Numerical analysis of a thermal energy storage tank charged with a flat type solar air collector

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Abstract. As energy and sustainability issues related to climate change gain importance day by day, the significance of energy storage systems is increasing. Carnot Batteries, where energy can be stored thermally, constitute one of the most outstanding alternatives for the storage of excess electrical energy produced from renewable energy in the concept of smart cities. The energy is stored in the Carnot Batteries during the hours when the electricity demand is lower than the electricity production, the energy stored in the Carnot Batteries is converted into electricity during the hours when the electricity demand is higher than the electricity production. In this respect, Carnot Batteries can offer a good solution to the imbalance between energy demand and production, which is a crucial problem in energy use, and therefore, it is likely that they will be an indispensable part of the future and smart city systems. In this study, a simulation covering the charging and discharging processes of a Thermal Energy Storage tank, which receives its energy from flat type solar thermal collectors, was carried out in MATLAB. In the simulation, a 6 m height tank was divided into 60 cells and discretized, the solar radiation values were calculated locally and a solar path was created. At the time of charging, the Thermal Energy Storage tank received its energy from the solar collectors, depending on the determined solar path. In the simulation, the effects of variables related to the energy storage media such as sphericity, void fraction, charging time were investigated.

Keywords. Carnot battery, energy storage, charge, discharge, solar thermal collectors, Organic Rankine Cycle.
DOI: https://doi.org/10.34641/clima.2022.339

1. Introduction

In today's world, the tendency towards renewable energy sources is increasing. While developed countries meet most of their electricity production from renewable resources, developing countries are constantly increasing their orientation towards renewable resources. Although renewable energy systems have many advantages, these also have some disadvantages such as intermittent operation characteristics. On the other hand, the increase in renewable energy investments will cause energy supply-demand imbalance at certain times during the day. Thermal energy storage systems can offer an effective and economic solution to the supply-demand imbalance. The motivation of this study will be to examine the effects of thermal energy storage in low temperature systems. The goal is to create a modeling code to include high-temperature systems. The storage of the produced energy is one of the most current research topics. So far, many different types of energy storage systems such as supercapacitor, battery and flow batteries, Compressed Air Energy Storage, Superconducting Magnetic Energy Storage, Pumped Hydroelectric Energy Storage, Thermal Energy Storage or Pumped Thermal Energy Storage, flywheel and Hydrogen Storage are in different technological stages (Benato A. and Stoppato A., 2018a). Among these systems, Pumped Hydroelectric Energy Storage, Compressed Air Energy Storage, Thermal Energy Storage, and Flow Batteries can be considered as mature, while other systems are still under research. Pumped Hydroelectric Energy Storage system offers high efficiency at low cost with longer operating hours. Compressed Air Energy Storage systems can offer high efficiency at low cost. Flow Batteries have higher energy density than Pumped Hydroelectric Energy Storage and Compressed Air Energy Storage systems, but have a shorter lifespan (Benato A. and Stoppato A., 2018b). Pumped Hydroelectric Energy Storage and Compressed Air Energy Storage systems cannot be installed in any region as these require certain geographical conditions. On the other hand, Pumped Thermal Energy Storage systems can be an important alternative to other energy storage systems with their high energy densities, high efficiencies, low costs and long lifetimes. Besides, there is no need for any geographical conditions in Thermal Energy Storage systems.

In Thermal Energy Storage systems, or Carnot Batteries, electrical energy is stored as heat energy. The basic principle in these systems is to store energy in the form of heat into the materials with thermophysical properties suitable for energy storage, such as water, oil, paraffin, wood, sand, concrete, brick, glass wool, and granite. When the electricity demand exceeds the electricity generation, the energy stored as heat is drawn from the storage media by means of a working fluid to generate electricity by conventional cycles, Rankine, Organic Rankine, Brayton etc.

