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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 stratifi-cation 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 condi-tion.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.

Nomenclature

D	Diameter of the storage tank, m
L	Length of the storage tank, m
h	Heat transfer coefficient, W=m2oC
Cp	Specific heat,kJ=kgoC
k	Thermal conductivity, W=moC
T	Temperature of water, oC
Tw	Temperature of wall ,oC
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
Bim	Modified Biot number
	Density, kg=m3
t	wall thickness of the storage tank, m

Subscript

l	layer
o	outside
a	Ambient
i	intial
f	fluid

Abbreviations

TES	Thermal Energy Storage
HTF	Heat transfer fluid

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-optional 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 sys-tem 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 mix-ing layer between hot and cold fluid known as thermo-cline region. Thermocline is a zone where the tempera-ture 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]

Inorder to maintain the stable vertical temperature gra-dient mixing should be minimized. The location and geom-etry 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 geome-try starts to influence on thermal stratification in storage tank for Richardson number below 3.6. [4] Three differ-ent 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 baf-fles, diffusers and stratifiers. Baffles are used to redirect the inlet jet or obstacle in order to mixing. The perforated baf-fle 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.Stratifies 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 ther-mal 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 stor-age tanks. [8] Heat loss through the walls and insulation to the ambient is the major effect of degradation of ther-mocline 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 ra-tio increases with Length to thickness ratio, hence thermal stratification increases. No significant thermal stratifica-tion 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. Develop-ment of mathematical modelling is important to study the thermocline effect within the tank. By using energy bal-ance model analysis of thermal energy storage on the stor-age tank is done.

The energy balance model is based on conservation of en-ergy, 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 Cp)l+(V Cp)t] dT/ dtl = qu qload (U A)t(Tl Ta) (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 balnce model is modified.

$$[(V C_p)_l + (V C_p)_t] \frac{dT_l}{dt} = q_u \quad q_{load} \quad hA(T_l \quad T_a) \quad @t$$

$$A(T_l^4 \quad T_a^4) \; kA \quad @x \quad (2)$$

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$T_{fo} > T_{l1}$

No flow occurs when$T_{fo} < l1$

Internal heat generation is absent

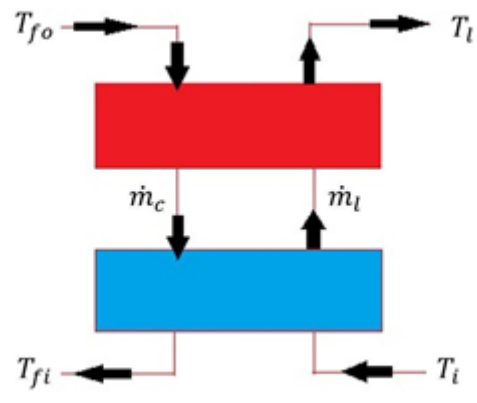

Figure 1: Analysis of a thermally stratified sensible heat storage

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 equationon 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 bottomof the tank called as 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.

$$(\rho V C_p)_{e1}\frac{dT_{l1}}{dt} = \dot{m}C_p(T_{fo}-T_{l1})-\dot{m}_{load}C_p(T_{l1}-T_{l2}) - T_a) - hA(T_l - T_a) - \sigma\epsilon A(T_l^4 - T_a^4) - kA\frac{\partial t}{\partial x} \quad (3)$$

$$(\rho V C_p)_{e2}\frac{dT_{l2}}{dt} = \dot{m}C_p(T_{l1}-T_{l2})-\dot{m}_{load}C_p(T_{l2}-T_{li}) - hA(T_{l2} - T_a) - \sigma\epsilon A(T_{l2}^4 - T_a^4) - kA\frac{\partial t}{\partial x} \quad (4)$$

Above differential equation to be solved simultane-ously for the unknown temperature.To solve energy bal-ance equation, The heat losses occur in the tank by con-duction, 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, con-vection and radiation through the wall.In this subsequent section each of there modes are discussed.

2.1.1 Conduction through the walls, roof, and bottom

Heat transfer by conduction from the cylindrical walls cal-culated using following equation. [14]

$$Q^{-} = \frac{2\ L(T_1\ \ T_2)}{\ln\frac{r_2}{r_1}} \quad (5)$$

Wall thermal resistance (R) is

$$R = \frac{\ln\frac{r_2}{r_1}}{2\ L} \quad (6)$$

Where T2 is the tank wall outside temperature and T1 is the tank wall inside temperature. The conduction heat transfer at the bottom and top of the cylindrical tank can be

treaated as plane walls.

$$Q^{-} = \frac{2\ r^2\ (T_1\ \ T_2)}{t} \quad (7)$$

With R equation:

$$R = \frac{t}{2\pi r^2 \kappa} \quad (8)$$

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

2.1.2 External convection

External convection for a TES tank varies based on the location where the tank is placed due to the variations in wind, and ambient temperature. For all the cylindrical tanks [14],

$$D \geq \frac{35L}{{Gr_L}^{1/4}} \quad (9)$$

Therefore the cylindrical tank wall consider as a vertical plate for Ra between 10^4 and 10^{13} , and the Nusselt number is as follows,

$$Nu = [0.825 + \frac{0.387{Ra_l}^{1/6}}{[1 + (\frac{0.492}{Pr})^{9/16}]^{8/27}}]^2 \quad (10)$$

The Ra denotes the Rayleigh number and subscript l is the characteristic length is nothing but the height of the cylinde.

