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Application of Solar Energy for Sensible Thermal Energy Storage in Cascade Tanks

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Abstract **-**Thermal Energy Storage (TES) has emerged as a pivotal technology in the pursuit of sustainable and efficient energy solutions. By storing excess thermal energy during periods of low demand and releasing it during high-demand periods, TES technologies play a crucial role in balancing energy grids, enhancing renewable energy integration, and reducing overall energy consumption. The purpose of this project is to conduct a mathematical model for a cascade sensible thermal energy storage system used for heating water. Different solid thermal storage materials have been employed in order to investigate their performance and storage capacity throughout time. The system is considered lumped and governing heat transfer equations are solve using this approach. The modeling is conducted both in Maple and TRNSYS. Results show that considering heat loss for the tanks can decrease thermal energy storage capacity up to 10kJ. Furthermore, due to short length of the tube and low convective heat transfer coefficient of the air, it is shown that heat loss consideration for the tubes connecting the tanks does not have significant impact on storing capacity.

Keywords: *Thermal Energy Storage; Cascade Thermal Storage; Solar Collector; TRNSYS; Maple*

1. Introduction

In recent years, there has been usually a discrepancy between the thermal energy consumed and the amount required in energy systems[1]. In order to address issue, it is vital to employ thermal energy storage (TES) systems that are both efficient and reliable [2]. Thermal energy storage can be divided into two main types of latent heat storage and sensible heat storage in which, unlike the sensible one, phase change happens in TES material [3]. Latent heat storage exhibits superior thermophysical characteristics and reliability according to having higher energy storage density and the relatively constant temperature maintained during phase transition as well as taking up a smaller space in comparison with sensible heat storage systems. However, the performance of this system is restricted due to the low thermal conductivity of thermal energy storage material implemented within them[4]. In recent years, there have been several studies conducted focusing on the performance of different thermal energy storage system with the main aim of improving their performance. Jain et al.[5] conducted an analysis of various cascade thermal energy storage (CTES) system designs. Their research revealed that a dual-stage CTES system utilizing $NaNO3/NaNO2$ demonstrated superior efficiency in charging compared to alternative setups. Mao et al. [6] explored the thermal dynamics of a packed bed solar energy storage system, experimenting with three distinct PCMs. Their study focused on the effects of variables such as particle size, porosity, and the ratio of height to diameter in the storage tank on both the capacity and efficiency of energy storage. In another study, Prieto et al.[7] investigated the application of PCM in TES systems for concentrated solar power facilities. They introduced a cascade-style PCM storage system and assessed its efficiency against current molten salt systems. Jain et al. [8] explored the impact of storage orientation and shell shape on the melting dynamics of shell and tube-type cascade latent heat storage. They implemented an enthalpy porosity method-based approach to assess and compare various storage configurations for cascade latent heat storage. Cheng et al. [9] proposed a cascaded packed bed cool thermal energy storage (CTES) unit using multiple phase change materials (PCMs). They used different types of PCMs with specific mole fraction to fill 150 spherical capsules. The investigation focused on the influence of HTF flow rate and intake temperature on charging rates, as well as cold and exergy storage, and exergy efficiency. Li et al. [10] formulated a one-dimensional transient model for packed bed CCSU and conducted numerical optimization specifically for charging PCMs enclosed in spherical capsules. various non-dimensional parameters, including the casing diameter, the temperature differential between the initial and final layers during freezing, and the quantity of stages involved. In their experimental arrangement, the natural convection within the melted PCM during the cold charging process was not considered. This approach of integrating multiple PCM stages led to a swifter and more uniform phase transition.

The results obtained from the optimization showed that number of stages in the range 0f 3-6 as well as 25℃ of temperature offset are the optimal values. Thermal storage systems for human comfort in the building have been studied throughout the recent years by many researchers. In another study conducted by Mosaffa et al. [11], they developed a numerical modeling for a multi PCM used for cooling of a building. this thermal energy storage system consisted of some PCM channels in rectangular shape which made the heat transfer fluid able to pass through. In this research, authors evaluated the effects of some parameters including gap of fluid passage and thickness of PCMs with optimization approach. This model was tested in city of Tabriz in Iran and the results obtained showed that the optimum COP of such a system would be 7.0. Yue et al. [12]proposed a mathematical model for a heating system working with a solar collector which used thermal storage system on the basis of zeolite water. In this study, authors proposed a mode in which during the time that irradiation was high, the system could collect high-temperature heat. Results obtained indicated that, in non-heating and heating season, the mean efficiency of collection was 2.8% and 7.4% more than that of a conventional one. Mao et al. [13] presented a numerical model for a PCM-based cascade thermal storage integrated with solar collector for building heating purposes. In this research, they employed three different PCM for the tank and studied the effect of the order of arrangement as well as the ratio of tank diameter to its height on thermal performance of the system and compared the results with that of a conventional thermal energy storage. Their findings showed that, after performing an optimization for the studied system, using such a system would result in 35% decrease in storage time while the rate of thermal storage go up by 42%.

