HEAT TRANSFER AND MECHANICAL CHARACTERISTICS OF THE ABSORBER IN SOLAR PHOTO-THERMAL POWER GENERATION SYSTEM

by

Zhijun XIAO *

School of Electrical and Electronic Information Engineering,
Hubei Polytechnic University, Wuhan, China

Original scientific paper
https://doi.org/10.2298/TSCI2302023X

In order to solve the problems of thermal fatigue, high temperature gasification and low temperature solidification of the heat receiver, a numerical calculation model for the heat transfer function of the tower type solar thermal power generation high temperature receiver is proposed. A perfect analysis method is used for the simulation, and a thermal simulation program for predicting the heat gain of the solar thermal energy tower is compiled. In this paper, considering the various field connection characteristics, numerical value and distribution of convective heat transfer coefficient of the heat absorption medium, the temperature of the outer wall of the heat pipe absorption, and the thermal image conversion work in a non-uniform heat flow boundary area of a model of heat receiver was studied. The experiments show that when the flow rate of molten salt in the tube increases from 1 m/s to 2 m/s, the heat collection efficiency of the heat collection increases rapidly, while the flow time is more 3 m/s, the heat collection efficiency increases more gradually. The efficiency of heat absorption of the heat receiver is in the middle of the heat receiver, which can achieve 88 of the thermal image conversion. In the same large enough value, the heat collected at the inlet and outlet of the heat sink is about 82. It is clear that the numerical simulation provides a reliable basis for the design engineering, and provide guidance for the design of a full control model of tower solar photovoltaic power generation.

Key words: *solar photovoltaic power generation, tower heat absorber, analog calculation*

Introduction

Solar photovoltaic power generation is also known as concentrated solar power (CSP), which reflects/refracts and collects solar rays by using parabolic or hyperbolic focusing, the working medium with high temperature and pressure is provided by the heat exchanger, and then the power is generated in a conventional way. Solar photovoltaic power generation technology is a clean and efficient way of power generation. Compared with traditional fossil fuel power stations, the use of solar energy to produce steam has replaced the traditional way of burning fuel in power stations to avoid secondary pollution [1]. At the same time, compared with the silicon crystal materials which are expensive in the solar photovoltaic power generation technology and produce a lot of pollution in the manufacturing process, the solar photovoltaic power generation technology only needs relatively simple equipment to achieve power gener-

* Author's e-mail: xzj202212@163.com

ation, which greatly reduces the power generation cost. In addition, solar photovoltaic power generation also has the incomparable advantage of solar photovoltaic power generation, that is, the capacity obtained for solar thermal conversion can be stored in a cheap and simple way. In this way, continuous power generation can be realized even at night or in the case of insufficient sunlight such as climate fusion, which can better reverse the disadvantage that solar energy is not stable and sustainable enough, making large-scale utilization of solar energy possible [2]. A typical CSP power station consists of five subsystems, namely, the concentrating and heat collecting subsystem, the heat storage subsystem, the auxiliary energy subsystem, the monitoring subsystem, and the thermal power generation system, the main components include the mirror field (lens), the heat absorber, the heat transfer medium, the heat exchanger, the heat storage equipment, the control equipment, and the generator, fig. 1 [3].

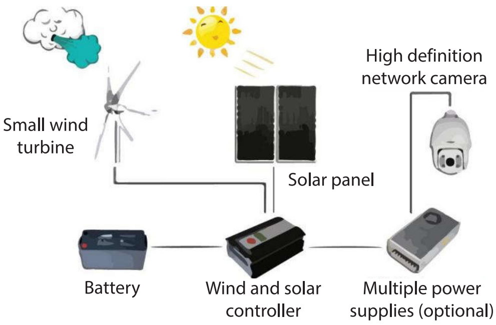

Figure 1. Structure diagram of solar photovoltaic power generation system

Literature review

At the beginning of the research on the heat receiver, domestic and foreign researchers mainly focus on the investigation of the heat transfer process of the heat receiver and analyze its performance thermal work. Analyzing the heat transfer process of heat sinks can help researchers design heat sinks with better efficiency and more heat, thus improving performance. of all solar photovoltaic power generation [4]. With the support of CSP technology, the collection of heat in solar photovoltaic power generation can increase the ratio to more than 3000, or even higher. There are many types of heat absorption, and their installation characteristics, performance characteristics and applications are different [5].

