Analytical and Experimental Analysis of Thermocline Thermal Energy Storage Tank

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ABSTRACT: Thermal energy storage systems are essential to fulfill the mismatch between thermal energy supply and energy demand. In particular, it is necessary in solar thermal energy systems because of the discontinuous nature of solar radiation. Thermocline energy storage systems have higher thermal efficiency and relative lower cost. The effectiveness and cost of thermal energy storage systems are the subject of continuous research for the improvement. A major issue in this system, is achieving stable thermal stratification and the destruction of thermocline during charging and discharging process. An analysis of the stratification in thermocline cylindrical tank storage systems is presented in this paper using an energy balance model and validate with experimental data. Also experimental analysis is conducted at a different mass flow rate and at different operating condition. The degradation of thermocline during static mode has been studied experimentally. The thermocline degradation is less due to new inlet design, aspect ratio 3, lower thickness and Richardson number 6.44 obtained.

Keywords: Thermocline, Energy balance model, Water tank.

I. INTRODUCTION

Solar thermal energy systems have the disadvantages of dependency on solar radiation in order to operate. Since solar radiation is intermittent thermal energy storage (TES) is needed to make up for the absence of sun and/or sub-optimal weather. TES using sensible heat with fluids are done in either one tanks or two tank systems. In single tank systems due to mixing of hot and cold fluids the available water temperature is lower than temperature available from the heat source. To overcome this problem the two tank system uses one tank to set of cold fluid and another for the set of hot fluid. Two tank system requires double tank-age volume for a given amount of water in storage, thus increasing the cost and
complexity of the storage system. Therefore, in order to obtain the maximum efficiency of stored energy and resulting output similar to two tank system within a single tank, thermal stratification technology has developed in recent years. [1] In stratified thermocline storage, mixing of hot and cold fluid is prevented, by the hot water which has lower density will float on the top of the cold water which has a higher density initially present in the same tank. When used with compatible with solar collector thermocline thermal energy storage tank systems offer advantages of higher collector efficiency due to sup-ply of cold water to collector and good quality of water temperature from the outlet of the tank to the load. On the other hand, decreasing the utilization hours of the auxil-iary energy supply, therefore improving efficiency of the whole systems. Fully stratified storage water tank the en-heat loss within the tank. energy storage efficiency increased up to 20 %. [2] The mixing layer between hot and cold fluid known as thermo-cline region. Thermocline is a zone where the temperature changes rapidly with depth of the tank. It separates hot and cold fluid in the same tank. It’s built as a thermal barrier because of gravity and buoyancy effect i.e. density difference. [2]

In order to maintain the stable vertical temperature gra-dient mixing should be minimized. The location and geometry of the inlet port is very important. Inlet and outlet ports are near the end walls and flow is directed towards these walls getting better results of stratification. [3] Richardsons number is calculated using tank diameter as the character-istic length and the tank average velocity. The inlet geometry starts to influence on thermal stratification in storage tank for Richardson number below 3.6. [4] Three different types of inlet having the same opening area were in-vestigated, in which impingement inlet with diffuser plate has the good performance to avoid mixing of hot fluid and cold fluid. [5] Diffusers are used to streamline the flow and equally distribute the hot water over top of the cold wa-ter. In this range perforated diffuser had the best perfor-mance among the other type of diffusers. [5] Due to poor inlet designs it impacts on thermal stratification. [6] There are several ways to enhance the stratification by using baffles, diffusers and stratifiers. Baffles are used to redirect the inlet jet or obstacle in order to mixing. The perforated baffle near the inlet performed the best in comparison to other configuration. Diffusers is a device that forces the inlet jet to flow through large area, with reduces the fluid speed ul-timately reducing mixing within the tank. Stratifiers delivers the incoming fluid into layer with the same temperature of water present in the tank.