Although there has been valuable research work conducted in the field of TES systems, some research gaps can be found according to the above literature review which holp possibilities for further research as bellow:

- Designing a series of sensible heat storage tanks connected to each other.
- Investigating the effect of using different materials used as thermal storage.
- Using the cascade thermal energy storage system for wall heating or floor heating of a building
- Investigating the applicability of using different systems as the source supplying the hot water, such as solar collector
- Integrating the CTESS with an auxiliary renewable-energy driven heat exchanger in order to supply the heating of a building completely renewable based.

Therefore, the main aim of this project is to develop a mathematical model for a cascade thermal energy storage system which is used for sensible heating of water. The modeling is conducted in Maple and is validated with the simulation TRNSYS. This system can be also used for further research by adding renewable-energy driven components, such as solar collectors.

2. Mathematical model

In this work, a set of cylindrical thermal energy storage tanks are set in series. As can be seen in Fig. 1, heat transfer fluid (HTF), which is water in this project, enters the first tank with a constant temperature of T_{i1}. The gap between HTF tube and the shell of the tank is filled with TES material. Furthermore, the storage tanks inside the wall are surrounded by insulation, and therefore, there is no heat loss from the tank to the surrounding. HTF enters the first tank and gives its heat to the tank and TES material and leaves it with the temperature of T_{o1}. Energy balance for the first tank considering it as a lump system is as below [25, 26]:

$$E_{in} - E_{out} = \frac{dE_{tank}}{dt} \quad (1)$$

$$E_{in} = \dot{m}_w \times C_{p,w} \times (T_{i1} - T_{o1}) \quad (2)$$

$$E_{out} = 0 \quad (3)$$

$$\frac{dE_{tank}}{dt} = \rho_{pcm} \times V_t \times C_{p,pcm} \times \frac{dT_1}{dt} \quad (4)$$

The main assumption in this model is that, due to considering no heat loss, the inlet temperature of HTF for each tank is equal to the outlet temperature of the previous tank. Therefore:

$$T_{i,n} = T_{o,n-1} \tag{5}$$

In this equation, n is the number of n_{th} tank in cascade configuration. Fig. 1 shows the side view configuration of the proposed cascade thermal energy storage which are connected to each other in series and Fig. 2 shows the up view of a single tank system.

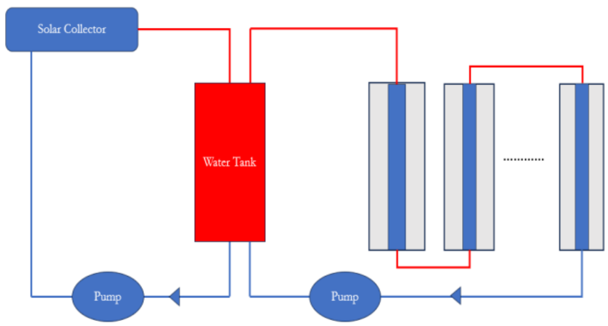

Fig. 1: side view of the cascade thermal energy system

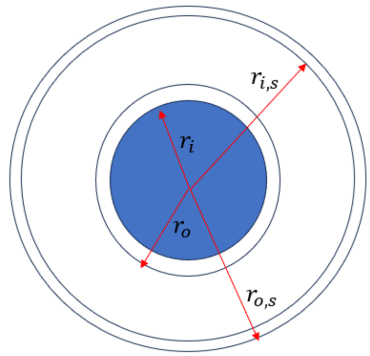

Fig. 2: up view of a single tank

According to the presented figure, energy equation for the nth tank (n>1) will be as below:

$$E_{in,n} - E_{out,n} = \frac{dE_{tank,n}}{dt} \tag{6}$$

$$E_{in,n} = \dot{m}_w \times C_{p,w} \times (T_{i,n} - T_{o,n}) \tag{7}$$

$$\frac{dE_{tank}}{dt} = \rho_{TESM} \times V_t \times C_{p,TESM} \times \frac{dT_n}{dt} \tag{8}$$

