ANALYSIS OF THERMAL STORAGE PERFORMANCES OF SOLAR THERMAL POWER GENERATION UNIT USING COMPUTER NUMERICAL SIMULATION ANALYSIS

by

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Objective: In this study, the single tank inclined layer heat storage system is simulated and analyzed by computer, so as to explore the performance of the heat storage device of the solar thermal generator system. Method: First of all, for the phase change thermal storage unit, its physical model of is established. Heat transfer fluid is Hitec salt, and phase change material is potassium nitrate. Then, as for the phase change thermal storage unit, its numerical model of is established. The simulation results of the numerical model are verified. Finally, through numerical simulation, how do the inlet velocity of the heat exchange fluid and the ambient temperature influence the heat storage performance is analyzed. Results: The heat storage period of the regenerator will decrease when the inlet velocity of the heat exchange fluid increases, but the heat storage efficiency of the regenerator will decrease. Therefore, *in this study, under the premise of ensuring a higher heat storage efficiency and a shorter heat storage cycle, it is more reasonable to choose 0.25 m/s as the inlet velocity. In winter and summer, it is necessary to insulate the tank. On the one hand, the heat loss can be reduced. On the other hand, the heat storage efficiency of single tank can be improved. Conclusion: Analysing the efficiency of the single tank thermal storage device can provide a reference for the optimal design of the solar heat plant thermal storage tank, and lay a certain foundation for its theoretical and experimental research.*

Key words: *solar energy, single tank heat storage system, phase change material, heat transfer fluid, numerical simulation*

Introduction

Due to the development of industry, economy as well as social progress, environmental problems and energy crisis are increasingly threatening the long-term and stable development of human society [1]. Therefore, it is an urgent need to study and develop new energy and renewable energy technologies for the countries all over the world. Among many new energy sources, solar energy has the characteristics of rich resources, wide distribution, clean and pollution-free. It is a clean, sustainable and potential fossil energy alternative, which has been widely concerned. Therefore, it is more competitive than the power generation of wind as well as solar photovoltaic [2]. At present, research at home and abroad has proved that there are many technologies that can be used to collect and utilize solar energy. Among them, solar photothermal conversion technology and PV conversion technology are the most mature and

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widely used methods [3]. Different from PV power generation where sunlight is directly converted into electric energy, photothermal power generation is a process of converting sunlight into heat energy, and then converting heat energy into electric energy [4]. Solar heat power generation stations usually adopt heat storage measures so as to solve solar energy instability problem. Therefore, in the solar thermal power generation unit, the heat storage technology plays an essential part, and capacity of its efficient heat storage as well as release is particularly important [5]. The solar thermal power generation unit can store the surplus heat by melting latent heat through solid-liquid phase change by adopting phase change heat storage technology [6]. The latent energy storage of the phase change accumulator can store the surplus heat by melting latent heat through the solid and liquid phase change. It has the characteristics of small volume and large heat storage density, and has certain advantages compared with the sensible heat storage [7]. At present, experts and scholars have studied the storage and heat release process of different phase change materials (PCM) as well as the structural optimization of the thermal storage device. Cheng *et al.* [8] performed numerical calculation on the solidification process of a PCM cold storage ball, and obtained the moving speed of phase change interface, the temperature distribution of each point with time and the relationship between solidification time and heat transfer temperature difference under the first type of boundary condition. For a new type of heat storage device with longitudinal straight ribs on the inner tube of the shell and tube type phase change regenerator, has been established the relevant model based on the melting law of the phase change in [9, 10]. At present, the most widely used heat storage system is the double tank type, but its investment cost is high.

Therefore, the single tank inclined layer type is proposed. Compared with the double tank type, it can effectively reduce the investment cost. Therefore, the single tank type has been widely concerned and studied, and scholars have conducted a lot of simulation and experimental research on this kind of system. In this study, Hitec salt is used as heat exchange fluid (HTF) material, KNO_3 is used as PCM. In addition, as for the single tank with inclined temperature layer, its numerical model is established. Studying the influence of inlet parameters and external temperature on the performance of phase change thermal storage unit (PCTSU) has great significance.

Method

The FLUENT is a widely used commercial CFD software package, which can be used in industrial fields like heat transfer as well as chemical reaction. There are many physical models, advanced numerical methods as well as powerful pre-processing functions, and has a wide range of applications [11].

