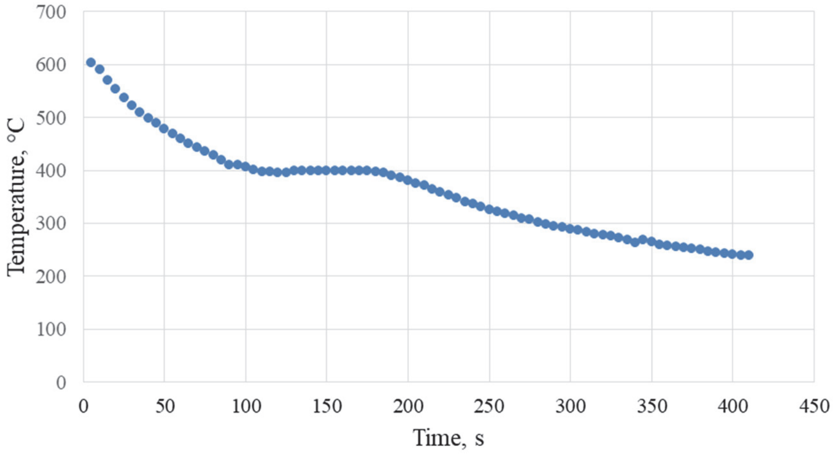


Fig. 1. Averaged thermogram of the heat transfer process by the heat storage when cooled on the outdoor air

Based on the experimental data, the heat flow from the heat storage to the environment was calculated, except for the heat of the phase change. This calculation is somewhat different from the approach used for phase transitions in liquid media, e.g. (Pavlenko & Koshlak 2019). In this case, only the explicit heat is taken into account in the value of the heat flux, since with the phase change the body temperature does not change. The heat flow diagram from the heat storage with the exception of the heat of the phase change is shown in Fig. 2.

Since the heat released by the heat storage into the environment is equal to the change in the internal energy of the heat storage, the heat flux, except for the heat of the phase change, is calculated by the formula (1):

$$Q = \frac{\left(m_1 c_1 + m_2 c_2\right)\left(t_2 - t_1\right)}{\tau}, \tag{1}$$

where:
m_1 – mass of the storage substance, kg; c_1 – specific heat capacity of the storage substance, kJ/(kgK); m_2 – mass of the heat storage shell, kg; c_2 – specific heat capacity of the heat storage shell, kJ/(kgK); Δt – temperature change of the storage substance, °C; τ – time period, sec.

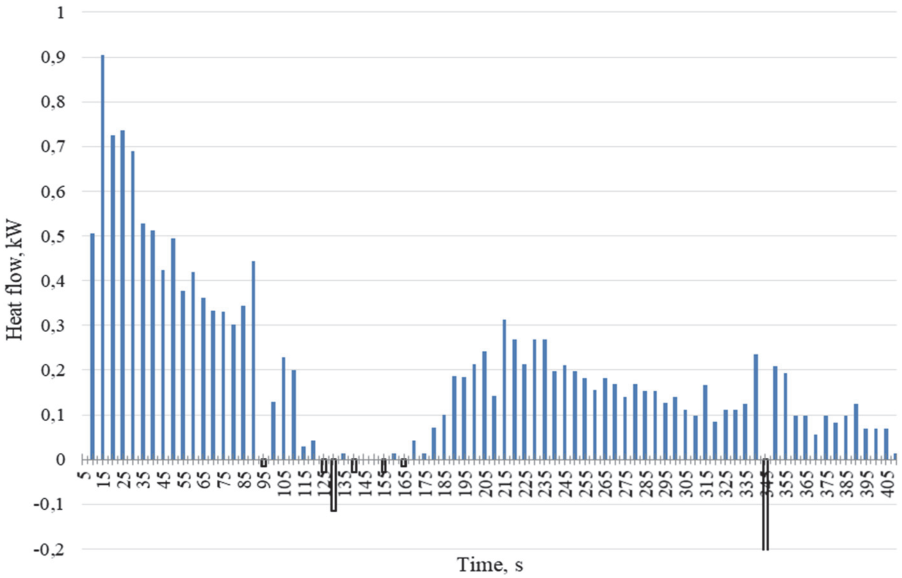


Fig. 2. Heat flow except heat of phase change from heat storage when cooling outdoors

The cooling process can be divided into three phases:

- cooling of the metal in the liquid phase,
- phase change,
- cooling of the metal in the solid phase.