For the mentioned equations, considering tank 1, we only have one equation with two unknown parameters which are T_{o1} and T_1, respectively. In order to solve the equation, energy balance equation for a shell and tube heat exchanger has to be applied to each tank. For tank 1, this equation is as follows[16]:

$$Q_{tank1} = \dot{m}_{water}.c_{p,w}(T_{i1} - T_{o1}) = U_1.A_{s1}.LMTD_1 \tag{9}$$

In this equation, A_{s1} is the internal surface area of HTF, U_1 is overall heat transfer coefficient, and LMTD is logarithmic average of the temperature difference. Overall coefficient of heat transfer is calculated according to the following equation:

$$U_1 = \frac{1}{R_{water} + R_{pipe}} \tag{10}$$

In this equation, R_{water} and R_{pipe} are thermal resistance of the layer of the water and pipe thickness. These resistances can be obtained as below:

$$R_{water} = \frac{1}{h.A_{s1}} \tag{11}$$

$$R_{pipe} = \frac{2k_{pipe}\pi L}{ln\left(\frac{r_o}{r_i}\right)} \tag{12}$$

In this equation k_{pipe} is thermal conductivity of pipe material and h is convection heat transfer coefficient of HTF. LMTD for heat transfer occurring between HTF and the tank is calculated according to eq.(13) [17]:

$$LMTD_1 = \frac{(T_{i1} - T_c) - (T_{o1} - T_c)}{ln[(T_{i1} - T_c)/(T_{o1} - T_c)]} \tag{13}$$

The mentioned equations can be applied to the next tanks as well. One thing that has to be notified is that, according to the no heat loss assumption of the tanks, the outlet temperature of HTF for a tank is equal to the inlet temperature of HTF for the next tank. Therefore, we will have:

$$T_{i,n} = T_{o,n-1} \tag{14}$$

For this project, different materials have been tested as sensible thermal energy storage medium for the cascade system. Table 1 shows thermophysical properties of these material [26, 27].

Table 1: Thermophysical properties of different heat storage materials used for the cascade system.

Material	**Density (kg.m^{-3})**	**Specific heat (kJ.kg^{-1}.K^{-1})**
Concrete	2200	0.88
Zeolite	2300	0.915
Silicon Carbide	3210	0.750
Rock	2240	1

3. Results

Different scenarios have been investigated for the proposed cascade system. Results of each case are depicted in terms of tanks temperature as well as the overall energy that can be stored. The details of each scenario can be seen in Table 2.

Table 2: Different scenarios considered for the cascade system.

Num.	**TES material**	**HTF tube material**	**Is heat loss considered?**	**Number of HTF passes**
1	Concrete	Copper	No	1
2	Concrete	Copper	Yes	1
3	Concrete	Copper	Yes	2
4	Zeolite	Copper	No	1
5	Silicon carbide	Copper	No	1
6	Rock	Copper	No	1

For case 1, as can be seen from Fig. 3, the final temperature of each tank reaches the inlet temperature of HTF for tank1 after a while since no heat loss is considered. The slope of temperature change reduces for the next tanks which is due to delay that happens for charging process. Regarding total thermal energy storage of the system, as depicted in Fig. 4, it is capable of storing near to 160 kJ before the temperature of all tanks hits 60 ℃. After this, no temperature change occurs inside the tank, and therefore, no more thermal energy will be stored.