The heat transfer process in the heat receiver is the heat transfer process, which involves the connection between heat, flow field and stress area. The solution the problems of heating of the receiver, high temperature vaporization of molten salt and low temperature solidification is based on understanding the law of heat transfer of the receiver. It is necessary to understand the convection heat transfer coefficient of the heat absorption medium in the heat receiver, the temperature of the outer wall of the heat receiver, the distribution law of convection heat change coefficient and other related details. The tower type heat receiver is a new technology, and there are few reports published abroad. At the same time, the domestic market policy is not mature, the related research is not deep, there is no demonstration of the molten salt put into operation, and there is not much knowledge to learn. In view of this, it is important to study the heat transfer characteristics of the heat receiver in the non-uniformity of the heat flow boundary [6]. In this paper, the theoretical model is developed to calculate the convection heat transfer coefficient, external temperature distribution and photo-thermal conversion function of molten salt receiving heat. The findings will support the engineering design of the building's electrical equipment and improve the overall control strategy of the tower solar thermal power plant.

Research methods

Structural form and calculation model

The solar thermal power tower usually uses molten salt as the heat carrier, and the heat receiver is a polygon with many patterns. In order to balance the heat gain of each branch, the structure is often combined in rows and parallel. In the northern hemisphere, the energy available to the Sun is large, and the molten salt in the receiver heats up from the north to the south [7]. In a typical model of tower solar photovoltaic power generation heat receiver, a model of heat receiver is made of several diameter small thin-walled stainless steel pipes in parallel, and the diameter of the heat absorption pipe in a model of the heat receiver is ⌀ 21 mm × 1.2 mm, and the effectiveness of the heat absorption height of the heat pipe is 5 m [8].

The tower type solar heat receiver involves complex multi physical field coupling processes such as flow, radiation, convection, conduction, stress and strain. The numerical simulation of multi physical field coupling is a complex subject, which involves the direct and indirect coupling mode of various physical equations, the discrete method of equations, the solution strategy and algorithm of discrete equations, and various schemes to ensure the convergence of the algorithm to stability [9]. In the process of building the model, the flow and heat transfer control equations and thermal stress control equations are mainly used, the thermal stress control equation applies the Hooke's law of thermodynamics, displacement equation and compatibility equation in thermoelasticity, the main modelling formulas are:

– The continuity equation:

$$\frac{\partial \rho}{\partial t}+\operatorname{div}(p u)=0 \tag{1}$$

– The N-S equation is as follows eqs. (2)-(4):

$$\frac{\partial(\rho u)}{\partial t}+\operatorname{div}(\rho u u)=\operatorname{div}(\mu \operatorname{grad} u)-\frac{\partial \rho}{\partial x}+S_{\mathrm{u}} \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+\operatorname{div}(\rho v u)=\operatorname{div}(\mu \operatorname{grad} v)-\frac{\partial \rho}{\partial y}+S_{\mathrm{v}} \tag{3}$$

$$\frac{\partial(\rho w)}{\partial t}+\operatorname{div}(\rho w u)=\operatorname{div}(\mu \operatorname{grad} w)-\frac{\partial \rho}{\partial z}+S_{\mathrm{w}} \tag{4}$$

– The relationship between h defined by Newton's cooling theorem on the solid wall and the temperature field in the fluid:

$$h\left(t_w-t_i\right)=-\lambda\left(\frac{\partial t}{\partial y}\right)_{y=0} \tag{5}$$

The definitions and units of the aforementioned symbols adopt international standards [10].

Boundary conditions

In a domestic demonstration project, the range of spot heat flux from the solar mirror field to the single module of the heat receiver is 301-649 kW/m^2. The distribution of light spot in the vertical direction is approximately parabola, and the inlet temperature of binary molten salt ($NaNO_3$: KNO_3 = 60% : 40%) in the module is 315 °C. The viscosity of molten salt at 300 °C is approximately twice that of water at 0 °C. The viscosity of molten salt above 400 °C is similar to that of water at 0-20 °C [11]. The viscosity curve of molten salt is shown in fig. 2. The distribution of molten salt on each branch pipe in a heat exchanger is determined based on the test results, as shown in fig. 3. The air temperature is 10 °C, the wind speed is 15 m/s, and the emissivity of the outer surface of the heat absorber layer is 8 [12].