Establishment of physical model

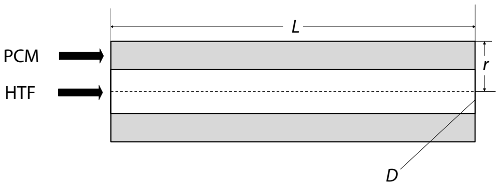

Figure 1. Physical model of PCTSU

Before the numerical simulation, the physical model of single tank inclined layer heat storage system should be established. The shell and tube structure is selected as the heat storage structure. The PCTSU model established is shown in fig. 1.

The physical model size of the PCTSU in fig. 1 is: the diameter of the PCTSU is $d = 2r = 0.2$ m, and the length of the PCTSU is $L = 1.2$ m. The PCM is a phase change material, HTF is a channel for heat exchange fluid to enter, and point D is a point in the phase change area of the inner wall of the regenerator. In the shell and tube PCTSU, HTF flows through the inner diameter. The PCM is stored in the outer ring. Through numerical simulation, the best inlet temperature and flow rate are selected. After setting, the numerical simulation is performed and the simulation results are analyzed.

Selection of phase change materials

The melting temperature range of pure salt, mixed salt, alkali, metal and other high temperature PCM is generally 120-850 °C. In the high temperature phase transformation technology, the most promising one is the molten salt phase transformation technology. Ghasemi *et al.* [12] discussed the effect of applying a variety of PCM mixtures in phase change thermal storage equipment, and provided the methods of enthalpy analysis and numerical simulation. Abdulateef *et al.* [13] analyzed the application of PCM in solar thermal power generation, and found several substances with high melting point and high thermal conductivity suitable for solar thermal power generation through numerical analysis. In this study, HITEC salt was selected as HTF material. Hitec salt has lower melting point, higher density and viscosity with temperature, and smaller thermal conductivity as well as specific heat capacity with temperature. Meanwhile, KNO_3 is selected as PCM. Its melting point is T_m = 330 °C, dissolution heat is L = 266 kJ/kg, average specific heat capacity is C_p = 11.22 kJ/kgK, density is ρ = 2110 kg/m^3, thermal conductivity is λ = 0.5 W/Mk.

Establishment of numerical model

To simplify the simulation calculation process, for the physical model previously established, the condition assumption is carried out:

- regardless of the thickness of the tube wall, the inner wall is set as the heat transfer wall; the outer wall is set as the heat insulation wall,
- considering the influence of temperature change on the characteristics of the heat storage material, *i. e.* the PCM is incompressible fluid after melting,
- the influence of turbulence and natural-convection is considered,
- the PCM is homogeneous and isotropic,
- the physical parameters of the PCM are independent of the temperature, and
- the initial condition of the heat storage stage is the fluid at the inlet of the upper end of the heat storage tank temperature T_{in} = 593 K, inlet velocity u_{in} = 0.25 m/s; fluid temperature in tank T_0 = 523 K.

Based on the aforementioned assumptions, the problem is simplified. The solidification/melting model in FLUENT software is used in the phase transformation area of the casing, and the enthalpy is the variable to be calculated. The governing equations used are:

- continuity equation

$$\frac{\partial u}{\partial x}+\frac{1}{r}\frac{\partial (ruv)}{\partial r}=0 \tag{1}$$

- equation of motion

$$\frac{\partial u}{\partial t}+\frac{\partial (u^2)}{\partial x}+\frac{1}{r}\frac{\partial (ruv)}{\partial r}=-\frac{1}{\rho}\frac{\partial p_{\mathrm{eff}}}{\partial x}+\beta \mathrm{g}(T-T_r)+\nu\nabla^2 u \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial (uv)}{\partial x}+\frac{1}{r}\frac{\partial (rv^2)}{\partial r}=-\frac{1}{\rho}\frac{\partial p_{\mathrm{eff}}}{\partial r}+\nu\nabla^2 v-\nu\frac{v}{r^2} \tag{3}$$

– energy equation

$$\frac{\partial h}{\partial t}+\frac{\partial(uh)}{\partial x}+\frac{1}{r}\frac{(ruh)}{\partial r}=\lambda\nabla^2 T \tag{4}$$

The Boussinesq approximation is adopted in the phase transition region, that is, the density change caused by pressure is ignored, only the density change caused by temperature is considered, and the density changes linearly with temperature. Pressure gradient and gravity terms in the axial upward motion equation:

$$-\frac{\partial p_{\text{eff}}}{\partial x}=\rho_r\alpha \text{g}(T-T_r) \tag{5}$$