Thus, Figure 2 describes the heat flow during the first and third phases. To determine the heat flux component of heat storage corresponding to the secreted heat release (phase 2), it is necessary to take into account the heat of the phase change of the substance and divide it evenly over the time during which the phase change occurs, since during this period the temperature of the heat storage does not change significantly and the amount of heat flux is permanent. But since the phase change process in the heat storage volume is uneven (the metal at the top of the heat storage reaches the phase change temperature earlier than the lower part), it is difficult to determine the time limits of the phase change. To correctly divide a thermogram into 3 zones, it is necessary to describe the temperature curves in each zone with a mathematical expression that reflects the nature of the temperature change. When the body is independently cooled, the temperature changes exponentially, and during the phase change the temperature is constant, so the schedule of the heat storage temperature changing will consist of two exponents and one horizontal section. The first interval is attributed to the period from 5 to 90 seconds, and to the third interval – from 185 to 410 seconds.

Since the process of the heat storage which cooled independently in the air is exponential, the schedule of temperature change should be described by the function (2).

$$t(\tau) = t_0 + ae^{-b\tau} \,. \tag{2}$$

As a result of the approximation of the experimental data in the first and third sections, a diagram of temperature change over time is presented in Fig. 3, and the corresponding heat flow diagram is shown in Fig. 4.

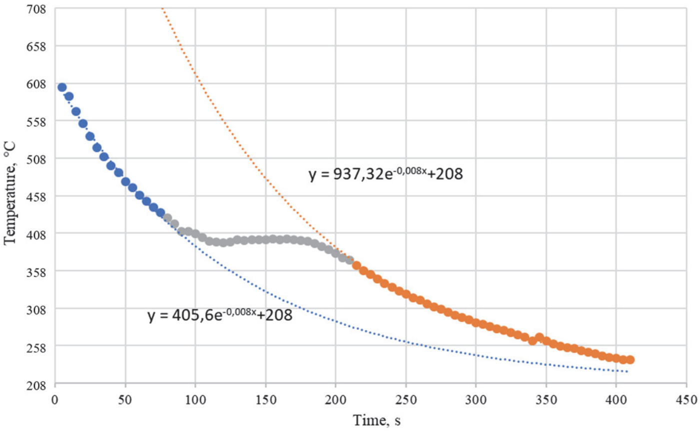


Fig. 3. Averaged thermogram of the heat transfer process by the heat storage after extrapolation of sections

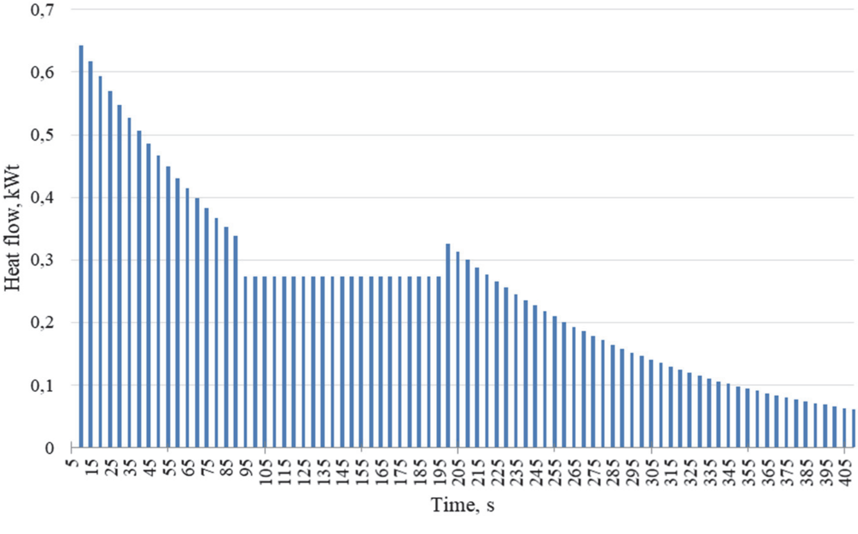


Fig. 4. The heat flow diagram is obtained from the result of mathematical analysis of experimental data

