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Unsteady Numerical Simulation For Studying The Thermocline Phenomenon Inside A Storage Tank For Molten Salt

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ABSTRACT

Thermal energy storage is considered an important component for the solar power plants. Unsteady–one dimension numerical model of single storage tank for molten salt is developed for studying the thermocline phenomenon inside the tank and the effects of the operating variables on this phenomenon. The model simulates the thermal performance of the storage tank including the heat transfer, temperature profile and the thermal losses. The thickness of the thermocline region was studied with time during charging and discharging processes of the storage tank. From the computation results, the effects of operating parameters, such as flow rate and inlet molten salt temperature, on the thermocline region thickness were investigated. The thickness of thermocline zone and its positions inside the tank were studied versus time. The study found that thickness of the thermocline zone affected by the charging flow rate and progressing time, where the ratio of the thermocline thickness to the total tank height increase from 21.5 to 34.5 % with increasing the flow rate from 0.5 to 2 kg/s, respectively. While during discharging process, the thermocline thickness was increased from 0.34 to 1.1 m with progressing time from 1 to 9 hr, respectively. The modeling based on unsteady and one dimension energy balance equations that were solved using EES software.

Keywords: thermocline phenomenon, numerical simulations, molten salt

Introduction

Power generation using concentrated solar thermal energy is one of the most promising renewable energy technologies. It has received a great amount of research and development work in the last decades. In particular, solar trough and solar tower concentrated thermal power generation systems are becoming more reliable and matured, and their cost also has been reduced with the increase of productivity and demand (Price et al., 2002).

It has been widely accepted that further cost reduction of concentrated solar thermal power systems may be accomplished by adding solar thermal storage system that provides heat for prolonged operation of the power plant and thus increases the operational capacity of the power plant and, at the same time, improves the ability of power dispatch (Pitz-Paal et al., 2007). When electricity is needed, the hot salt is pumped to a conventional steam-generator to produce superheated steam for a turbine/generator as used in any conventional coal, oil or nuclear power plant.

Thermal energy storage (TES) has been proved an important sub-system for the solar energy generation systems (SEGSs). A well designed, operated and managed molten salt TES system for SEGS achieves several goals; the first is to release energy for electricity generation after sunset for several hours to meet the power consumption peak without the fossil fuel backup, and make the SEGS more independent of the weather fluctuations over time so that it increases the efficient annual usage of sunlight. The second is to generate higher temperature steam, e.g. over 450 ºC, for turbines so that it raises the Rankine cycle efficiency up to 40%. In comparison, the expensive high-temperature oils generate steam around 390 ºC, which gives only 37% Rankine cycle efficiency.

Molten salt can be employed as thermal energy storage medium (ESM) and as a heat transfer fluid (HTF) to retain thermal energy collected by a solar tower or solar trough so that it can be used to generate electricity in bad weather or at night. It was demonstrated in the Solar Two project from 1995-1999. Two types of TES system, in which molten salt was used as the heat transfer fluid and also served as the energy storage medium have been investigated at Sandia National Laboratories for large scale SEGS application. One of them is the so called two-tank molten salt thermal storage. It was also successfully used for parabolic trough solar plants and tower solar plants as well (Herrmann and Kearney, 2002) and (Pacheco et al., 2002. Though the two-tank TES system was found to substantially benefit the performance of the SEGS plant and made it operate much more economically, the system investment cost was up to $24/kWh (Gil et al., 2004) and (Qiang et al.,2010). To cut costs, the single-tank molten salt TES, in which porous fillers was used as a packed bed in the tank to reduce the
molten salt inventory, was then investigated. A single tank TES used thermocline to separate the hot and cold fluids (Flueckiger et al., 2011). It was estimated that a single tank TES system can save 35% of investment cost compared to a two-tank storage system (Kearney et al., 2003) and (Yang and Garimella, 2010).

Single storage tank is based on maintaining a thermal separation between hot charged molten salt and cold return molten salt. There are various methods of separating the warm and cold molten salt in the same tank. Thermally stratified storage systems take advantage of temperature dependence of molten salt density to store both warm and cold fluid in a single tank. A large temperature gradient exists in a zone separating the warm and cold molten salt, this small thickness of interfacial zone is called a thermocline. In a well-designed stratified storage system the thickness of thermocline zone should be very thin to ensure minimum mixing of the cold and warm molten salt. The maintenance of a thin thermocline in the tank is essential to achieve a high discharging efficiency of the storage system.

