Solar Energy Vol. 49, No. 4, pp. 273–277, 1992
Printed in the U.S.A.

0038-092X/92 $5.00 + .00

EFFECT OF WALL CONDUCTIVITY ON THERMAL STRATIFICATION

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Abstract—The growing desire to find alternate energy sources to meet the ever-increasing energy demands of mankind has led to extensive research in the field of solar energy. Energy devices working on solar energy need energy storage subsystems because of the intermittent nature of solar radiation. Thermal energy storage systems which keep the warm and cold water separated by means of gravitational stratification have been found to be attractive in low and medium temperature thermal storage applications due to their simplicity and low cost. Experimental investigations have been carried out on scaled model storage tanks of various materials and wall thickness to study their effect on the stratification. It has been found that degradation of thermoclines is slower for tanks whose walls have a higher thermal resistance.

1. INTRODUCTION

Thermal storage systems which separate the warm and cold water by means of gravitational stratification are being used widely for load management and energy conservation in a number of installations, such as solar power plants.

The thermodynamic availability (exergy) of the stored water degrades due to heat losses to the ambient, thermal diffusion from hot layers to cold layers, axial conduction in the tank wall, which along with the heat loss to the ambient, induce mixing in the fluid body, and also mixing introduced during charge and discharge cycles. An increase in the degree of stratification results in improved system performance. A prolonged stratification is desired in a stratified storage tank.

Earlier investigations have revealed that for the storage tank a length-to-diameter ratio of 3 is the minimum requirement for stratification[1,2]. Gupta and Jaluria[3,4,5] have concluded experimentally that energy transfer in the stratified region is mainly due to thermal diffusion. The experiments also showed that the temperature field in the stratified storage body is largely dependent on the inflow and outflow configurations. It was concluded that large energy losses occur from the sides of the tank and also the top. A simple one-dimensional model developed on the basis of the observed experimental results was used to predict the temperature profiles, and these temperature profiles showed close agreement with the experimental results.

Abdoly and Rapp[6] found that heat loss through the walls and insulation to the ambient is the major heat transfer mechanism in stratified storage tanks, and that heat losses across the thermoclines can be minimized. They predicted that a longer tank with a smaller wall thickness and better insulation may improve the stratification.

Reddy[7] and Miller[8] found experimentally that even with the best exterior insulation, the thermoclines degraded due to heat leak from the hot fluid zone to the cold fluid zone through the wall of the storage tank.

Shyu *et al.*[9] also concluded from their experiments that wall conduction plays an important role in the degradation of thermoclines.

The investigation reported here[10] deals with the effect of storage tank wall thermal conductivity and thickness on the degradation of thermal energy in a dynamic system. Most of the investigators limited their work only to discharging operations, but the present investigations cover also simultaneous charging and discharging.

2. APPARATUS AND INSTRUMENTATION

Three tanks of the same internal diameter of 260mm and length 780mm, two made of mild steel (wall thickness of 1.0mm and 2.4mm) and one of aluminium (wall thickness 1.0mm) are used as storage tanks. These tanks are labeled as MS-I, MS-II, and Al, respectively; their modified Biot numbers ($hL^2/K\delta$) in terms of h are $14.076h$, $5.865h$, $3.690h$. The storage tanks were insulated on the lateral surface and top and bottom with the same thickness of glass wool mats. A small air gap between the top layers of water in the tank and the tank top helps in reducing the heat losses from the top to a minimum. Suitable inlet and outlet connections were provided for charging and discharging operations with little disturbance to preserve stratification in the tank. Flow rates were measured with calibrated rotameters. A thermostatic water bath simulates the solar collector and is connected to the tank. Monoblock pumps of fractional horse power are used for pumping and withdrawing water at desired rates. Figure 1 shows the experimental set-up of the investigation. The temperatures of the water body along the axis of the tank are sensed by thermocouples attached to a central thermocouple probe and a multipoint millivolt recorder.