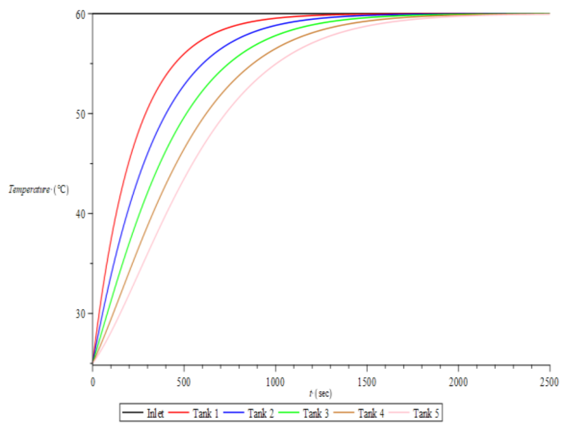

Fig. 3: Temperature distribution for case 1

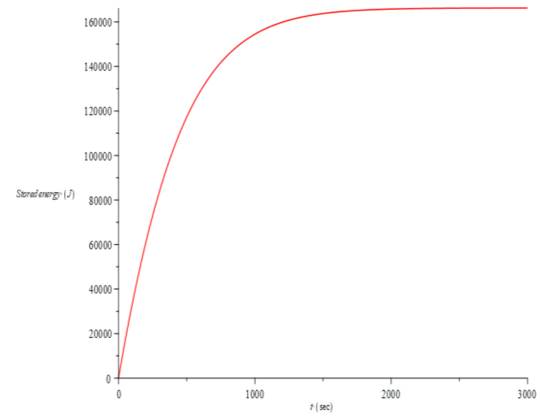

Fig. 4: energy stored by the system for case 1

Fore case 2, according to what Fig. 5 shows, final temperature of none of the tanks reaches 60°C due to heat lass by convection and radiation. Furthermore, this heat loss results in different final temperature for each tank after reaching steady state situation. Moreover, as can be seen from Fig. 6, these heat losses reduce to thermal storage capacity of the whole system by nearly 10 kJ.

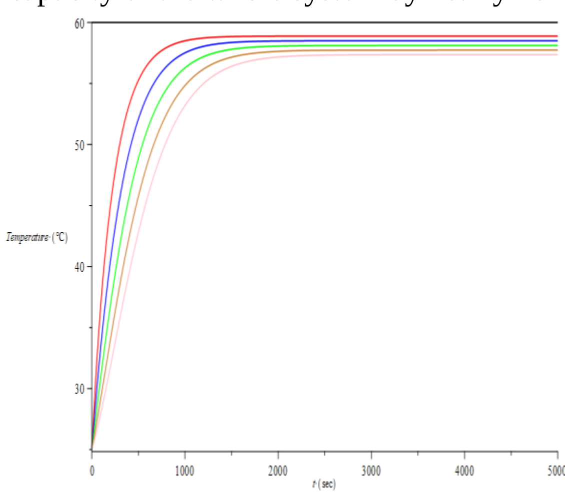

Fig. 5: Temperature distribution for case 2.

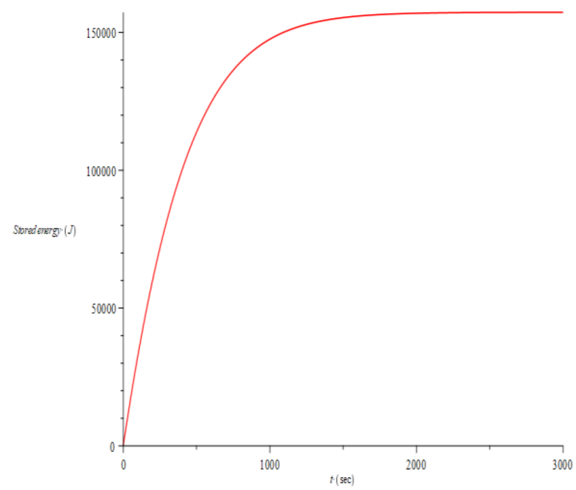

Fig. 6: energy stored by the system for case 2.

For case 3, as illustrated in Fig. 7, increasing the number of HTF tube passes from 1 to 2 not only increases the final stabilized temperature of each tank, but also it decreases the time of reaching steady state condition. Furthermore, Fig. 8 indicates that the increase of the passes can compensate the reduction in thermal energy storage that occurs due to the heat losses.

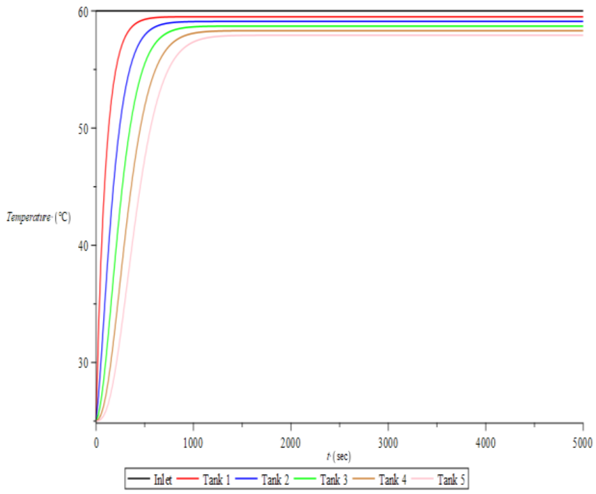

Fig. 7: Temperature distribution for case 3.