– effective pressure

$$p_{\text{eff}}=p+\rho_r \text{g}x \tag{6}$$

The density of any point in the melting area:

$$\rho=\rho_r-\rho_r\alpha(T-T_r) \tag{7}$$

where p_{eff} [Pa] is the effective pressure, ρ [kgm^{-3}] – the reference density of PCM, α [k^{-1}] – the volume expansion coefficient of PCM, T [K] – the molten salt temperature, T_r [K] – the reference temperature, u [ms^{-1}] – the horizontal velocity, v [ms^{-1}] – the longitudinal velocity, v [m^{2}s^{-1}] – the kinematic viscosity, h [kJkg^{-1}] – the specific enthalpy at any time, λ [WM^{-1}k^{-1}] – the thermal conductivity, t [s] – the heat storage time of the heat storage tank, and r [m] – the radius of the regenerator.

Because the physical model structure is relatively simple, GAMBIT software is used to divide the grid. The 2-D model and quadrilateral mesh are used for horizontal placement of pipes. The solver adopts the uncoupled and 2-D implicit method. Gravity effects are considered. Boussinesq model is driven by buoyancy in the phase transition region. Simple is adopted to realize the coupling of pressure and speed. In the solver, the relaxation factor of energy equation is 0.8, and the relaxation factor of momentum equation is 0.7. The relative residuals of energy equation are less than 10^{-6} as convergence criteria. The patch panel is used to set the initial temperature of the flow region and phase transition region. In the process of simulation, it is found that the number of grids has a great influence on the simulation results. When the number of grids reaches 6200, the temperature distribution of PCM in the tank is going to be stable, which can meet the accuracy of the calculation requirements.

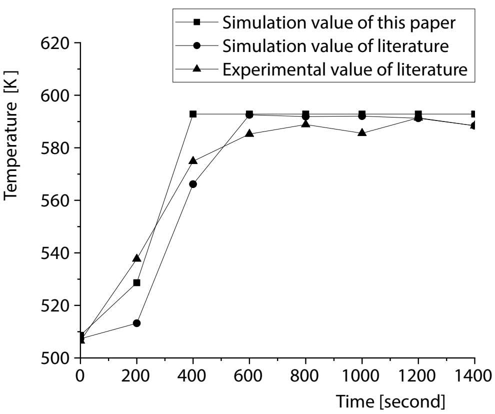

Figure 2. Comparison of temperature change of point D with literature results

Comparison and verification of numerical model

In the process of heat storage, the simulation results of temperature at point D (as shown in fig. 1) of single tank heat storage unit model at different times are compared with the experimental results and numerical simulation results in reference [14], as shown in fig. 2.

Figure 2 shows that the curve of experimental results shows certain dispersion, which indicates that the experiment has certain uncertainty factors, while the numerical simulation results show obvious regularity. The results of numerical simulation and experiment are well coupled, that is, the trend of temperature change is consistent, which shows the correctness of the single tank heat storage model and the reliability of the numerical simulation method.

Numerical simulation

In the simulation, how do HTF inlet velocity as well as ambient temperature influence the thermal storage performance is explored. The following points need to be considered.

– The transition layer between HTF and PCM is inclined temperature layer. The existence of inclined temperature layer will affect the effective heat storage efficiency of the regenerator. According to the thickness of the inclined layer, the effective heat storage efficiency η is defined:

$$\eta = 1 - \frac{\delta(t)}{L} \tag{8}$$

where $\delta(t)$ [m] is the thickness of the inclined layer and L [m] – the total length of the heat storage tank.

– If the model is reduced in equal proportion according to the similarity principle, how do boundary conditions influence the numerical simulation results of the model should be considered. When the wall of the single tank thermal storage system is in adiabatic condition, winter condition and summer condition, the temperature distribution of the PCM as well as the thickness change of the inclined layer are analyzed. The tank body radiates heat outwards (compound heat transfer) by convection as well as heat radiation. To facilitate the calculation, when selecting the calculation model, the effect of radiation heat transfer is converted into the heat transfer effect of convection heat transfer [15]:

$$\psi = \psi_c + \psi_r = (h_c + h_r)A(t_w - t_f) = h_f A(t_w - t_f) \tag{9}$$

$$h_f = h_c + h_r \tag{10}$$

In eqs. (9) and (10), h_f is the composite heat transfer coefficient, h_c indicates the convective heat transfer coefficient, h_r indicates the radiation heat transfer coefficient. In the equation, the expression of h_c :