In Pumped Thermal Energy Storage systems, the charging process takes place in two different ways. In these systems, either a heat pump or an electrical resistor is used during the charging process. In the discharge process, a gas turbine, Rankine cycle or a hybrid system is used. The storage part is realized in three different ways as sensible heat storage, latent heat storage, and thermochemical storage. Latent heat storage is done with substances called phase change materials. These materials also store and/or use an extra phase energy by changing phase during storage and/or discharge of thermal energy. However, the costs and total cycle availability of these materials should be considered. In sensible heat storage, materials with high thermal permeability, non-toxic, non-flammable and inexpensive are used. Rocks, metals, stones, concrete, sand, and salts are suitable materials for use in sensible heat storage.

Singh et al., (2008) numerically investigated a Thermal Energy Storage system powered by solar collectors. As a result of the 8-hour charging process, it was found that the maximum energy stored in the tank to be approximately 175 MJ by assuming the solar radiation as constant. Peterson (2011) examined a Thermal Energy Storage system consisting of a heat pump, a heat engine, and a latent heat storage tank. The effect of isentropic efficiency of compressor and turbine on system efficiency was investigated. Morandin et al. (2012) investigated a Thermoelectric Energy Storage system consisting of transcritical CO_2 cycles (heat pump and Rankine cycle). As a result, the efficiency of the Pumped Thermal Energy Storage system was found to be 60%. Henchoz et al., (2012) performed a thermoeconomic analysis of an energy storage system including solar thermal collectors. The optimum efficiency was found to be 43.8% – 84.4% in the system, the working fluid was ammonia. Kuravi et al., (2013) designed a sensible heat storage system for concentrated solar power plants. Air was used as the working fluid and it was observed that the increase in the air flow rate decreased the energy storage time. Steinmann (2014), examined a latent heat storage system operating on the conventional Rankine cycle. Okazaki et al., (2015) examined three different energy storage systems. It was observed that the wind powered Thermal Energy Storage system using a heat generator is more economical than other systems. Vinnemeier et al., (2016) investigated the Pumped Thermal Energy Storage system integrated into a number of different thermal power plants. As a result, the maximum exergy of the system was found to be 70%. Ayachi et al., (2016) constructed a thermodynamic model of a Pumped Thermal Energy Storage system consisting of transcritical CO_2 cycles, geothermal energy storage and a ground heat exchanger. According to the results, it was stated that the system efficiency is 50%, however, it is possible to reach up to 66% with more complex systems. Guo et al. (2016) examined Pumped Thermal Energy Storage and Pumped Cryogenic Energy Storage systems. It was found that the overall performance of the Pumped Thermal Energy Storage system is better than the overall performance of the Pumped Cryogenic Energy Storage system. Benato (2017) reviewed Pumped Thermal Energy Storage system with an electric heater and heat exchanger and the materials stored. Air was used as the working fluid and the system was modelled as 1D. It was concluded that the configuration with the lowest specific cost and the highest energy density was the packed bed consisting of aluminum oxide spheres. Frate et al., (2017) studied a hybrid Pumped Thermal Energy Storage system utilizing a low-grade heat source. Different working fluids were considered in the model and it was found that the system efficiency can be over 100%. Roskoch and Atakan (2017) investigated the thermodynamic potential of a Pumped Thermal Energy Storage system consisting of a compression heat pump, latent heat energy storage tank, and organic Rankine cycle. The results show that the system efficiency increased with increasing storage temperature and increased superheating effect at the expander inlet. Smallbone et al., (2017) performed an economic analysis of a Pumped Thermal Energy Storage system and compared this system with other energy storage systems. It was reported that the Pumped Thermal Energy Storage system can compete with the Compressed Air Energy Storage system economically, and that it can even compete with the Pumped Hydroelectric Energy Storage system, since the Pumped Thermal Energy Storage system does not need any geographical conditions. Georgiou et al., (2018) analyzed and compared the Liquefied Air Energy Storage and Pumped Thermal Energy Storage system thermodynamically and economically. It was revealed that the efficiency of the Pumped Thermal Energy Storage system is higher, but the Energy Storage system with Liquefied Air is more economical. Farres-Antunez et al., (2018) examined a hybrid system consisting of Liquefied Air Energy Storage and Pumped Thermal Energy Storage systems. In the thermodynamic analysis-based study, the efficiency of the hybrid system was found to be 70%. It was also reported that the energy density of the hybrid system is higher than that of the Liquefied Air Energy Storage system and the Pumped