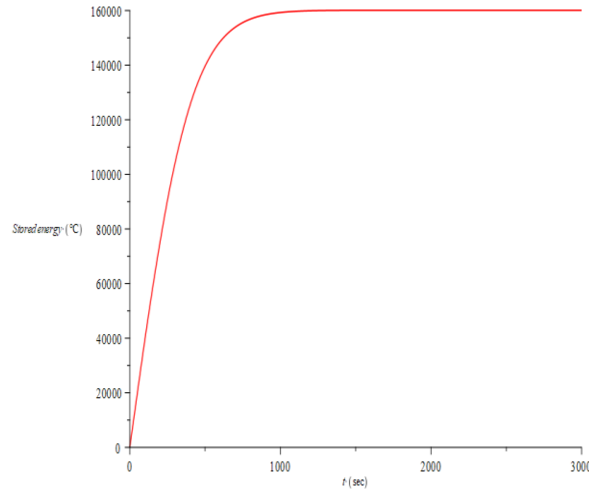

Fig. 8: Energy stored by the system for case 3.

For the next case, a heat loss is considered for the tubes connecting the tanks to each other. Fig. 9 Shows the temperature change for this case. As can be seen, heat loss does not have a significant effect on the change of the inlet temperature of HTF for the next tank. This can be justified due to the length of these tubes. Since the tanks are in a closes distance from each other, therefor the length of these tubes will not be longer than 60 cm. on the other hand, the convective heat transfer coefficient of air is not that much big. Due to the mentioned reasons, air does not affect the temperature change that much through the tube.

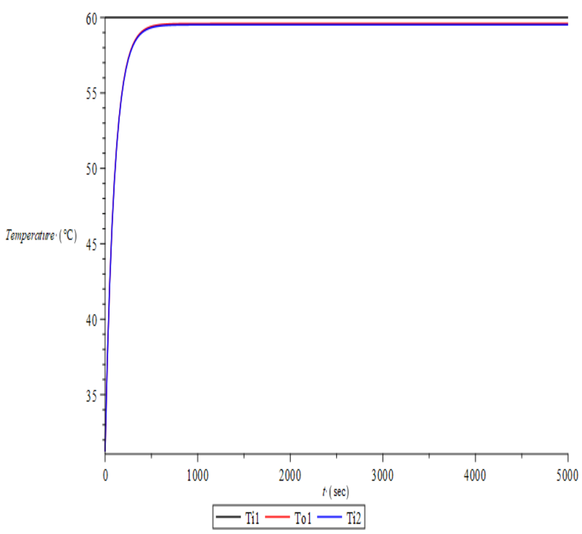

Fig. 9: Temperature change with heat loss for the tube

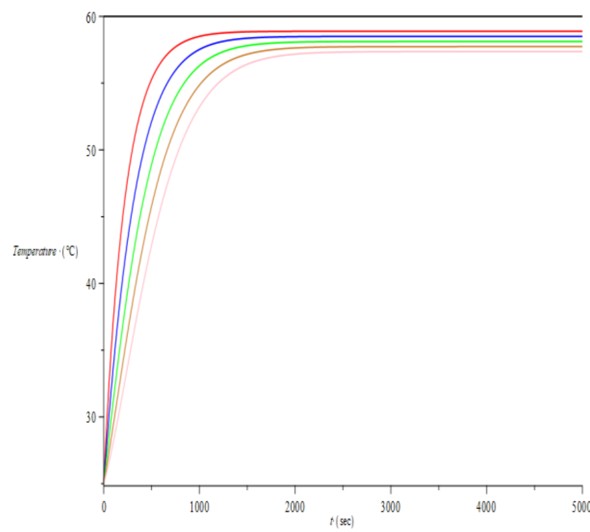

Fig. 10: Temperature distribution for case 4 with heat loss.