Thus, the amount of heat stored by the heat storage due to the heating of the liquid metal is 46.3 kJ, during the phase change is 22.2 kJ and during the cooling of the solid phase of the metal is 36.6 kJ. The amount of stored heat per unit mass of the HSD is 0.31 kJ/g.

3. Modeling the process of the heat storage cooling on the air using SolidWorks software

Numerical modeling is used to solve various problems of conversion and storage of thermal energy. Modeling of processes in heat exchangers and heat accumulators is often carried out using the universal ANSYS software package. Examples can be given of using ANSYS for internal and external problems in heat exchangers (Deshko et al. 2016, Orlowska et al. 2019) and for thermal storage (Xu et al. 2015, Gorobets et al. 2018). In our study, we used Solidworks software product as more adapted to the specific problem being solved.

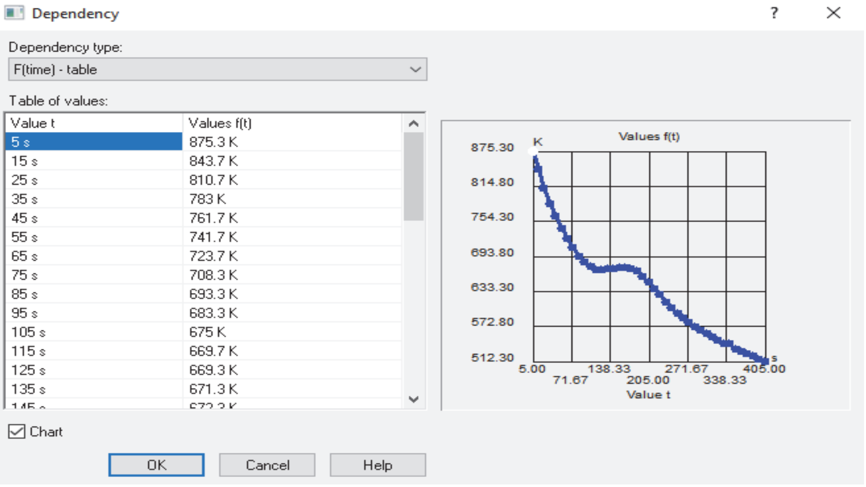
Using the data obtained from the experiment, a heat storage model was developed. The outer walls of the heat storage are adiabatic. The inner walls are the real walls that take part in both convective and radiation heat transfer. Heat storage wall material is AISI 304 stainless steel. Heat storage temperature depends on time and consistents with the results of the experiment.

Fig. 5 shows the dependence of the heat storage temperature on time.

The appearance of the model and calculation area is shown in Fig. 6.

The simulation resulted in the following data:

- heat fluxes (convective and radiation component),
- heat transfer coefficients from the heat storage,
- air temperature distribution heated by the heat storage.



Dependency type: F(time) - table

Value t	Values f(t)
5 s	875.3 K
15 s	843.7 K
25 s	810.7 K
35 s	783 K
45 s	761.7 K
55 s	741.7 K
65 s	723.7 K
75 s	708.3 K
85 s	693.3 K
95 s	683.3 K
105 s	675 K
115 s	669.7 K
125 s	669.3 K
135 s	671.3 K

Fig. 5. Dependence of the heat storage temperature on time (experimental data)