Thermal Energy Storage system. Pillai et al., (2019) examined a Carnot Battery consisting of a heat pump and Organic Rankine cycle from a thermodynamic perspective. In the simulated Carnot Battery, it was also examined the latent and sensible heat behavior and tried various working fluids in the simulations. In addition, it was reported that the highest exergy amount was in the HFO-1336mzz(E) fluid, and the lowest exergy amount was in the R1234ze(Z) fluid. Attonaty et al., (2019) investigated a Thermal Energy Storage system with a capacity of 200 MWh, consisting of an electric heater and a Brayton-Rankine hybrid cycle. The system efficiency was found to be 50% at a storage temperature of 900°C. Dietrich et al., (2020) analyzed a Thermal Energy Storage system consisting of the Joule/Brayton cycle exergo-economically. As a result of the transient numerical studies, it was found that the efficiency of the Thermal Energy Storage system is 42.9%. It was also concluded that the examined system has the highest power-specific cost compared to other installed systems. Frate et al., (2020) investigated a Thermal Energy Storage system consisting of a heat pump and Organic Rankine Cycle. In the analytical study, it was observed that the efficiency of the system can exceed 50%, provided that the temperature of the waste heat source does not exceed 60°C. As a result of the literature review, it was seen that there are many studies on Thermal Energy Storage systems. Thermal Energy Storage systems are quite suitable for today's energy policies, but it is expected to become a necessity in the near future.

In this study, a Thermal Energy Storage (TES) system, in which solar radiation will be used as a variable according to the region and the day of the year, is numerically simulated. A solar path, giving the hourly solar radiation is created and the charging and discharging characteristics of the system are obtained according to this solar path. Sensible energy storage media with different physical properties is modelled. On the power side, an Organic Rankine cycle with a working fluid R245fa is considered. The efficiency of the power side during dischange process is also obtianed.

2. METHODOLOGY AND NUMERICAL MODEL

Thermal Energy Storage systems can be configurated in many ways. However, the selected media and subsystems can affect the charge and discharge properties of the storage systems. Heat pump or electrical resistance is generally used in the charging process of the TES systems. Rankine cycle, Organic Rankine cycle, gas turbine cycle or hybrid systems can be considered in the discharge process. In this study, flat type solar collectors are considered for the charging process. Organic Rankine Cycle (ORC) is considered for the discharge part of the investigated system. A sensible heat storage tank is considered due to its lower cost and availability. The main components of the simulated system is shown in Fig. 1.

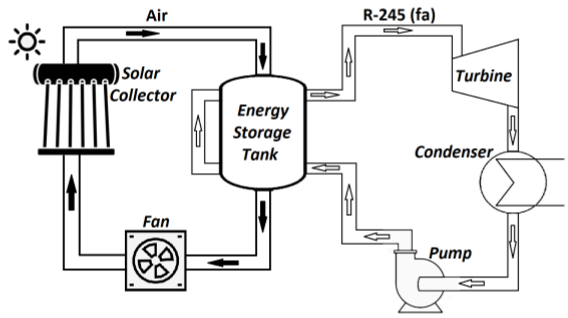


Fig. 1. Schematic of the simulated system

The system consists of a flat type solar air collector, fan, heat storage tank, and Organic Rankine cycle. The working fluid for the charging process is air and for the discharge process the working fluidi s R245fa. Initially, the air in the system is drawn towards the tank by the fan. The drawn air is heated in the solar air collectors. The heated air moves towards the tank filled with rocks after the solar collectors. The hot air raises the tank temperature to a certain temperature level after a charging period of 8 hours. After the charging process, the discharge process starts as the refrigerant enters the hot tank and heats up. At this stage, the refrigerant passed through copper pipes placed in the tank, unlike air. The pipes are designed in multiple bundles, straight and placed along their length. The energy storage tank acts as evaporator for the ORC. The working fluid expands in the turbine to generate electricity.