2.1.3 Natural convection inside cylindrical tanks

Natural convention 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 towords the top of the tank. Lin and Akin performed an experimental study to calculate the pseudo- steady state natural convection heat transfer inside a verti- cal cylinder. [15]

$$L = 6\frac{volume}{surface\ \ area} = D\,[\frac{3(\frac{H}{D})}{1 + 2(\frac{H}{D})}] \quad (11)$$

Rayleigh number and geometrical aspects are influence natural convection inside the tank .Prandtl number has no significant effect on natural convection . The Nusselt number for inside cylindrical tank:

$$Nu = 0.519Ra^{0.255} \quad (12)$$

The Rayleigh number is calculated as,

$$Ra_L = \frac{\rho g \beta (T_s - T_c) L^3}{\nu^2} \quad (13)$$

2.1.4 Heat losses due to radiation

$$Q_{radiation} = \sigma \epsilon A (T_l^4 - T_a^4) \quad (14)$$

Where all temperature 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

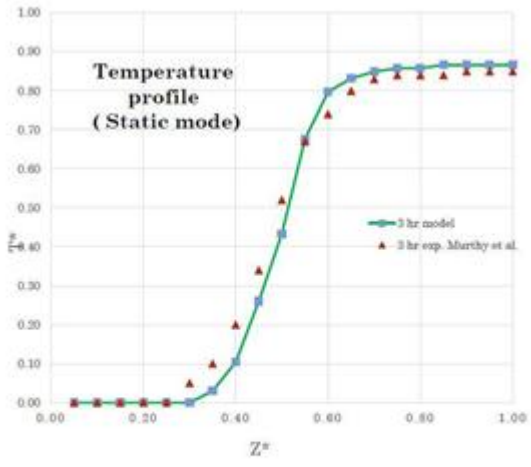

Figure 2: Predicted temperature profiles for 3 hrs (static mode)

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

2.3 Validation of model for Dynamic mode

Intially 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 insu-lated storage tank. Tank diameter = 580 mm Tank length =1000 mm Wall thickness = 2 mm Flow rate = 11.1 lit/min

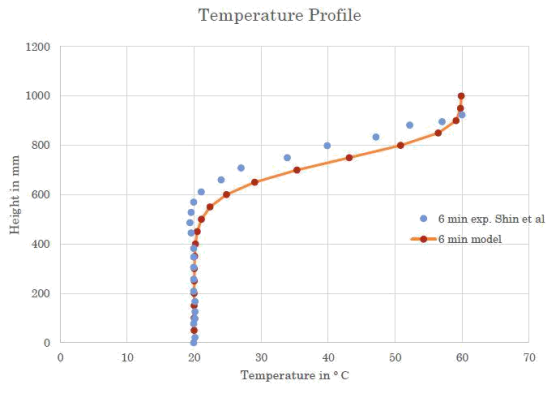

Figure 3: Predicted temperature profiles for 6 min (Dy-namic mode)

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 differnt effects which is useful for design the thermal energy stor-age 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.

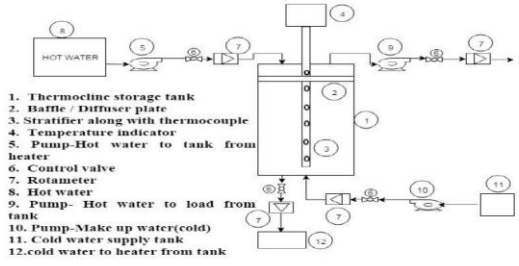

Figure 4: Schematic of experimental set up

3.1 Specification of the tank

Water storage tank capacity =300 kg=Volume of tank

Table 1: Specification of the tank

Sr No.	Specification	Size/Properties
1	Height (mm)	1510
2	Diameter(mm)	505
3	Thickness of Tank(mm)	1.6
4	Aspect ratio	3
5	Glass wool insulation thickness(mm)	50
6	Thermal conductivity(W/m k)	0.033

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 2: Specification of RTD trees

Sr No.	Specification	Size/Properties
1	Wire construction	3 wire
2	Distance between 2 RTD(mm)	125
3	Angle Between 2 RTD	30 degree
4	Sensor Length(mm)	125
5	Wire Length(mm)	2000