$$h_c = \frac{\lambda}{L}\mathrm{Nu} \tag{11}$$

The expression of h_r:

$$h_r = \frac{\varepsilon\sigma(T^4 - T_f^4)}{t - t_f} \tag{12}$$

Results and discussion

Influence of HTF inlet velocity on heat storage performance

When the HTF inlet velocity is different, the velocity field in the tank will change, which will affect PCM temperature distribution, and then affect the thermal storage performance of the whole tank. Therefore, the aforementioned other conditions are kept unchanged, and only the inlet flow rate of HTF is changed, so as to explore how does the inlet flow rate of HTF influence the thermal storage characteristics of PCTSU. Figure 3 shows the change of the time required for PCM to melt completely in the PCTSU at different inlet speeds.

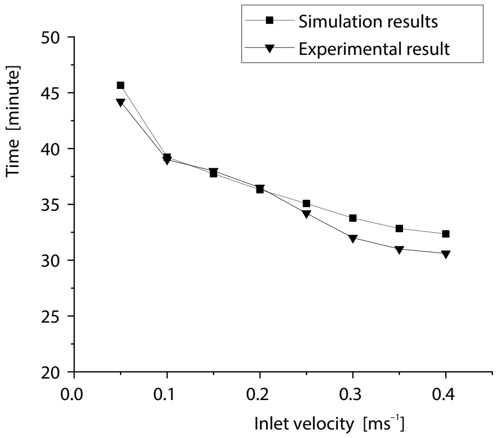

Figure 3. Change of PCM melting time with inlet flow rate

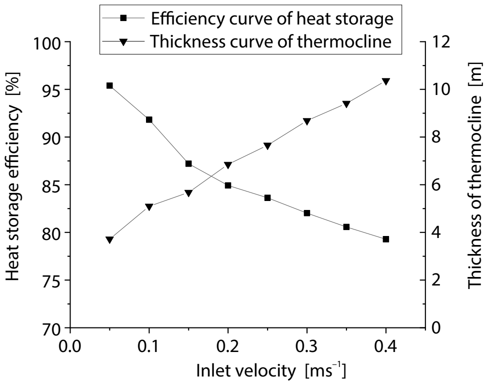

Figure 4. Effect of inlet velocity on the thickness of inclined layer and heat storage efficiency

As can be seen from fig. 3, the simulation results are basically consistent with the experimental results. When HTF inlet flow rate increases, the time required for PCM to melt completely in PCTSU is shortened. Meanwhile, with the increase of HTF inlet velocity, the tangent slope of the curve is constantly decreasing, which shows that when HTF inlet velocity is low, increasing HTF inlet velocity can greatly shorten the heat storage time, that is to say, the heat storage period of the heat storage tank is significantly shortened, and the diffusion speed of the inclined temperature layer is gradually accelerated.

When the HTF velocity increases, the heat transfer effect inside and outside the thermocline is strengthened, which makes the thermocline expand to the high temperature fluid area, and the diffusion degree is more serious, and the temperature gradient in the thermocline decreases gradually. Therefore, at the same height of the regenerator, the thickness of the inclined layer increases when the inlet velocity of the molten salt fluid increases, and the top surface of the inclined layer moves up. Combined with eq. (8), when the inlet velocity increases, the effective heat storage efficiency of the regenerator decreases gradually. Figure 4 shows the specific changes.

Figure 4 shows that controlling the inlet flow rate of HTF can effectively reduce the inclined layer thickness, thus improving the efficiency of the heat storage tank. However, the decrease of flow rate will prolong the heat storage period of the heat storage system. In addition, the long heat storage period will increase the requirements of mechanical strength and operation parameters of the heat storage system, and the investment cost of the system will also increase. Therefore, choosing a reasonable HTF inlet velocity cannot only ensure the good heat transfer as well as heat storage characteristics of the regenerator, but also ensure its proper heat storage period. According to eq. (8), the change rate of efficiency and time of the heat storage tank under different inlet flow rates is shown in tab. 1.