Numerical analysis of the TES is performed in a MATLAB code. The tank is divided into “n” cells and discretized, and the charging and discharging processes are calculated by repeating for each determined unit time step. Besides, a solar path is created that calculates solar radiation based on the coordinates of the region and the day of the year. The model chosen for use in each discretized control volume is a hybrid model that consists of the Mumma and Marvin model and thermal resistance analogy.

Validation of the model

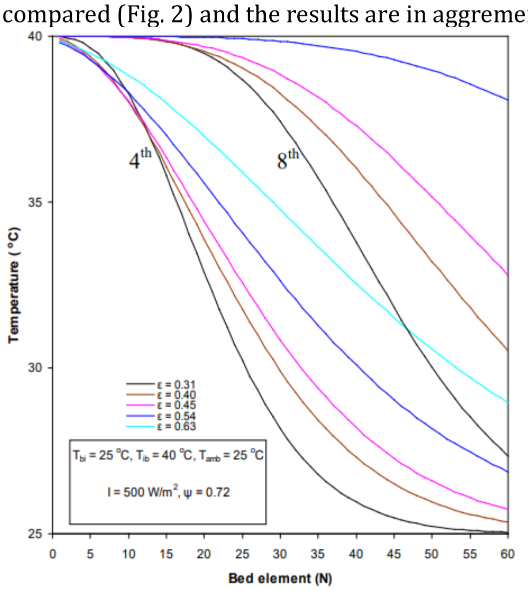
A validation study is carried out for testing the Mumma and Marvin model (Singh et al., 2008). The charging process of the tank that receives its energy from a solar air collector is investigated. Singh et al., and used air as the working fluid in the simulations. The air at room temperature warmed up from the solar collectors and then entered the energy storage tank filled with storage material. The air warmed the tank to a certain extent after a charging time of 8 hours. Besides, the effects of changing the material values such as the sphericity and void ratio of the storage materials is investigated. The parameters used by Singh et al., are given in Table 1.

Table 1. Validation case material properties

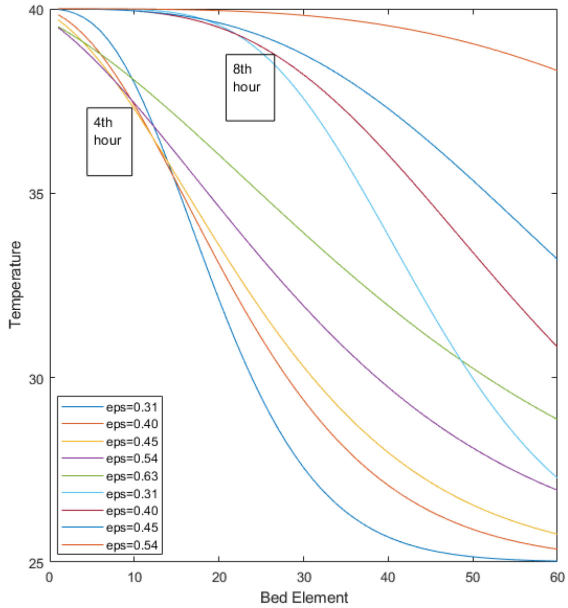
Parameter	Value/Range
Volume of packed bed	15 m^3
Length of packed bed	6 m
Number of bed elements	60
Initial bed temperature	25°C

Sphericity of material element	0.55 – 1.00
Void fraction	0.31 – 0.63
Density of storage material	1920 kg/m³
Density of air	1.1 kg/m³
Specific heat of storage material	0.835 kJ/kgK
Specific heat of air	1.008 kJ/kgK
Thermal conductivity of storage material	0.70 W/mK
Dynamic viscosity of air	0.0000185 kg/ms
Ambient temperature	25°C
Inlet air temperature to bed	40°C
Insolation	500 W/m²