Stratification of water inside the tank is dependent on following factor such as the tank Geometry, tank size, tank aspect ratio H/D for cylindrical tanks, dimensionless num-bers such as Reynolds, Richardson, and Modified Biot number and material of the tank. The tank with sharp corner has the highest degree of thermal stratification. The storage capacity of the sphere and barrel are the best. The thermal energy storage efficiencies of the sphere, barrel and cylinders are 72.69 %, 72.46 % and 69.56 % at 12 hours time interval. [7] In a vertical tank mixing is restricted near the inlet port compare to horizontal tank, the stratification efficiency of vertical tank is higher than horizontal tank, hence the vertical orientation is the efficient design of storage tanks. [8] Heat loss through the walls and insulation to the ambient is the major effect of degradation of thermocline in stratified storage tank. [1] The degradation of thermocline is due to radial heat losses, axial wall con-duction and thermal diffusion within the fluid between hot and cold fluid zones. Tank having smaller wall thickness, lower thermal conductivity and better insulation improves the stratification. [9] Insulating the tank by lining the inte-rior of the tank with any low thermal conductivity material fitted with fluid improve the stratification. [10]

Stratification improves with increasing aspect ratio (height to diameter) of the tank. An aspect ratio between 3-4 is compromise reasonable. [3] The thermal diffusion decreases with the increase in the length of the tank. The surface area to volume ratios of the tanks increase with an increase in the aspect ratio. The thermal stratification proportional to surface area to volume ratio of the tank. The thermal degradation of thermoclines depends upon the heat capacity ratio. When the heat capacity of fluid is much higher than the heat capacity of tank material the thermocline degradation is negligible. The heat capacity ratio increases with Length to thickness ratio, hence thermal stratification increases. No significant thermal stratification is observed at Length to thickness ratio greater than 200. [11] For discharge cycles in which thermocline zone is either partial or total extracted. If no thermocline is ex-tracted, efficiency after a second process is 77 % compared with the 50 % thermocline is extracted 97 % obtained. [12] Present paper contains heat loss calculation procedures for the cylindrical storage tank, Energy balance model with validation, and experimental set up design and its perfor-mance on thermocline effect.

II. ANALYTICAL MODELING OF THERMOCLINE STORAGE TANK

Analytical modelling is the representation of real life problem in the form of mathematical equations. Development of mathematical modelling is important to study the thermocline effect within the tank. By using energy balance model analysis of thermal energy storage on the stor-age tank is done.

The energy balance model is based on conservation of ener-gy, In this system, the change in the internal energy of the storage tank is equal to energy added to the tank from heat source minus energy extract to the load minus storage.[13]

\[(V \cdot Cp) \cdot (V \cdot Cp) \cdot dt = q_{load} \cdot (U \cdot A) \cdot (T_l - T_a)\]  (1)
The above equation is unstedy state because thermal en-ergy in the storage tank changes with respect to time. LHS of equation indicates that the change in internal energy of the storage tank with respect to time and the RHS of the equation where, $q_u$ is the rate of useful heat gain from source, $q_l$ is the rate of energy discharged to load and stor-age heat losses within the tank.

In the above energy balance by considering the heat loss due to conduction between hot and cold fluid effect is taken within the storage tank, and the energy balance model is modified.

$$[(V C_p)_h + (V C_p)_l] \frac{dT}{dt} = q_u - q_{load} - hA(T_i - T_a)$$

$$A(T_i^d - T_a^d) kA \frac{dT}{dx} \tag{2}$$

The above equation is used to determine the tempera-ture profile within the storage tank for static mode and dy-namic mode. These equations are expressed in the finite difference form under the assumption are

One dimensional heat flow i.e. axial direction

Hot water can enter in a storage tank at top section when $T_{f_0} > T_H$

No flow occurs when $T_{f_0} < l_1$

Internal heat generation is absent

In thermocline storage tank the temperature of the fluid varies from the bottom to top of the tank. Stor-age tank is divided in n number of nodes and writing down the energy balance equa-tion on each node.

As shown in fig. two node is taken for the study and the energy balance equation is writing down as equa-tion no. 3 and 4.

The hot water is added from the top of the tank, same amount of water extracted from the bottom of the tank called charging process of the tank.

The hot water is extracted from the top of the tank, same amount of water make up from the bottom of the tank called as discharging process of the tank.
Above differential equation to be solved simultaneously for the unknown temperature. To solve energy balance equation, the heat losses occur in the tank by conduction, convection and radiation calculation is required. In the next section the heat loss calculation in a cylindrical tank has been discussed.