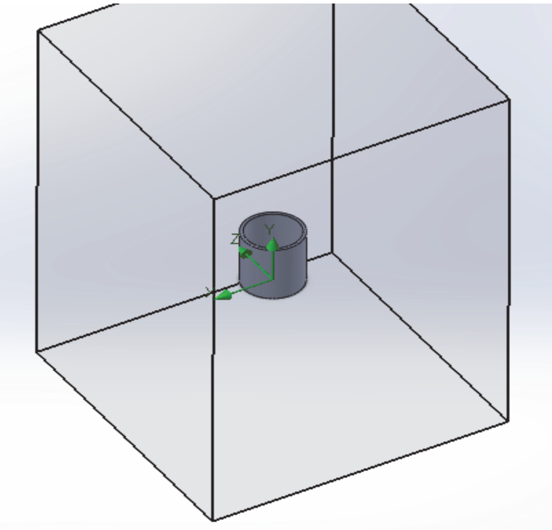


Fig. 6. Appearance of the model

The distribution of temperature fields at time 5, 135 and 405 seconds is shown in Fig. 7-9.

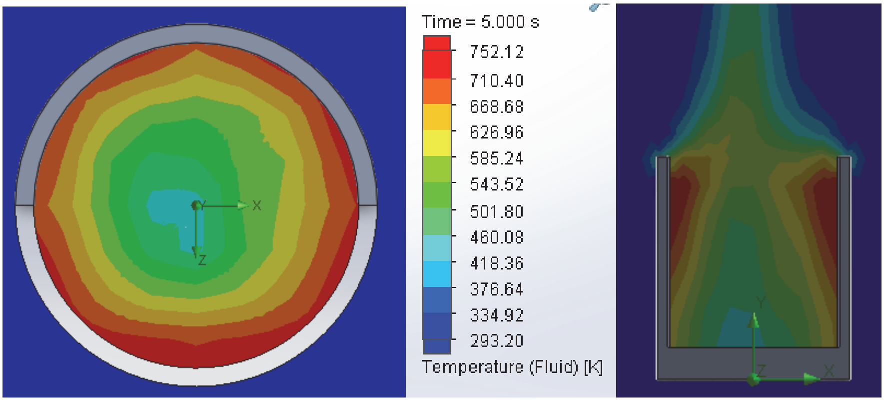


Fig. 7. The distribution of air temperature fields at a time of 5 seconds

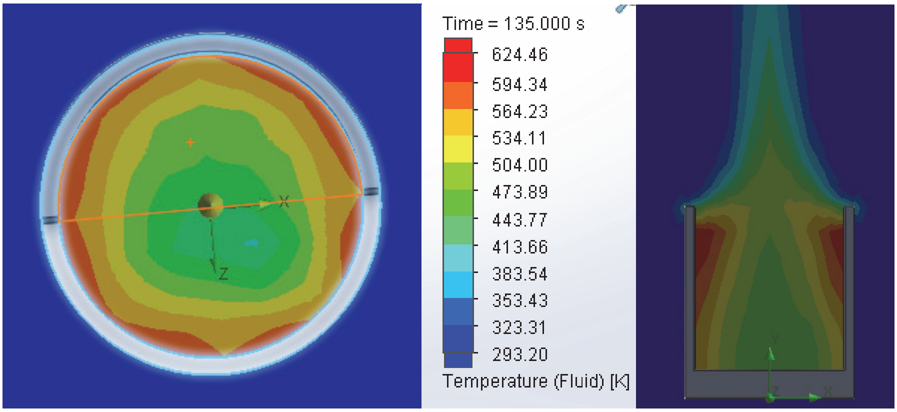


Fig. 8. The distribution of air temperature at a time of 135 seconds

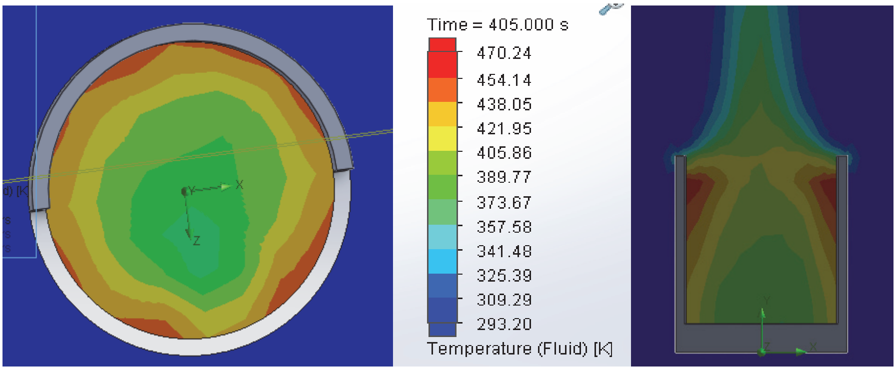


Fig. 9. The distribution of air temperature fields at a time of 405 seconds

Fig. 10-12 show diagrams of heat loss of the heat storage over time.

The simulated heat flux values shown in Fig. 12 are correlated with the values obtained after processing the experimental data and are presented in Fig. 2.