The aspect ratio of the thermocline tank geometry was reported by Yang and Garimella (2010) to have a strong influence on the storage performance. For equal internal tank volume, tall and narrow tanks perform considerably better than short and wide tanks due to increased thermal stratification of the molten salt in the former case. For a tank of fixed height, increasing the diameter does not influence thermal stratification, but only scales the maximum internal energy content of the molten salt and filler.

The aim of this paper is to use one-dimensional numerical modeling techniques for simulating the transient one-dimensional fluid dynamics within the thermal energy storage tanks, with the view of improving thermal stratification and the overall efficiency of the system. More specifically, this paper will develop one-dimensional models to quantify the level of thermal stratification in a tank and to investigate the effects of inlet flow rate and temperature on the level of thermal stratification. It is expected that the outcome of this investigation will provide insight into the effects that these parameters have on thermal energy storage, which will be crucial for the maximization of the efficiency of a molten salt storage tank.

Numerical modeling:

The storage tank was modeled as a transient one-dimensional stratified tank with interior heat convection and conduction between tank nodes. The thermal losses from the tank surface as well as mixing at the tank inlet and outlet boundaries were considered in the model. During the charging (heating) period, hot molten salt coming from the solar collector field enters the storage tank from the upper port and exits the storage tank at a lower temperature through the bottom port. The hot molten salt is pushed from the hot layer to the heat exchanger (steam generator), losing part of its thermal energy, and return to the tank with lower temperature at the bottom layer of the tank. The heat exchanger may be located inside or outside the tank. The tank is divided into N equal horizontal segments with equal height as shown in Fig. 1. Three electric heaters were placed vertical inside the tank for the emergency case.

It is a fact that a stratified tank will not remain stratified forever. Conduction through the fluid in the tank will cause the nodes to come into thermal equilibrium. However, the stratification decays more rapidly than at a rate calculated theoretically using the conductivity of MS. One primary cause of this phenomenon is conduction in the tank wall, which is usually made of metal and has a higher conductivity than storage media

Fig. 1: A schematic diagram illustrate dividing the tank into horizontal layers.

The following assumptions are made in the analysis:
• The temperature and flow rate distribution of MS in the TES are assumed to be 1-D.
• The temperature in one segment is homogenous.
• The temperature of the MS and the tank wall are the same at each node.
• No heat losses through the inlet and outlet tubes.
• The molten salt and stainless steel properties are function in temperature

Transmission of the thermal energy to or from the tank layers (node) is accompanying with or without mass flow. The thermal energy flows indicated by the solid arrows, as shown in Fig. 2, represent energy transfer associated with mass flow, and the dashed arrows represent the energy transfer without mass flow.

![Fig. 2: Energy flow in a node.](image)

Taking all the energy flows shown in the Fig. 1 into account, the differential form of the node energy balance is given by the following equation:

\[
\frac{dT_i}{dt} = \left( \frac{\gamma_1 \cdot (KA_{eff} \cdot T_{i-1} - T_i)}{m \cdot C_p \cdot \Delta x} + \frac{\gamma_1 \cdot m_{down}}{m} + \frac{\gamma_2 \cdot m_{th}}{m} \right) T_{i-1} + \left( \frac{\gamma_3 \cdot m_{up}}{m} + \frac{\gamma_4 \cdot m_{dis}}{m} \right) T_i + \left( \frac{\gamma_5 \cdot m_{in}}{m} + \frac{\gamma_6 \cdot m_{out}}{m} \right) T_{i+1} - \left( \frac{\gamma_7 \cdot m_{down}}{m} + \frac{\gamma_8 \cdot m_{dis}}{m} \right) \frac{UA_{ta}}{m \cdot C_p} + \left( \frac{\gamma_9 \cdot m_{in}}{m} + \frac{\gamma_10 \cdot m_{dis}}{m} \right) \frac{Q_{in}}{m \cdot C_p} + \left( \frac{\gamma_11 \cdot Q_{ex}}{m \cdot C_p} \right) + \left( \frac{\gamma_12 \cdot Q_{out}}{m \cdot C_p} \right)
\]

Once it is known which terms must be included in the energy balance node, equation 2 is computed for each node. Each node’s temperature is affected by adjacent nodes. All of the constants and variable can then be grouped together to become a coefficient on each node temperature. Equation 2 would then take the form of equation 3:

\[
\frac{dT_i}{dt} = a_i T_{i-1} + b_i T_i + c_i T_{i+1} + d_i
\]
The coefficient a, b, c and d are computed by determining all constants and variables values in equating 2. However, some of these variables need the temperature of the node to be known, so a simple iteration method was used to calculate these variables and nodes temperature. Energy Equation Solver EES code was built to solve a set of the above partial differential equations for any required numbers of nodes.