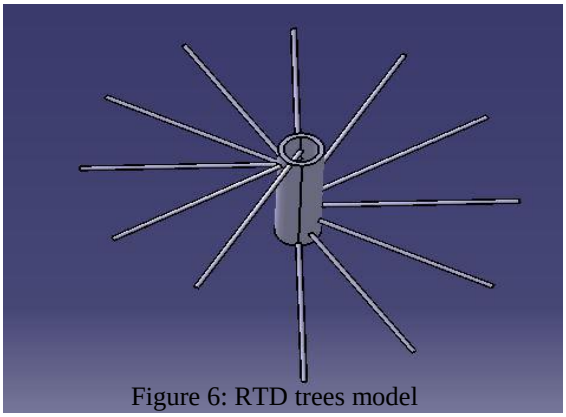

Figure 6: RTD trees model

3.3 Experimental investigation

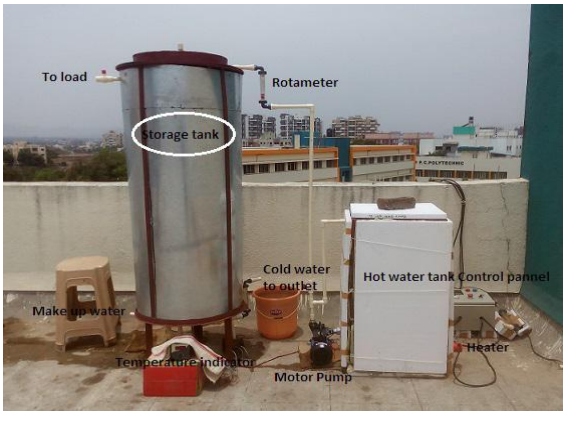

Figure 7: Actual experimental set up

To determine heat losses occurs within the tank , in-tially the tank was filled with hot water with uniform temperature. The drop of temperature at various loca-tion measured various time interval. In static mode analysis of thermocline effect,initially the tank is filled with cold waterthen 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 at the same rate 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 distribu-tion of the storage fluid, inlet and outlet temperature of the fluid, and flow rates are noted at various inter-vals of time.

IV. RESULTS AND DISCUSSIONS

4.1 Influence of heat loss on thermal stratifica-tion

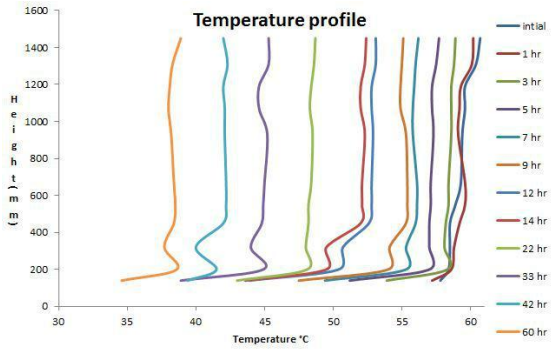

Figure 8: Influence of heat loss on thermal stratification

Initially tank filled with 60 ^{o}C uniform temperature. At different time interval heat loss from the side of the tank , which creats a downward flow along the tank wall. due to presence of downword flow the colder fluid accumulates at the bottom of the part of the tank.In this way the buoy-ancy driven flow gradually builds up thermal stratification in the tank. Also from Fig.8 , there is almost no tempera-ture 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 wa-ter at 60 ^{o}C and half of the filled with cold water 38 ^{o}C. At differnt time interval the temperature profile shows that the thermocline degrades due to heat loss to the surround-ing 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.

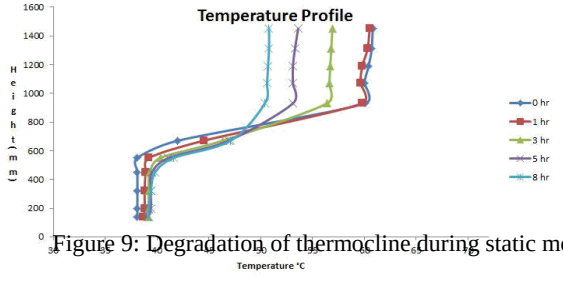

Figure 9: Degradation of thermocline during static mode

4.2.1 Storage efficiency of the tank

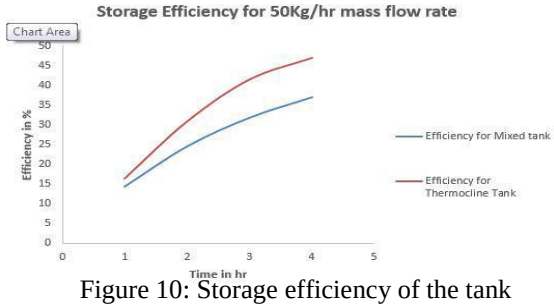

Figure 10: Storage efficiency of the tank

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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 ther-mocline 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.

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