3. PROCEDURE

Initially static unstratified tests were performed to determine the heat losses. The tank was first filled with

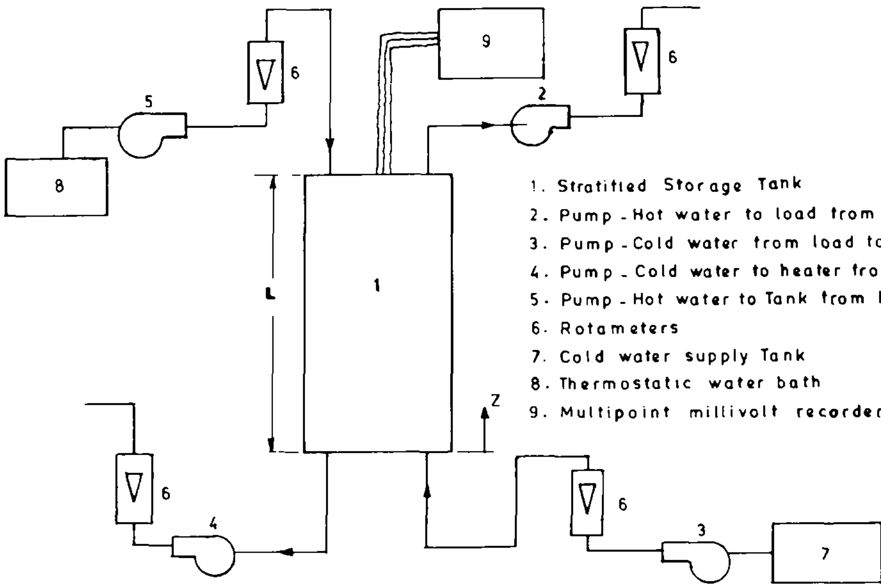

Fig. 1. Schematic diagram of experimental set-up.

hot water at uniform temperature. The temperature drop at various axial locations is measured both for insulated and bare tanks at different intervals of time.

In static stratified tests, the tank is filled with hot water, and cold water is pumped from the bottom of the tank till half the volume of hot water is displaced by cold water. The temperature profiles at various intervals of time are determined for insulated as well as uninsulated tanks.

In the dynamic mode, the tank is initially filled with hot water, and the fluid is allowed to settle down. The discharge cycle operation is simulated by pumping in cold water at the bottom of the storage tank at the same rate at which the hot water is drawn out by the pump at the top. The process of a simultaneous charging and discharging cycle is simulated when hot water from the thermostatic water bath is pumped into the tank from the top at the same rate at which the cold water is withdrawn from the bottom while the discharge cycle is in operation.

In both operation modes the axial temperature distribution of the water body, inlet and outlet temperatures of the water, and flow rates are noted at various intervals of time for different initial conditions till the stratification is completely destroyed in the storage system.

4. RESULTS AND DISCUSSION

The experimental results of the stratification decay under static stratified conditions for different storage tanks are shown in Fig. 2 (a & b) by plotting nondimensional temperature, T^* against nondimensional axial coordinate, Z^* for MS-I, MS-II, and Al tanks for time intervals of 3 and 6 h. In the above figures it is observed that the upper layers of hot water—almost isothermal initially—degrade in temperature due to radial heat loss from the lateral surface of the tank to the ambient air. In addition to this, thermal conduction between top hot layers and bottom cold layers of water and axial conduction through tank wall contribute to the heat loss from the upper layer. These two effects increase the temperature of the lower layers of water. The thermoclines degrade faster in the MS-II storage tank ($\delta/D = .0093$) compared to MS-I ($\delta/D = .004$). The bottom layers of cold water in MS-II rise in temperature due to higher axial conduction. From the above it is observed that a lower δ/D ratio results in better stratification due to the reduction in axial conduction of heat through the tank wall for the same material.

Both the MS-I and Al tanks have the same δ/D ratio of 0.004. The thermoclines degrade faster in the Al tank due to its higher thermal conductivity compared to MS-I. The higher the thermal conductivity of the wall, the faster the degradation of thermoclines, for the same δ/D ratio of the tanks. Walls of higher thermal conductivity enhance the axial conduction through the tank wall and this is reflected in the raising of the temperature of cold layers at the bottom and cooling of the top hot water layers.