The molten salt mixtures vary. The most extended mixture contains sodium nitrate, potassium nitrate and calcium nitrate. It is non-flammable and nontoxic, and has already been used in the chemical and metals industries as a heat-transport fluid, so experience with such systems exists in non-solar applications. The molten salt used in this study is molten salts mixture (60% NaNO3 + 40% KNO3) and served as a HTF and ESM. The physical properties of the molten salt were simulated as function of the temperature using the following equations fitted from the experimental data carried out by ENEA institute.

\[
\rho_{ms} = 2090 - 0.636T_{ms}
\]  
(4)

\[
C_{pms} = 1443 + 0.172T_{ms}
\]  
(5)

\[
\mu_{ms} = 2.083 \times 10^{-2} - 1.0241 \times 10^{-4} T_{ms} + 1.787 \times 10^{-7} T_{ms}^2
\]  
(6)

\[
k_{ms} = 0.443 + 1.9 \times 10^{-4} T_{ms}
\]  
(7)

Density:

Specific heat:

Viscosity:

Thermal conductivity:

The axial heat conduction through the MS fluid and tank wall were included in one term called the effective conduction heat transfer coefficient (\(kA_{eff}\)) which can be evaluated as follows:

\[
kA_{eff} = \frac{K_{st}A_{st} + K_{ms}A_{ms}}{A_{st} + A_{ms}}
\]  
(8)

Where the \(K_{st}\) and \(K_{ms}\) are the thermal conductivity of the stainless steel and the molten salt, respectively. The equation of the overall heat transfer coefficient of the tank wall is computed by determining the resistance value. The \(U_{Ata}\) of the tank wall is computed as follow [12]:

\[
\frac{1}{U_{Ata}} = R_{inside} + R_{wall} + R_{outside} = \frac{1}{h_iA_i} + \frac{\ln(d_i/d_o)}{2\pi h_{seg} K_{st}} + \frac{\ln(d_{ms}/d_i)}{2\pi h_{seg} K_{ms}} + \frac{1}{h_o A_o}
\]  
(9)

The outdoor storage tank may be subjected to two modes of convection; the first is natural convection when the air moves vertically, due to the air density difference near the wall. The second is the forced convection when the air flows horizontally with high speed such as wind. Whether the convection is natural or forced, the heat transfer coefficient outside the tank (\(h_o\)) is calculated from the following the Nusselt number (\(Nu\)) as follow:

\[
h_o = \frac{k * Nu}{L}
\]  
(10)

Where \(k\) is the thermal conductivity of the air at wall temperature and \(L\) is the tank height. For forced convection an empirical relation is used to evaluate the convection coefficient of air flowing around a cylinder kept at constant temperature as follow (Kreith and Bohn, 1997).

\[
Nu = 0.32 + 0.43Re^{0.52}
\]

For natural convection the expression reported by Lienhard (2008) to evaluate the Nusselt number was used as follow:

\[
Nu = 0.678 \left( \frac{Pr}{0.952 + Pr} \right)^{0.25} \left( \frac{Ra}{0.25} \right)^{0.25}
\]  
(11)

Where \(Ra\) is the Rayleigh number

\(Pr\) is the Prandtl number

Where Rayleigh number given by the following equation (Lienhard, 2008):
\[ Ra = \frac{[g/(T_o + 273)](T_o - T)L^3}{K_a \alpha_a} \]  

(12)

Where \( \alpha_a \) is the thermal diffusivity of the air. 
\( T \) is temperature far from the wall surface.

Table 1 lists the storage tank dimensions and material type used in this simulation also listed the insulation material type and its thickness. The equation physical properties of the tank wall material and the insulation material as a function of temperature range used in this study were included in the EES program.

<table>
<thead>
<tr>
<th>Specified of the molten salt storage tank.</th>
<th>Stainless steel AISI 316 Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank material</td>
<td>Stainless steel AISI 316 Ti</td>
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<tr>
<td>Outer diameter</td>
<td>1.916 m</td>
</tr>
<tr>
<td>Tank height</td>
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</tr>
<tr>
<td>Wall thickness</td>
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<tr>
<td>Molten salt height</td>
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</tr>
<tr>
<td>Insulation material</td>
<td>Rock wool</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>0.4 m</td>
</tr>
</tbody>
</table>

Results and Discussion

The simulation began by setting the initial molten salt temperature at 300 °C during charging process. The simulation investigate performance at charging mass flow rate ranging from 0.5 to 2 kg/s, also investigate the performance at charging inlet temperature ranging from 470 to 550 °C with 20 °C step. While the initial temperature of the molten salt have been appointed at 550 °C during the discharging process. The discharging flow rate ranges from 0.5 to 1.25 kg/s. The stainless steel was selected to be the tank material; the rock wool sheet was selected to be the tank insulation. The properties of the stainless steel, molten salt and the insulation material were involved in the program as a variable in its temperature.