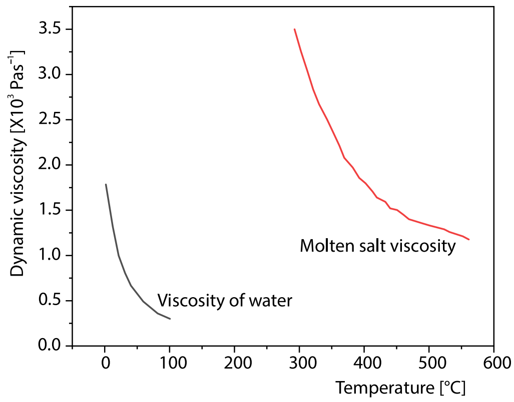

Figure 2. Viscosity comparison between molten salt and water

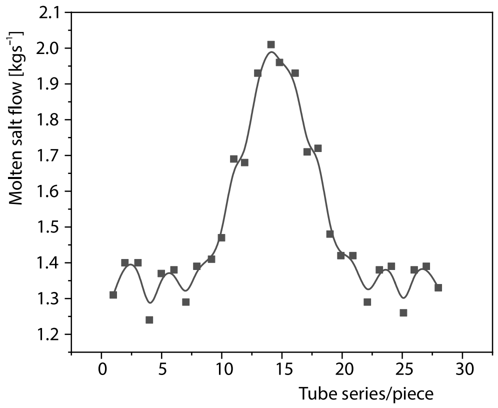

Figure 3. Molten salt flow rate distribution

Thermal strain of heat receiver

When the solar collector is actually working, the collector tube receives the highly concentrated solar energy reflected by the condenser mirror and is expanded by heat, as time goes on, it will gradually recover to the thermal equilibrium state, and then it will shrink due to the influence of the low temperature at night [13]. This cycle of expansion and contraction will cause thermal fatigue damage to the heat absorption tube. However, such thermal fatigue damage must be limited to a maximum allowable range within the service life of 30 years. Therefore, the heat pipe fatigue damage caused by the thermal strain borne by the heat pipe is an important factor affecting the reliability and service life of the pipe [14]. For the heat absorbing tube wall material, its circumferential thermal strain can be expressed:

$$\varepsilon = \alpha \left\{ \left[\frac{T_{\rm oc} - T_{\rm ic}}{2(1-\nu)} \right] + \left(\frac{T_{\rm oc} + T_{\rm ic}}{2} - T_{\rm ave} \right) \right\} \tag{6}$$

where $T_{\rm oc}$ and $T_{\rm ic}$ are the outer and inner wall temperatures of the heat absorbing tube, respectively, and $T_{\rm ave}$ is the average circumferential temperature of the heat absorbing tube wall, and the calculation formula:

$$T_{\rm ave} = T_{\rm m} + \frac{\left[\left(\frac{T_{\rm oc} + T_{\rm ic}}{2} \right) - T_{\rm m} \right]}{\pi} \tag{7}$$

The purpose of the author's research on the material stress of the solar heat receiver is to determine whether the bearing capacity of the heat receiver structure meets the safety requirements. The definition of bearing capacity is completed by uniaxial failure test of universal compressor. The stress obtained from ANSYS calculation is compared with the results obtained from uniaxial failure test [15]. However, in the research of 3-D solid structure, the stress distribution is more complex than 2-D, and cannot accurately represent the stress value here by using the stress in a single direction only [16].

Result analysis

Optimization of flow rate of molten salt in pipe

The relationship between the flow rate of molten salt in the pipe and the heat collected is shown in fig. 4. The flow rate of molten salt directly affects the Reynolds number and is related to heat transfer effect. From the calculation results, when the flow rate of molten salt in the tube increases from 1 m/s to 2 m/s, the heat collection function of the heat absorption tube increases faster, when it is more than 3 m/s, the heat collected has increased more slowly [17]. At the same time, assume that the flow rate increases, the system resistance increases, and the system's circulating energy increases. Considering the important factors of business operation and temperature change, it is said that the flow rate of molten salt in the heating tube should be controlled at 2-3 m/s [18].

It can be seen from fig. 5 that the heat capacity of the outlet of the heat sink decreases with the increase of the flow rate of the molten salt inlet of the heat sink. It can be seen that the average thermal strain at the exit of the endothermic tube can be reduced by choosing a larger molten salt inlet velocity [19].