For case3, zeolite is considered as sensible TES material for cascade system. Fig. 10 shows temperature change when considering heat loss from the tank. As can be seen, the overall trend is pretty much like the case of concrete. Fig. 11 and Fig. 12 show energy storage capacity of zeolite considering no heat loss and heat loss, respectively. As can be seen by comparing two figures, thermal storage capacity of zeolite decreases by nearly 4000 J in case of considering heat loss.

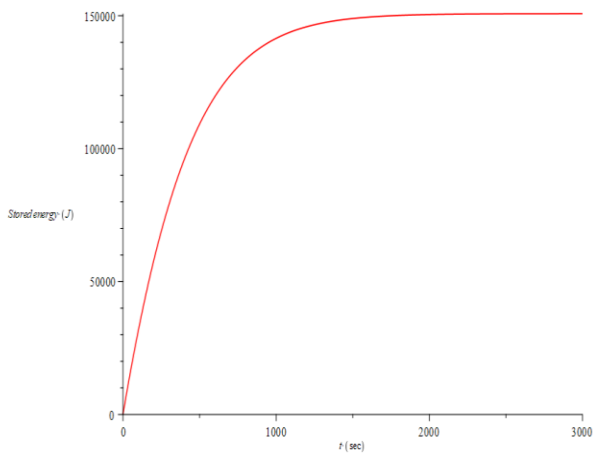

Fig. 11: Energy stored by zeolite with heat loss.

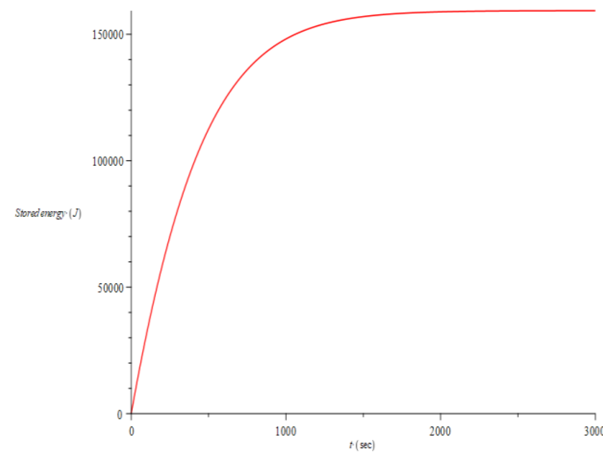

Fig. 12: Energy stored by zeolite without heat loss.

Fig. 13 and Fig. 14 show thermal storage capacity of silicon carbide and rock during the operation time of cascade system, respectively. As can be seen, silicon carbide can store the greatest amount of thermal energy among the four investigated TES materials which is nearly 200 kJ. Or rock, the trend is pretty much similar to that of zeolite.

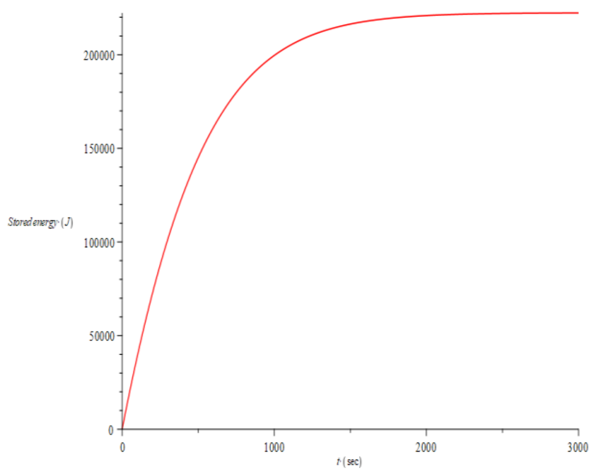

Fig. 13: Thermal energy stored by silicon carbide.

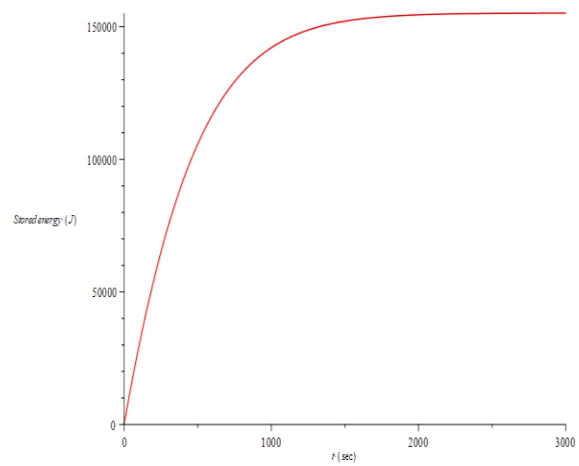

Fig. 14: Thermal energy stored by rock.