The tank divided to 100 horizontal segments and the height of each segment is 0.02 m. the equation solved using the EES code with accuracy of 1.0E-06. The results of the simulation program were analyzed to show the effects of the operating variables on thermocline region inside the storage tank during the charging and discharging processes.

Charging process:

The effect of the operating parameters such as MS flow rate and inlet MS temperature in the thermocline thickness and temperature profile inside the tank during the charging process will be presented in this following part.

The effect of the MS mass flow rate on the thermocline zone and the temperature profile inside the storage tank during the charging process are illustrated in Figs. 3 for flow rate ranging from 0.5 to 2.0 kg/s, respectively.

Increasing the MS mass flow rate from 0.5 to 2.0 kg/s during charging process move the thermocline zone from up to down pushing the cold MS down leading to increase the energy stored inside the tank of the hot MS and decrease the volume of the cold MS. From Fig. 3, at flow rate of 0.5 kg/s the fraction of the hot zone volume is 5 % of the total volume after 4 hr. The thermocline zone occupied 21.5 % of the tank volume and the rest fraction occupied by the cold MS is 73.5 % of the tank volume. While with increasing the charging flow rate to 2 kg/s, it can be observed that the hot zone fraction increased to 51 %, and the thermocline zone occupied about 34.5 % of the tank volume and the rest fraction which occupied by the cold MS become 14.5 %. The previous observation can be attributed to flow high rate of thermal energy to the tank with high charging mass flow rate compare to the low flow rate. For high mass flow rate, the flow disturbance is increased inside the tank. Consequently, the mixing zone is expanded between the cold and hot layers leading to increase the thermocline thickness, which is not preferred for the efficient discharging.

Fig. 4 illustrates the effect of the inlet MS temperature and the charging mass flow rate on the thermocline thickness. From the figure we can see a very small effect of the inlet temperature compare to the mass flow rate. The average thermocline thickness is increased from 0.432 to 0.692 m with increasing the mass flow rate from 0.5 to 2.0 kg/s, respectively. These results confirm that thermal diffusion makes a relatively minor contribution to thermocline degradation while fluid mixing due to current convection and fluid movement are much more important.
Fig. 3: Effect of the inlet MS Temperature on the tank temperature profile for charging flow rate: (a) 0.5 Kg/s (b) 1 kg/s (c) 1.5 kg/s and (d) 2 kg/s after 4 hr charging.

Fig. 4: Effect of the inlet MS flow rate on the thermocline zone thickness at different MS inlet temperature during charging process.

Fig. 5: Temperature profile of the molten salt inside the tank at flow rate of 1 kg/sec.
Fig. 5 shows that there is a thermal gradient, or thermocline, running vertically through the tank. With the increase in the charging time, the thermocline region moves downward, pushing the cold region to the base part and more hot region at the top part of the tank. From the figure, it can be observed that the thermocline zone thickness doesn’t change with time progressing, where the thermocline thickness increase from 26 to 55% of the total height with increasing the charging time from 1 to 6 hr, respectively. Fig. 6 and Fig. 7 show the effect of time progressing during charging on the temperature profile and the thermocline thickness at charging flow rate of 1.5 and 2 kg/s respectively. Fig. 6 and Fig. 7 show the effect on tank temperature profile for a charging mass flow rate of 1.5 and 2 kg/s, respectively.

Fig. 6: Temperature profile of the MS inside the tank at flow rate of 1.5 kg/sec.

Both figures show movement of the thermocline zone downward with increasing the mass flow rate. This effect appear clearly and significant with progressing time at flow rate of 2 kg/s. For flow rate of 1.5 kg/s, the thermocline thickness increase from 27 to 58% of the total height with increasing the charging time from 1 to 6 hr, respectively. While, at flow rate of 2 kg/s, the thermocline zone starts to decay after 5 hours due to the disappearance of the cold zone.