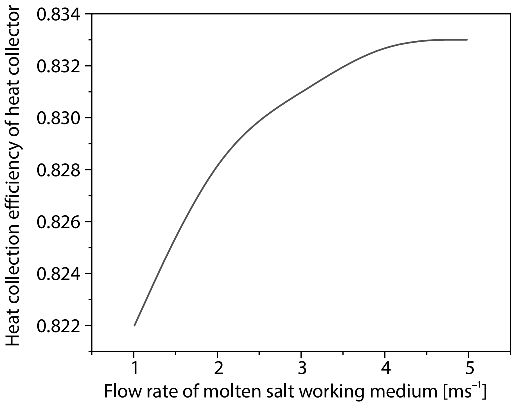

Figure 4. Relation between molten salt flow rate and heat collection efficiency well F_1 (recharge well)

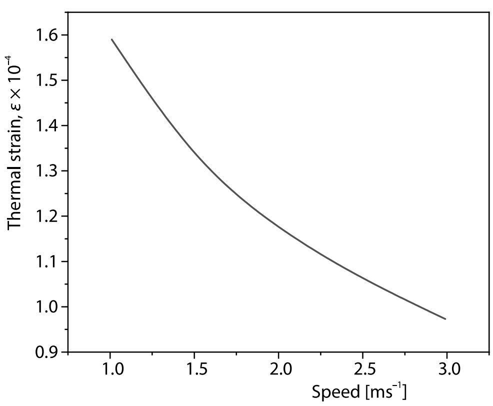

Figure 5. Relation between thermal strain of outlet section and inlet velocity of molten salt

Temperature distribution on the outer wall of the heat receiver

The solar energy is converted and arranged on the outside of the heat receiver by the mirror field, and the outside of the heat receiver is coated with a layer with high absorption convert the solar energy into hot energy. The temperature on the outside of the heat pipe directly affects the selection of pipe materials and the safety of the heat transfer medium in the pipe. The difference between the temperature of the outer wall of the heat sink and the temperature of the molten salt is shown in fig. 6 [20]. Because of the characteristics of light, the energy flow speed

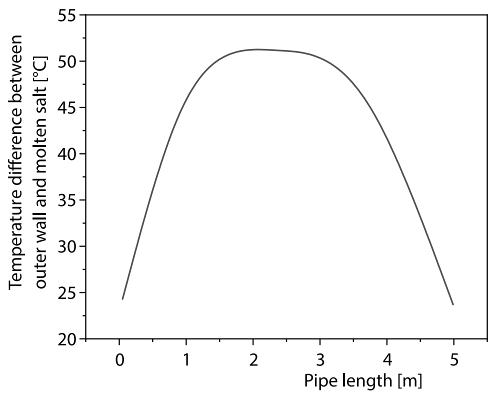

Figure 6. Temperature difference between the external wall surface of the heat absorber and the molten salt

distribution, the light heat flow speed in the middle of the heat sink is large, and when the difference of convection heat transfer coefficients in the tube is small, the heat transfer difference should increase. From the test results, because of the characteristics of the light distribution, the temperature of the outer wall of the heat pipe absorption characteristics of the first rise and then fall. The outer wall of the tube has a maximum temperature of approximately 3.5 m in the vertical direction [21]. After that, although the temperature of the medium carrier has increased, the temperature of the outer wall of the tube has decreased, that is, the temperature change temperature is different from the side outside the wall of the tube and the heating medium is reduced. The inlet molten salt temperature of the first tube of a sample is 315 °C, and the maximum temperature of the outside of the tube is about 355 °C [22].

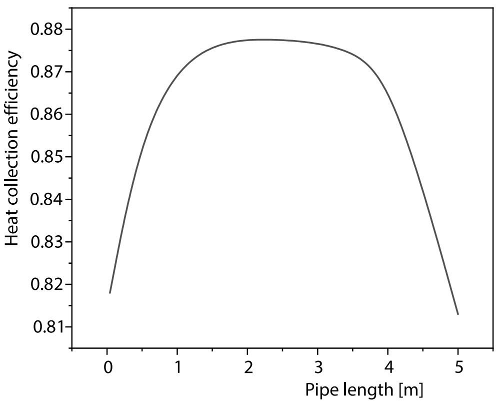

Figure 7. Distribution of collector efficiency

Distribution of collector efficiency

The heat collection efficiency of the heat is an important parameter of the heat exchanger, which has a positive impact on the overall performance of the solar thermal power plant. The heat collection efficiency of the heat collection is directly affected by the outer wall temperature of the heat collector, which has important guidelines for the design of solar panels and design of the efficiency of heat absorption of the heat exchanger. Figure 7 shows the distribution of the heat produced by a tube and a model of the heat receiver. It can be seen from fig. 7 that the heat absorption efficiency of the heat receiver is in the middle of the heat receiver, which can achieve 88 of photo-thermal conversion. In the same large enough value, the heat collected at the inlet and outlet of the heat sink is about 82. In view of this, it is said that when the mirror field and the heat receiver is built together, the lighting should be in the center of the heat receiver as far as possible in the event that the equipment is safe [23].