The charging characteristics of the energy storage tank and the Mumma and Marvin model is validated. In the simulations, the energy storage tank subjected to a charging period of 8 hours and examined the results obtained according to different void ratios and sphericity values. Likewise, in this study in which the Mumma and Marvin model will be used, a validation study is carried out by using the parameters and equations. To show the consistency and compatibility of the validation the temperature values at the end of the 4-hour charging period and the 8-hour discharging period according to the different void ratios of the energy storage tank are compared (Fig. 2) and the results are in aggrement.



(a)



(b)

Fig. 2. Comparison of the results for the validation (a) reference work (b) this study The temperature change according to the different void ratios of the energy storage tank at the end of the 4 and 8 hour charging periods.

The Mumma and Marvin Model

The energy storage tank is divided into 60 control volume (Fig. 3). The generated equations are solved for each cell. At the same time, the equations created for each control volume were also repeated for each time step.

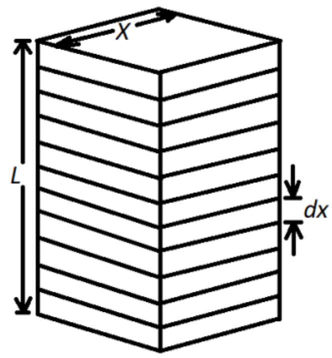


Fig. 3. The discritized view of the tank

The thermal energy storage tank is considered as a rectangular prism. While the cross-sectional area of the tank is 1.5x1.5 m², its height is assumed to be 6 m. The tank is discretized by dividing it into 60 compartments along its height. The useful heat energy is calculated from Eq. 1.

$$Q_u = A_c[S_t F_R(\tau\alpha) - F_R U_l(T_i - T_{amb})] \qquad (1)$$

In Eq. (1), A_c collector surface area (m²), S_t insolation (W/m²), F_R heat removal factor, $(\tau\alpha)$ effective transmittance-absorption product, U_l overall heat transfer coefficient (W/m²K), T_i air inlet temperature to the collector (°C) is T_{amb} outside temperature (°C). Q_u is the amount of useful heat transfer (W). The useful heat transfer amount Q_u is also included in Eq. 2.

$$Q_u = \dot{m}C_p(T_o - T_i) \quad (2)$$

which, $\dot{m}$ is the mass flow rate of the air (kg/s), and C_p is the specific heat of the air (kJ/kgK). T_o is the exit temperature of the air from the collector. The equations that are solved by repeating in the discretized tank are as follows.

$$T_{a,m+1} = T_{s,m} + (T_{a,m} - T_{s,m})e^{-\emptyset_1} \quad (3)$$

$$T_{s,m\,(t+\Delta t)} = T_{s,m\,(t)} + \Delta t[\emptyset_2(T_{a,m} - T_{a,m+1}) - \emptyset_3(T_{s,m\,(t)} - T_{amb})] \quad (4)$$

which $T_{a,m+1}$ is air temperature at outlet of control volume element "m" (°C), $T_{a,m}$ is air temperature at inlet of control volume element "m" (°C), $T_{s,m\,(t)}$ is mean temperature of control volume element "m" at time t (°C), $T_{s,m\,(t+\Delta t)}$ is mean temperature of control volume element "m" after time interval Δt (°C). Δt is the time step (s). Also, $\emptyset_1$, $\emptyset_2$ and $\emptyset_3$ are empirical coefficients.