Fig. 7: Temperature profile of the molten salt inside the tank at flow rate of 2 kg/sec

Discharging process:

Effects of the discharging flow rate on the tank temperature profile and thermocline thickness are shown in Fig. 8 for different discharging flow rate and different initial temperature. With increasing the discharging mass flow rate from 0.5 to 1 kg/s the average thermocline thickness increases from 0.48 to 0.56 m, respectively. Fig. 8 (d) shows the effect at discharging flow of 1.25 kg/s after 8 hrs. We can observe a disappearance of the hot zone. Consequently the thermocline zone starts to decay and its thickness start to decrease. The volume of the hot zone in the tank represent 50% of the total volume at flow rate of 0.5 kg/s and this volume decrease to 25% at increasing the flow rate to 0.86 kg/s. From the figure we can observe no effect of the initial tank temperature on the thermocline thickness during the discharging process where the slop of curves is the same of all initial temperature.

The tank temperature profiles during the discharging process are illustrated in Fig. 9 with time progressing at discharging flow rate of 0.86 kg/s. The figure illustrate a decreasing in the temperature to minimum value of 448 °C (cold zone) in the bottom layers and the length of cold zone expand upward with time progressing to reach 57% of the tank height after 10 h. Consequently the temperature of the hot zone, which is 550 °C in the
top layer, was disappeared after this time. Also we can observe an increasing in the thermocline thickness from 0.34 to 1.1 m with time progressing from 1 to 9 hours, respectively. Moreover, it is interesting to see that the thermocline region continues to expand with the discharging time, indicated by the reduced slopes of the temperature profiles. This expanding in the thermocline thickness has bad effect on the discharging process where the mixing between the hottest and lowest layer takes place in a bigger volume reducing the volume of the hottest layers, which are required to generate the steam with the favorite conditions. Increasing in the thermocline thickness may be attributed to two reasons: the first one is the flow of molten salt upward from the coldest layers to the hottest one due to pumping the fluid, the second reason is the thermal diffusion due to the big difference in the temperature value between the hot and cold zone inside the tank.

Fig. 8: Effect of the inlet MS Temperature on the tank temperature profile after 8 hr for discharging flow rate: (a) 0.5 Kg/s (b) 0.86 Kg/s (c) 1 Kg/s (d) 1.25 Kg/s.

Fig. 9: Tank temperature profile with time progress during discharging process (mdis = 0.86 kg/s).

Conclusion:

During the charging process, the effect of the MS mass flow rate has the big contribution on the thermocline thickness compare with the inlet MS temperature. The occupancy of thermocline zone is expanded from 21.5 to 34.5 % of the tank height with increasing the charging mass flow rate from 0.5 to 2 kg/s, respectively. The progressing time has the big effect where it increases the thermocline thickness from 26 to 55 % of the tank height with time progressing from 1 to 6 hour, respectively. The inlet charging temperature has very small effect on the thermocline zone thickness.
For the discharging process the thermocline increase from 0.48 to 0.56 m with increasing the flow rate from 0.5 to 1.25 kg/s, respectively. The thickness of the thermocline zone is effected more with progressing the time of discharging, where the thickness ratio increase from 0.34 to 1.1 m with increasing the progressing time from 1 to 9 hour, respectively. The progressing time has biggest role in expanding the thermocline zone this role significant with the high flow rate for charging and discharging process.

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Nomenclature:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross section area</td>
<td>(m²)</td>
</tr>
<tr>
<td>K</td>
<td>Thermal conductivity</td>
<td>(W/m °C)</td>
</tr>
<tr>
<td>ṁ</td>
<td>Mass flow rate</td>
<td>(kg/s)</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td>(kg)</td>
</tr>
<tr>
<td>Cp</td>
<td>Specific heat</td>
<td>(J/kg °C)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>(s)</td>
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<tr>
<td>Q</td>
<td>Heat energy</td>
<td>(J)</td>
</tr>
<tr>
<td>U</td>
<td>Overall heat transfer coefficient</td>
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<tr>
<td>D</td>
<td>Diameter</td>
<td>(m)</td>
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<tr>
<td>h</td>
<td>Heat transfer coefficient</td>
<td>(W/m² °C)</td>
</tr>
<tr>
<td>R</td>
<td>Heat resistance</td>
<td>(m² °C/W)</td>
</tr>
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</table>

Subscripts:

a  Air  
el electric  
amb Ambient  
ms Molten salt  
st Stainless still  
dis Discharging  
ch Charging  
out outlet  
in inlet  
ins insulation material  
seg segment

Greek latter:

α  The thermal diffusivity of the air.  (m²/s)  
ρ  density.  (kg/m³)  
μ  viscosity  (pa. s)

References