Calculation of heat transfer coefficient of heat absorption tube

The convection heat transfer coefficient in the tube of molten salt heat receiver is related to the physical strength of molten salt, the flow rate, the heat flow speed, the emission coefficient of the outer wall of the tube and so on thing. At the same time, the heat receiver is heated on the half wall, which has some influence on the distribution of all the flow areas in the tube. The total convection heat transfer coefficient of one heat receiving module is about 6 kW/m^2/°C in the area such that the velocity of molten salt in the tube is 2-3 m/s and the average wind speed is 15 m/s [24].

Comparative analysis

Solar two is a tower type solar thermal power station that has been put into operation before. The station uses molten salt as a heat carrier. The diameter of the heat sink is 5.1 m, the height of the heat sink is 6.2 m, and the number of heat sinks is 768 ⌀ 21 mm × 1.2 mm S304L stainless steel is made of Black Pyromark Pain coating technology. The heat absorption area of the heat receiver is 99.3 m^2, and the heat gain of the heat receiver is 42699 kW.

According to the previous tests, the total heat transfer coefficient is 6 kW/m²/°C, the total heat transfer temperature is 55 °C, and the thermal conversion figure of the air receiver temperature is 0.82. The heat absorption area of the heat receiver is 106 m², which is similar to the results published by Sun Two [25].

Conclusions

- In this paper, the theoretical calculation model of tower type molten salt heat receiver is developed by using the perfect analysis method, considering the thermal field, flow field, stress field, and other things.
- In the distribution of the solar energy flow speed prepared by the solar mirror field in China, through experimental calculation, it was obtained that the control flow rate of molten salt in in molten salt heat receiver is 2-3 m/s, convection heat transfer coefficient of molten salt in the heat receiver is 6 kJ/m²/°C, and the average heat transfer temperature difference is 50-60 °C .
- By comparing the calculation results with the existing data, the research results are reliable. The research results provide a reliable basis for the engineering design of the tower type molten salt heat receiver and use for the design of the overall control structure of the tower type solar thermal energy generation.

References

[1] Yuan, L., *et al*., Performance Evaluation of a Co-Production System of Solar Photovoltaic Power Generation and Seawater Desalination, *Renewable Energy*, *169* (2021), 6, pp. 1121-1133
[2] Alirahmi, S. M., *et al*., Development and Multi-Criteria Optimization of a Solar Thermal Power Plant Integrated with PEM Electrolyzer and Thermoelectric Generator, *International Journal of Hydrogen Energy*, *47* (2022), 57, pp. 23919-23934
[3] Mudi, J., *et al.*, Frequency Stabilization of Solar Thermal-Photovoltaic Hybrid Renewable Power Generation Using Energy Storage Devices, *Iranian Journal of Science and Technology*, *Transactions of Electrical Engineering*, *45* (2021), 2, pp. 597-617
[4] Arabkoohsar, A., *et al*., Thermodynamics, Economic and Environmental Analyses of a Hybrid Waste-Solar Thermal Power Plant, *Journal of Thermal Analysis and Calorimetry*, *144* (2021), 3, pp. 917-940
[5] Babu, N. R., *et al*., Load Frequency Control of a Multi-Area System Incorporating Realistic High-Voltage Direct Current and Dish-Stirling Solar Thermal System Models under Deregulated Scenario, *IET Renewable Power Generation*, *15* (2021), 5, pp. 1116-1132
[6] Jamshed, W., *et al*., Solar Energy Optimization in Solar-HVAC Using Sutterby Hybrid Nanofluid with Smoluchowski Temperature Conditions: A Solar Thermal Application, *Scientific Reports*, *12* (2022), 1, pp. 1-19
[7] El Haj Assad, M., *et al*., Renewable Hybrid Energy Systems Using Geothermal Energy: Hybrid Solar Thermal-Geothermal Power Plant, *International Journal of Low-Carbon Technologies*, *16* (2021), 2, pp. 518-530
[8] Hu, S., *et al*., Optimal Solar Thermal Retrofit for Geothermal Power Systems Considering the Lifetime Brine Degradation, *Renewable Energy*, *186* (2022), 4, pp. 628-645
[9] Panchal, H., *et al.*, Mini-Review of Different Co-Generation Systems: Solar Thermal Perspective, *International Journal of Ambient Energy*, *43* (2022), 1, pp. 1-3
[10] Kumar, N., *et al*., Progress and Application of Phase Change Material in Solar Thermal Energy: An Overview, *Materials Today: Proceedings*, *44* (2021), 87, pp. 271-281
[11] Senthil, R., *et al*., A Holistic Review on the Integration of Heat Pipes in Solar Thermal and Photovoltaic Systems, *Solar Energy*, *227* (2021), 3, pp. 577-605
[12] Wang, Z., *et a*l., The Cu_3BiS_3/MXenes with Excellent Solar-Thermal Conversion for Continuous and Efficient Seawater Desalination, *ACS Applied Materials and Interfaces*, *13* (2021), 14, pp. 16246-16258
[13] Chen, K., *et al*., Study on Enhanced Heat Transfer Characteristics of Metal Foam Solar Receiver in Solar Power Tower Plants, *Energy Reports*, *27* (2021), 1, pp. 1504-1512
[14] Shatnawi, H., *et al*., Experimental Study of Heat Transfer Enhancement in Solar Tower Receiver Using Internal Fins, *CMC-Computers Materialis and Continua*, *68* (2021), 2, pp. 1693-1711