$$\emptyset_1 = \frac{h_v AL}{\mathrm{N}(\dot{m}C_p)} \quad (5)$$

$$\emptyset_2 = \frac{N(\dot{m}C_p)}{\rho_s AL(1-\varepsilon)C_s} \quad (6)$$

$$\emptyset_3 = \frac{(UA_s)}{N(\dot{m}C_p)}\emptyset_2 \quad (7)$$

which A is the cross-sectional area of the tank (m²), L is the height of the tank (m), N is the number of compartments in which the tank is discritized, ρ_s is the density of the storage material (kg/m³), C_s is the specific heat of the storage material (kJ/kgK), and ε is the void ratio. hv is the volumetric heat transfer coefficient (W/m³K) and at the same time the volumetric heat transfer coefficient, Nusselt number and Reynolds number can be found from the equations below;

$$h_v = \frac{KNu}{D_e^2} \quad (8)$$

$$Nu = 0.437(Re^{0.75})(\Psi^{3.35})(\varepsilon^{-1.62})\{\exp[29.03((log\Psi)^2)]\} \quad (9)$$

$$Re = \frac{\rho V D_e}{\mu} \quad (10)$$

Here, ρ_a is the density of the air (kg/m³), D_e is the equivalent diameter of the storage materials (m), K is the thermal conductivity of the air (W/mK), and Ψ is the sphericity. The pressure loss is calculated with Eq. 11.

$$\Delta P = \frac{fG^2}{\rho_a D_e} \quad (11)$$

which ΔP is the pressure loss (Pa), G is the mass velocity of the air (kg/m²s), f is the friction coefficient.

$$f = 4.466(Re^{-0.2})(\Psi^{0.696})(\varepsilon^{-2.945})\{\exp[11.85(log\Psi)^2]\} \quad (12)$$

The sphericity and void ratio values are obtained from Eq. 13 and 14.

$$\Psi = \frac{a_s}{a_e} \quad (13)$$

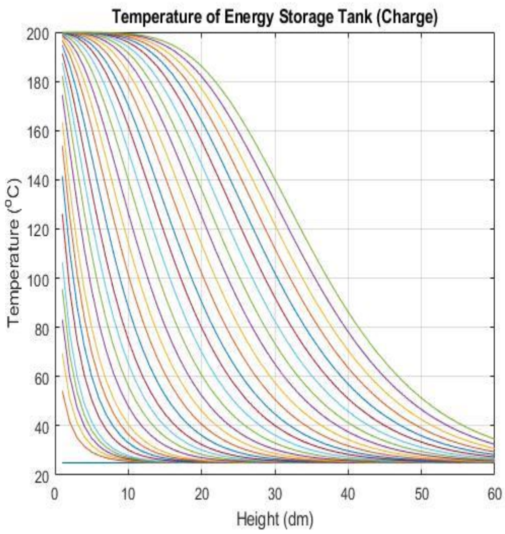
$$\varepsilon = \frac{V_t - V_s}{V_t} \quad (14)$$

In Eq. 13 and 14, a_s is the surface area of a sphere with a volume equal to the volume of the storage material (m²), while a_e is the surface area of the storage material (m²) (Benato, 2017).

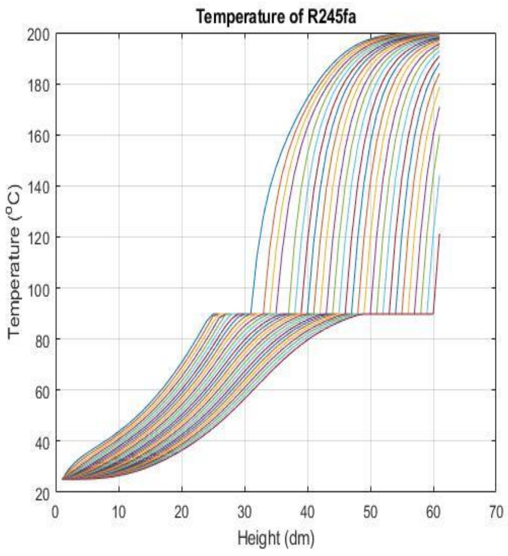
RESULTS

The temperature change in the tank during the charging and discharging processes is investigated according to the height of the tank and time. It is repeated according to different void ratios and sphericity values. During the discharge process the efficiency of the ORC is also investigated. To observe the availability of the energy stored thermally in the tank and then converted into electricity via the ORC, the hourly electrical efficiency is calculated. The most important parameter for the charging process of the Carnot Battery system, which is powered by solar collectors, is the solar radiation. In this study, solar radiation is not considered as a constant and varied according to the day of the year and the latitude of the region. In this context, a hot day of the year and the Ankara (Turkey) are chosen.