2.1 Heat loss calculation in a cylindrical tank

Heat loss occurs in a cylinder tank by conduction, convection and radiation through the wall. In this subsequent section each of these modes are discussed.

2.1.1 Conduction through the walls, roof, and bottom

Heat transfer by conduction from the cylindrical walls calculated using following equation. \(^{[14]}\)

\[
Q = \frac{2 \, L (T_1 - T_2)}{\ln \frac{2}{r_1}}
\]

Wall thermal resistance (R) is

\[
R = \frac{\ln \frac{2}{r_1}}{2 \, L}
\]

Where \(T_2\) is the tank wall outside temperature and \(T_1\) is the tank wall inside temperature. The conduction heat transfer at the bottom and top of the cylindrical tank can be treated as plane walls.

\[
Q' = \frac{2 \, r^2 \, (T_1 - T_2)}{t}
\]
2.1.3 Natural convection inside cylindrical tanks

Natural convection inside the cylindrical tank will occur due to buoyancy effect caused by variation of temperature of the fluid along the height. Because of the buoyancy low density fluid rises towards the top of the tank. Lin and Akin performed an experimental study to calculate the pseudo-steady state natural convection heat transfer inside a vertical cylinder. [15]

\[ R = \frac{t}{2\pi r^2} \]

Where \( t \) is the thickness of the tank, and \( r \) is the radius of the inner tank.

2.1.4 Heat losses due to radiation

Heat losses occur within the tank calculated by using equation no. 5-14

\[ Q_{\text{radiation}} = \sigma e A (T_1^4 - T_2^4) \]

Where all temperatures are in Kelvin. Heat losses occurs within the tank calculated by using equation no. 5-14.

In next section validation of energy balance model is discussed.
2.2 Validation of model for static mode

The tank was first filled with cold water then hot water is added from the top side of the tank till half the volume of cold water is displaced by hot water. The temperature profiles at various time intervals are determined for insulated storage tank (MS-I). Tank diameter = 260 mm, Tank length = 780 mm, Wall thickness = 1 mm

![Temperature profile (Static mode)](image)

Figure 2: Predicted temperature profiles for 3 hrs (static mode)

To visualize the thermocline stability effect and movement during the static mode, non-dimensional temperature data points along the Y axis and non-dimensional height on X axis plotted in the cylindrical tanks for 3 hrs. time interval. % Error for 3 hr model= 5.77 % compare with experimental data.

2.3 Validation of model for Dynamic mode

Initially the tank was first filled with cold water then hot water is added from the top side of the tank at the flow rate of 11.1 lit/min and at the same flow rate cold water is extracted from the bottom of the tank. The temperature profiles at various time intervals are determined for insulated storage tank. Tank diameter = 580 mm Tank length = 1000 mm Wall thickness = 2 mm Flow rate = 11.1 lit/min

![Temperature profile](image)

Figure 3: Predicted temperature profiles for 6 min (Dynamic mode)
In order to visualize the thermocline stability effect and movement during the dynamic load, temperature data points along the Y axis and non-dimensional height on X axis plotted in the cylindrical tanks for 6 min. time in-terval. % Error for 6 min. model= 0.82 % compare with experimental data.

Analytical method is very useful to predict the different effects which is useful for design the thermal energy storage tank. In next section, Thermocline effects is studied experimentally in details.

III. EXPERIMENTAL SET UP AND APPARATUS

The vertical circular cylinder of diameter 505 mm and length 1510 mm were used in the study. Suitable inlet (for charging) and outlet (discharging) connection is provided in the tank. 50 mm thickness of glass wool mats having 0.033 thermal conductivity is provided on the cylindrical tank. Flow rate measured with calibrated rotameter. To measure the temperature of fluids at different location RTD are used within the tank. Figure shows the experimental set up to study the thermocline effect.