[15] Mahboob, K., *et al*., Design and Modelling of Tubular Receiver of a Solar Tower Power Plant, *Pakistan Journal of Engineering and Technology*, *4* (2021), 1, pp. 201-206
[16] Wang, W. Q., *et al*., Optical-Thermal-Mechanical Analysis of High-Temperature Receiver Integrated with Gradually Sparse Biomimetic Heliostat Field Lay-Outs for the Next-Generation Solar Power Tower, *Solar Energy*, *232* (2022), 94, pp. 35-51
[17] Chen, Y., *et al*., Effects of Design Parameters on Fatigue-Creep Damage of Tubular Supercritical Carbon Dioxide Power Tower Receivers, *Renewable Energy*, *176* (2021), 38, pp. 520-532
[18] Wang, W. Q., *et al*., A Multi-Scale Solar Receiver with Peak Receiver Efficiency Over 90% at 720 °C for the Next-Generation Solar Power Tower, *Renewable Energy*, *200* (2022), 59, pp. 714-723
[19] Chen, J., *et al*., Experiment and Dynamic Simulation of a Solar Tower Collector System for Power Generation, *Renewable Energy*, *196* (2022), 21, pp. 946-958
[20] Atalay, T., *et al.*, Experimental and Thermal Analysis of Solar Thermoelectric System Performance Incorporated with Solar Tracker, *International Journal of Precision Engineering and Manufacturing-Green Technology*, *9* (2022), 2, pp. 587-602
[21] Mahmoudinezhad, S., *et al*., Response of Thermoelectric Generators to Bi_2Te_3 and Zn_4Sb_3 Energy Harvester Materials under Variant Solar Radiation, *Renewable Energy*, *146* (2020), 35, pp. 2488-2498
[22] Kumar, P. M., *et al*., Experimental Analysis of a Heat Sink for Electronic Chipset Cooling Using a Nano-improved PCM (NIPCM), *Materials Today: Proceedings*, *56* (2022), 22, pp. 1527-1531
[23] Zhu, K., *et al.*, System Efficiency and Power: The Bridge between the Device and System of a Thermoelectric Power Generator, *Energy and Environmental Scienc*e, *13* (2020), 10, pp. 3514-3526
[24] Abdollahpour, A., et al., Exergoeconomic Analysis and Optimization of a Transcritical CO_2 Power Cycle Driven by Solar Energy Based on Nanofluid with Liquefied Natural Gas as Its Heat Sink, *Journal of Thermal Analysis and Calorimetry*, *139* (2020), 1, pp. 451-473
[25] Maduabuchi, C. C., *et al*., Numerical Study of a Phase Change Material Integrated Solar Thermoelectric Generator, *Journal of Electronic Materials*, *49* (2020), 10, pp. 5917-5936

Paper submitted: June 23, 2022
Paper revised: August 22, 2022
Paper accepted: August 30, 2022