The solar radiation reached its maximum value around 12:00 and the sun rays reached the earth from the atmosphere for about 14 hours a day. During this 14-hour period, an effective 8-hour period is selected and the charging process is considered. The temperature profiles are obtained along the height of the tank in the charging process and at different time intervals (Fig. 5).



(a)



(b)

Fig 5. Temperature distribution of the energy storage tank for the charge process (a) and the temperature of the fluid for the discharging process (b)

In the TES tank, it is seen that the temperature decreases as it progresses along the height axis. This shows that thermal stratification is complied with in the simulation. It was also observed that this stratification continued as time passed and the temperature increased over the entire height of the tank. Each of the lines in Fig. 5 represents the temperature lines of the tank at different time intervals. The temperature of the tank from one end to the other increases as time passes during the charging stage. The temperature change of the fluid during discharge is shown in Fig. 5b. While the temperature of the fluid increased until and after the phase change, its temperature remained constant in the phase change region. After the charging process was completed according to different parameters, the discharge process is started. For the discharge process, the working fluid is passed through the tank for a discharge period of approximately 7 hours. While the tank temperature has its maximum temperature at the beginning of the discharge process, it decreased to its minimum temperature at the end of the discharge process as it transfered thermal energy to the working fluid.

The efficiency of the ORC is calculated as the ratio of net energy, which is the difference of the energy obtained in the turbine and the energy consumed in the pump and heat delivered by the thermal energy storage tank to the fluid. In the model, the thermal storage continues to be used until about 10°C above the saturation temperature, depending on the degree of the quality of the working fluid at the turbine inlet. The small increase in efficiency after the 5th hour in the discharge state can be explained by the decrease in the heat energy transferred to the working fluid. The variation of the efficiency of Organic Rankine cycle according to the discharge process hours is given in Fig. 6. The efficiency progressed steadily at 12% for approximately 7 hours.

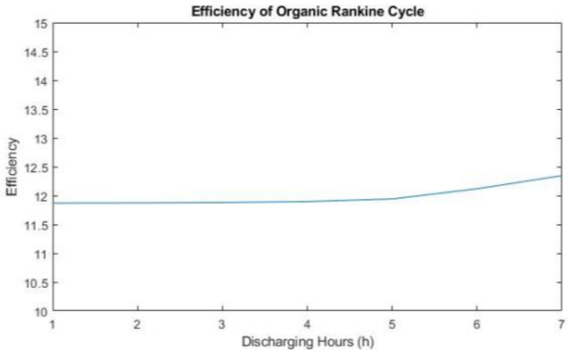


Fig 6. Efficiency of Organic Rankine Cycle according to discharging hours

CONCLUSION

In this study, the thermal storage of solar energy and the generation of electricity from stored energy with ORC are discussed. On the solar side, flat type solar air collectors are used and the working fluid of the solar side is air. On the power side, the working fluid is R245fa. Sensible heat storage on a solar path in Ankara conditions is considered. In the numerical model, the transient solution of the storage tank is considered. In case of discharge, the total efficiency of the system is obtained. According to the results, it was calculated that the electrical efficiency of the system will be approximately 12% in case of discharge. The temperatures of the storage tank with working fluids are obtianed according to the time step.
In the next step of this study, storage with Carnot batteries will be discussed. In this structure, which started to gain importance with the concept of smart cities, the conversion of excess electricity into heat and its storage and then its conversion to electricity in case of demand will be discussed. It is aimed to expand this study with exergy and economic analysis.

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c.The datasets generated during and/or analysed during the current study are not available because [due to the ongoing thesis study] but the authors will make every reasonable effort to publish them in near future.