In Fig. 15, the effect of change in convective heat transfer coefficient of water is illustrated. The more the amount of water mass flow rate, the greater its convective heat transfer coefficient. As can be seen, decreasing this coefficient leads the temperature of the tank to reach steady state in a longer time, and as this decrease continues, the required time to reach this state gets higher. According to what Fig. 16 shows, changing the material of HTF tube can significantly affect the time that it takes for each tank to reach its steady state situation. For example, using Titanium-based tube would nearly double the time required for stabilization in comparison to Copper of Aluminum.

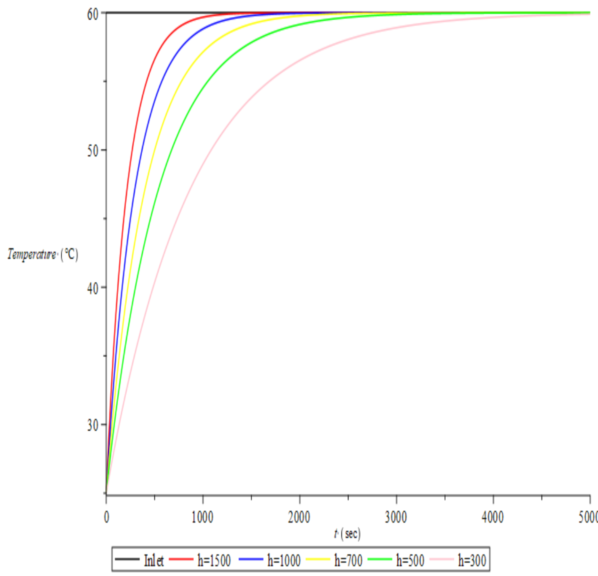

Fig. 15: Effect of HTF convective heat transfer coefficient on tank temperature.

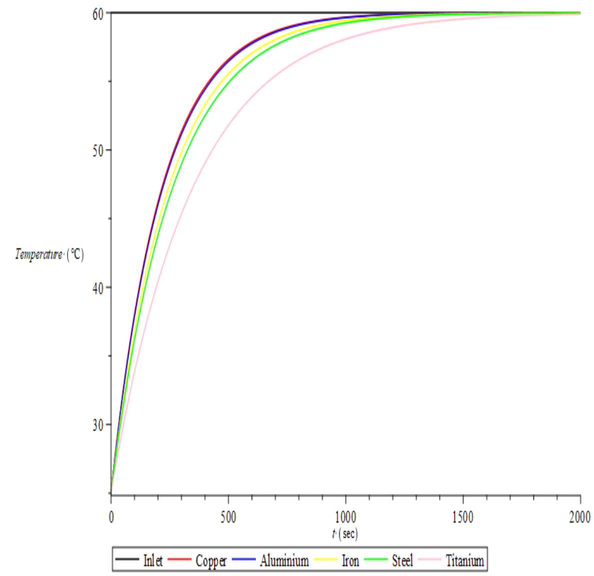

Fig. 16: Effect of HTF tube material on the time it takes for a tank to reach steady state situation.

4. Conclusion

The purpose of this project was conducting a mathematical model for a cascade thermal energy storage system using governing lumped heat transfer equations. The cascade system consists of 6 shell and tube heat exchanger. HTF passes through the tube side, while that shell side is filled with sensible thermal energy storage material which are solid including concrete, zeolite, silicon carbide and rock. During the charging process, this HTF transfers its heat to the tank which is then released during discharging process. Different scenarios, such as considering the tank with or without heat loss or considering heat loss for tubes connecting to sequential tanks to each other, were tested to investigate their effect of thermal storage performance of the system. Obtained results indicated that heat loss in the tanks can decrease the storage capacity by up to 10 kJ which can be compensated by increasing the number of tube passes in each tank from 1 to 2. Furthermore, it was shown that silicon carbide can store the highest amount of thermal energy compared to other materials. Also, it was shown that heat loss occurrence along the connection between two tanks would not have significant impact on temperature change as well as storage capacity of the whole system. Therefore, considering equal temperature for outlet temperature and inlet temperature of two sequential tanks would be reasonable.

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