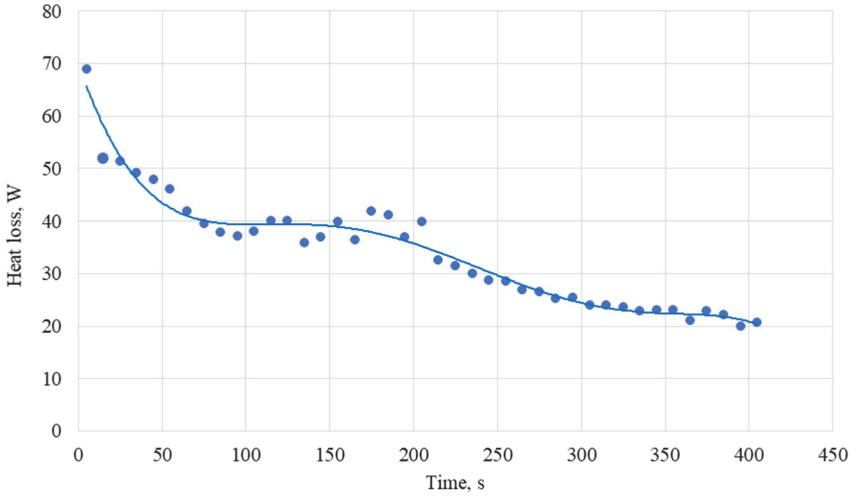


Fig. 10. Dependence of convective heat loss of the heat storage on time

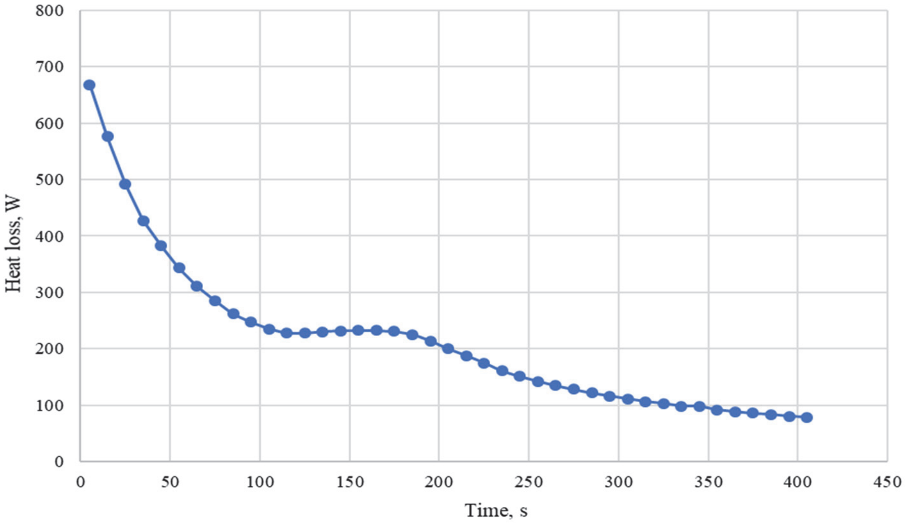


Fig. 11. Dependence of radiation heat loss of the heat storage on time

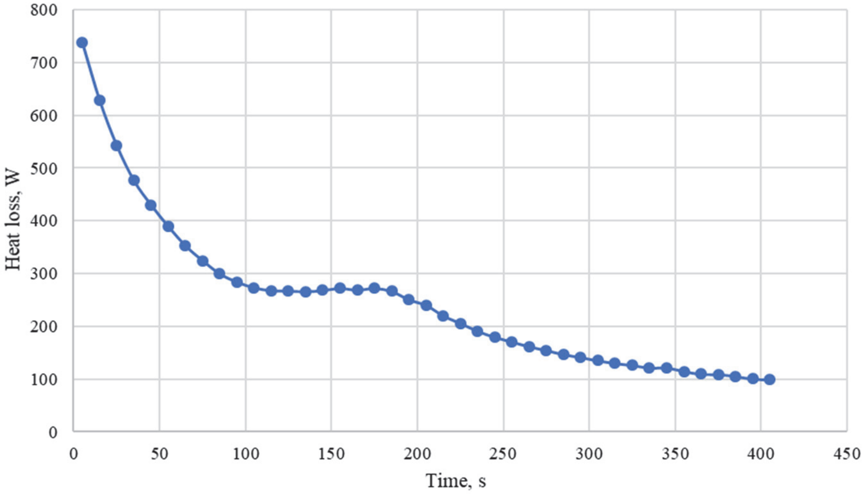


Fig. 12. Dependence of total heat loss of the heat storage on time

On the basis of the obtained results, the heat capacity of the heat storage in different temperature ranges of its use was calculated (Fig. 13). The phase change is included in each range. The difference between the initial and final temperatures of each range is 200°C.

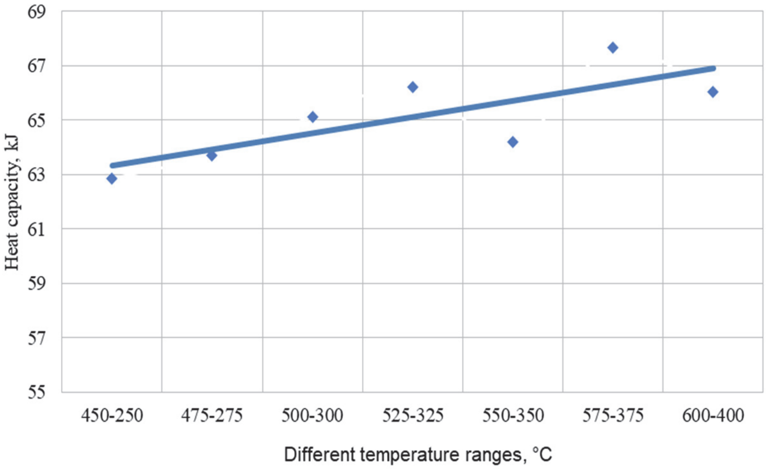


Fig. 13. Dependence of heat storage heat capacity on temperature ranges

4. Conclusions

As a result of the studies, the following HSD basic energy characteristics were obtained.

1. The total amount of heat given off by the HSD according to the simulation results is 102.2 kJ. When approximating the experimental data, the corresponding value is 105.1 kJ. Thus, the difference between the calculation results and the simulation is less than 3%.
2. The amount of heat stored by the heat storage due to the heating of the liquid metal is 46.3 kJ, during the phase change – 22.2 kJ and during the cooling of the solid phase of the metal – 36.6 kJ.
3. The amount of stored heat per unit mass of the HSD is 0.31 kJ/g.
4. The dependence of heat capacity on the interval of operating temperatures of the heat storage is determined. At higher initial and final temperatures (at regular working intervals) the heat capacity is higher.

References

Andraka, C.E., Kruizenga, A.M., Hernandez-Sanchez, B.A., & Coker, E.N. (2015). Metallic phase change material thermal storage for dish Stirling. International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014, No.SAND2014-15888C. *Energy Procedia, 69,* 726-736.

Blanco-Rodríguez, P., Rodríguez-Aseguinolaza, J., Risueño, E., Faik, A., Tello, M., Doppiu, S. (2014). Corrigendum to “Thermophysical characterization of Mg-51%Zn eutectic metal alloy: A phase change material for thermal energy storage in direct steam generation applications”. *Energy*, *75*, 630.