Figure 4: Schematic of experimental set up

3.1 Specification of the tank

Water storage tank capacity =300 kg=Volume of tank

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<th>Sr No.</th>
<th>Specification</th>
<th>Size/Properties</th>
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<td>1</td>
<td>Height (mm)</td>
<td>1510</td>
</tr>
<tr>
<td>2</td>
<td>Diameter (mm)</td>
<td>505</td>
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<tr>
<td>3</td>
<td>Thickness of Tank (mm)</td>
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<tr>
<td>4</td>
<td>Aspect ratio</td>
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<tr>
<td>5</td>
<td>Glass wool insulation thickness (mm)</td>
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</tr>
<tr>
<td>6</td>
<td>Thermal conductivity (W/m k)</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Figure 5: Storage tank model
3.2 Specification of RTD trees

RTD having: High output signal, greater sensitivity to small temp. change, higher accuracy, stability and repeatability

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Specification</th>
<th>Size/Properties</th>
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<tr>
<td>1</td>
<td>Wire construction</td>
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<tr>
<td>2</td>
<td>Distance between 2 RTD(mm)</td>
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</tr>
<tr>
<td>3</td>
<td>Angle Between 2 RTD</td>
<td>30 degree</td>
</tr>
<tr>
<td>4</td>
<td>Sensor Length(mm)</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>Wire Length(mm)</td>
<td>2000</td>
</tr>
</tbody>
</table>

3.3 Experimental investigation

To determine heat losses occurs within the tank, initially the tank was filled with hot water with uniform temperature. The drop of temperature at various locations measured various time intervals. In static mode analysis of thermocline effect, initially the tank is filled with cold water then hot water is added from the top of the tank till half the volume of cold water is displaced by hot water. The temperature profiles at various time intervals are determined. In dynamic mode analysis of thermocline effect, the tank is filled with cold water, and hot water is added at some mass flow rate from the bottom of the tank and cold water is drawn from the bottom of the storage tank. The process of simultaneous charging and discharging cycle is simulated when hot water is added from the top of the tank at the same rate cold water is drawn from the tank and hot water is drawn from the top of the tank to the load at the same rate cold water is added from the bottom of the tank. In both operation mode the axial temperature distribution of the storage fluid, inlet and outlet temperature of the fluid, and flow rates are noted at various intervals of time.
IV. RESULTS AND DISCUSSIONS

4.1 Influence of heat loss on thermal stratification

Initially tank filled with 60 °C uniform temperature. At different time interval heat loss from the side of the tank, which creates a downward flow along the tank wall. Due to presence of downward flow the colder fluid accumulates at the bottom of the part of the tank. In this way the buoyancy driven flow gradually builds up thermal stratification in the tank. Also from Fig.8, there is almost no temperature stratification in 3/4 th of the tank i.e the temperature difference is very small. Hot water filled in tank requires approximately 60 hours to reach to ambient temperature.

4.2 Degradation of thermocline during static mode

In static mode the half of the tank filled with hot water at 60 °C and half of the filled with cold water 38 °C. At different time interval the temperature profile shows that the thermocline degrades due to heat loss to the surrounding and the heat transfer to liquid by conduction as shown in Fig.9. Average reduction in temperature of hot water is 10 °C after 8 hours.

4.2.1 Storage efficiency of the tank
ACKNOWLEDGEMENTS

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The efficiency of the mixed storage tank and thermo-cline storage tank is plotted against different time interval for 50 kg/hr mass flow rate. As shown in fig 10, efficiency of the tank are after 4 hr for Mixed tank efficiency = 36.9 % and thermocline tank efficiency= 47.5 %. Efficiency for thermocline tank is higher by 10.6 % compared to mixed tank storage systems.

V. CONCLUSIONS

The analytical model is capable of capturing the thermocline phenomena in cylindrical storage tank. Effect of stratification during static mode and charging mode is an-alyzed by using energy balance model and validated with experimental data from research paper. Thermocline stor-age tank has 10-15 % higher thermal storage efficiency compared to mixed storage tank for the same load pro-file. The degradation of thermocline during static mode has been studied experimentally. The thermocline degradation is less due to new inlet design, aspect ratio 3, lower thick-ness and Richardson number 6.44 obtained.

REFERENCES