Table 1. Change rate of efficiency and time of heat storage unit under different inlet flow rates

Inlet velocity [ms^{-1}]	Thickness of thermocline [m]	Heat storage time, t [s]	Heat storage efficiency, η [%]	Rate of change of t [%]	Rate of change of η [%]
0.05	3.72	36.0	92.39	–	–
0.15	5.68	17.5	89.20	51.39	3.45
0.25	7.66	5.1	83.63	70.86	6.24
0.4	10.36	3.1	81.27	39.22	2.82

Table 1 shows that when the inlet flow rate increases, the heat storage efficiency of the heat storage tank gradually decreases and the heat storage time gradually shortens. Moreover, the change rate of efficiency and time shows a trend of increasing first and then decreasing. Therefore, on the premise of ensuring a high heat storage efficiency (83.63% in comprehensive condition) and a short heat storage time (5.1 second), it is reasonable to choose the HTF inlet flow rate of 0.25 m/s. Therefore, when the flow rate of HTF inlet is 0.25 m/s and porous media is not added, the formation of large temperature difference inclined layer can be realized. However, because of the large thickness of the inclined layer, and the comprehensive thermal storage efficiency is only 83.63%, the thickness of the inclined layer can be further reduced and the thermal storage efficiency can be improved by filling the appropriate porous media.

Influence of ambient temperature on thermal storage performance

According to eqs. (9)-(12), the performance of the regenerator under adiabatic condition, winter condition and summer condition is compared. If the ambient temperature is t_f = 5 °C in winter and t_f = 30 °C in summer, the relevant parameters of the heat storage tank can be obtained after the radiation heat transfer is converted into convection heat transfer, as shown in tab. 2.

Table 2. Relevant parameters of heat storage tank in winter and summer

Parameter	t_f [°C]	Nu	h_c [Wm^{-2}K^{-1}]	h_r [Wm^{-2}K^{-1}]	h_f [Wm^{-2}K^{-1}]
Summer	30	62.76	3.97	2.43	6.40
Winter	5	83.72	4.95	2.17	7.12

During the operation of solar heat power generation system, it is necessary to detect the temperature at the central axis and the wall of the tank at the same time, supplemented by measures such as the utilization of residual heat of the power plant and the installation of thermal insulation materials on the wall of the tank, so as to avoid the interruption of the heat storage process and ensure the integrity of the cycle, so as to reduce the heat loss of the tank when waiting for life. In this study, 0.02 m thick insulation material is laid outside the tank, with a density of 2000 kg/m^3, a specific heat of 960 J/kgK and a thermal conductivity of 0.1 W/Mk. Based on tab. 2, the temperature distribution of phase change material in the regenerator is shown in fig. 5 when the regenerator is on standby.

It can be seen from fig. 5 that the diffusion degree of the inclined layer in the heat storage tank under the adiabatic condition is far less than that under the winter and summer conditions, because there is a temperature difference heat exchange between the heat storage tank and the external environment, which increases the mixing speed and heat exchange effect of the cold and hot fluid in the heat storage tank, thus increasing the diffusion speed of the inclined layer. In addition, compared with summer, the temperature difference between the regenerator and the external environment is larger in winter, so the inclined layer thickness of the regenerator is larger and the diffusion de-

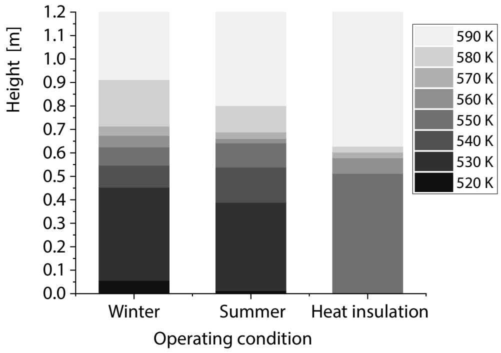

Figure 5. Temperature distribution of PCM in regenerator under three working conditions

gree is more intense in winter, resulting in the decrease of the thermal storage efficiency. Considering the external conditions on the basis of the adiabatic condition, although the composite heat transfer coefficient is very small, it will still have a huge impact on the temperature field of PCM in the heat storage tank and reduce the heat storage efficiency. Therefore, in order to reduce unnecessary energy loss, a good thermal insulation layer must be laid outside the heat storage tank.