Blanco-Rodríguez, P., Rodríguez-Aseguinolaza, J., Risueño, E., Tello, M., (2014). Thermophysical characterization of Mg-51%Zn eutectic metal alloy: A phase change material for thermal energy storage in direct steam generation applications. *Energy*, *72*, 414-420.

Bondarenko, V.V. (2018). Doslidzhennia teplovoho akumuliatora dlia soniachnoi enerhoustanovky na bazi dvyhuna Stirlinha (Research of thermal accumulator for solar power unit based on Stirling engine). *Proceedings of the scientific and technical conference “Enerhetyka. Ekolohiia. Liudyna (Energy. Ecology. Human) 2018*”. Institute of Energy Saving and Energy Management of NTUU "KPI". 165.

Bondarenko, V.V. (2018). Vyhotovlennia teplovoho akumuliatora dlia soniachnoi enerhoustanovky na bazi dvyhuna Stirlinha (Manufacturing of thermal battery for solar power unit based on Stirling engine). *Proceedings of the 16th International Scientific and Practical Conference of Postgraduate, Undergraduate, and Students “Suchasni problemy naukovoho zabezpechennia enerhetyky (Modern Problems of Scientific Energy Supply)” April 24-27, 2018. Kyiv*. 233.

Deshko, V.I., Karvatskii, A.Y., & Sukhodub, I.O. (2016). Heat and mass transfer in crossflow air-to-air membrane heat exchanger in heating mode. *Applied Thermal Engineering*, *100*, 133-145.

Gorobets, V., Antypov, I., Trokhaniak, V., Bohdan, Y. (2018). Experimental and numerical studies of heat and mass transfer in low-temperature heat accumulator with phase transformations of accumulating material. *MATEC Web of Conferences, 240*, 01009.

Liu, M., Tay, N.S., Bell, S., Belusko, M., Jacob, R., Will, G., ... & Bruno, F. (2016). Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies. *Renewable and Sustainable Energy Reviews*, 53, 1411-1432.

Orlowska, M., Szkarowski, A., Mamedov, Sh. (2019). Numerical Analysis of the Influence of the Angle of Inclination of the Screen on the Intensity of Heat Exchange from a Flat Heat Exchanger in a Partially Limited Space. *Rocznik Ochrona Środowiska, 21*(1), 728-737.

Pavlenko, A., Koshlak, H. (2019). Heat and Mass Transfer During Phase Transitions in Liquid Mixtures. *Rocznik Ochrona Środowiska, 21*(1), 234-249.

Stoudenets, V.P., Dudarchuk, D.V. (2019). The 1 kW Stirling Engine for Solar Power System with Parabolic Concentrator and Electric Generator. *Journal of New Technologies in Environmental Science.* 153-165.

Stoudenets, V.P., Tsyrin, N.N., Ievtushenko, O.V. (2019). *Solar Power Systems Based on Stirling Cycle Machines and Thermomolecular Technology.* Management of Technological Processes in Energy Technologies / General editorship of A.M. Pavlenko // Politechnica Świetokrzyska Kielce University of Technology. 146-182.

Xu, B., Li, P., & Chan, C. (2015). Application of phase change materials for thermal energy storage in concentrated solar thermal power plants: a review to recent developments. *Applied Energy*, *160*, 286-307.

Zhang, H., Baeyens, J., Caceres, G., Degreve, J., & Lv, Y. (2016). Thermal energy storage: Recent developments and practical aspects. *Progress in Energy and Combustion Science*, *53*, 1-40.

Abstract

The work concerns determining the energy performance of the heat storage device based on the phase change material for the solar dish Stirling unit. Experimental studies were performed with the heat storage material, made of the eutectic metal alloy Mg-51%Zn. The energy characteristics are determined by mathematical analysis of the experimental data and simulation of the process of cooling the heat storage.

Keywords:
heat storage, phase change material, solar dish Stirling