Conclusion

The thermal storage performance of solar thermal power generation system is simulated by computer. It is found that the heat storage period of the regenerator decreases with the increase of HTF inlet velocity, and the thickness of the inclined layer increases with the increase of HTF inlet velocity, but the heat storage efficiency of the regenerator decreases with the increase of HTF inlet velocity. Moreover, the larger the inlet velocity is, the greater the expansion and diffusion degree of the inclined layer in the regenerator will cause the serious decrease of the heat storage capacity. However, if the inlet velocity is too small, the mechanical strength and toughness of the tank will be increased, and the heat storage period will be prolonged. Therefore, on the premise of ensuring high heat storage efficiency and short heat storage cycle, it is reasonable to choose 0.25 m/s as HTF inlet velocity. The change of different ambient temperature will reduce the heat storage efficiency. Therefore, in order to improve the heat storage efficiency of single heat storage tank, a good thermal insulation material should be laid outside the tank during the operation of the heat storage system. The analysis results of the thermal storage performance of the single tank inclined layer thermal storage device can provide a reference for the optimal design of the thermal storage tank of solar thermal power plant, and lay a certain foundation for its theoretical and experimental research.

Reference

[1] Sharma, C., *et al*., Uncertainty in Estimating Renewable Energy Utilisation Potential: A Case of Solar Thermal Power Generation in India, *International Journal of Ambient Energy*, *38* (2017), 8, pp. 765-773
[2] Shaofei, W., Study and Evaluation of Clustering Algorithm for Solubility and Thermodynamic Data of Glycerol Derivatives, *Thermal Science*, *23* (2019), 5, pp. 2867-2875
[3] Bishoyi, D., Sudhakar K., Modelling and Performance Simulation of 100 MW LFR Based Solar Thermal Power Plant in Udaipur India, *Resource-Efficient Technologies*, *3* (2017), 4, pp. 365-377
[4] Montanes, R. M., *et al*., Dynamic Modelling of a Parabolic trough Solar Thermal Power Plant with Thermal Storage Using Modelica, *Heat Transfer Engineering*, *39* (2018), 3, pp. 277-292
[5] Liu, J., *et al*., Proposition of a Critical Design Direct Normal Irradiance for Solar Thermal Power Plant, *International Journal of Energy Research*, *42* (2018), 13, pp. 4108-4119
[6] Tao, P., *et al*., Magnetically-Accelerated Large-Capacity Solar-Thermal Energy Storage Within High Temperature Phase-Change Materials, *Energy and Environmental Science*, *12* (2019), 5, pp. 1613-1621
[7] Zhang, L., *et al*., Solar-Thermal Conversion and Thermal Energy Storage of Graphene Foam-Based Composites, *Nanoscale*, *8* (2016), 30, pp. 14600-14607
[8] Cheng, H., *et al*., In Situ Synthesis and Thermal Shock Resistance of a Cordierite-Mullite Composite for Solar Thermal Storage, *International Journal of Applied Ceramic Technology*, *16* (2019), 2, pp. 772-780
[9] Shaofei, W., *et al*., Research on Internet Information Mining Based on Agent Algorithm, *Future Generation Computer Systems*, *86* (2018), Sept., pp. 598-602
[10] Ranjan, S., *et al*., Parabolic trough Solar-Thermal-Wind-Diesel Isolated Hybrid Power System: Active Power/Frequency Control Analysis, *IET Renewable Power Generation*, *12* (2018), 16, pp. 1893-1903
[11] Lee, H. J., *et al*., Numerical Study on Optical Performances of the First Central-Receiver Solar Thermal Power Plant in Korea, *Journal of Mechanical Science and Technology*, *30* (2016), 4, pp. 1911-1921
[12] Ghasemi, S. E., Ranjbar, A. A., Effect of Using Nanofluids on Efficiency of Parabolic trough Collectors in Solar Thermal Electric Power Plants, *International Journal of Hydrogen Energy*, *42* (2017), 34, pp. 21626-21634

[13] Abdulateef, A. M., *et al.*, Thermal Performance Enhancement of Triplex Tube Latent Thermal Storage Using Fins-Nanophase Change Material Technique, *Heat Transfer Engineering*, *39* (2018), 12, pp. 1067-1080
[14] Augspurger, M., Udaykumar, H. S., A Cartesian Grid Solver for Simulation of a Phase-Change Material (PCM) Solar Thermal Storage Device, Numerical Heat Transfer, *Fundamentals – Part B*, *69* (2016), 3, pp. 179-196
[15] Mao, Q., *et al.*, Numerical Simulation of Single Spiral Heat Storage Tank for Solar Thermal Power Plant, *International Journal of Hydrogen Energy*, *42* (2017), 29, pp. 18240-18245

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