Figure 2b depicts the temperature profiles in the MS-I, MS-II, and Al tanks after a time interval of 6 h on a nondimensional basis. The degradation is the highest in the Al tank, which has the lowest modified Biot number of $3.69h$.

Shyu *et al.*[9] presented their results by plotting Z against T. For comparison with our results, their results are replotted in Fig. 2c on nondimensional coordinates, T^* versus Z^* for a time interval of 5 h for three different steel tanks of wall thicknesses 0.5, 3.0, and 6.0 mm. The modified Biot numbers of their tanks are $16.5h$, $2.75h$, and $1.38h$, respectively. Temperature profiles 1, 2, and 3 in Fig. 2c correspond to these tanks respectively. All the tanks were provided with the same thickness of exterior insulation. It is seen from the temperature profiles that the lower the Biot number the faster the degradation. Also on this graph are plotted

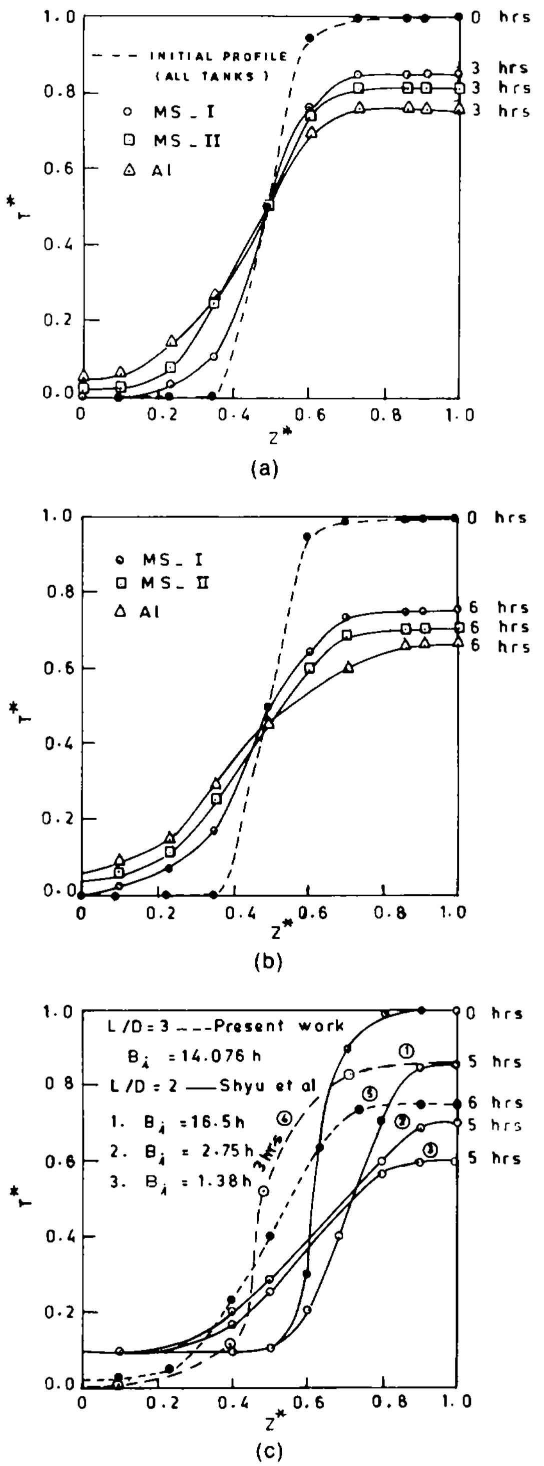

Fig. 2. (a, b, c) Temperature profiles (static stratified and insulated).

the results of the present work for two time intervals of 3 and 6 h for the MS-I tank (temperature profiles 4 and 5). The 5-h profile, if it were available, would have fallen between profiles 4 and 5, and this definitely lies below Shyu's profile 1, which was for 5 h. This establishes that the stored energy degrades faster in MS-I (Bi = $14.076h$) compared to the stainless steel tank of Shyu (Bi = $16.5h$) during the same interval of time. This MS-I tank has a modified Biot number of $14.076h$ which is less than Shyu's modified Biot number of $16.5h$. This once again establishes that degradation increases with the decrease in the value of the modified Biot number.

In dynamic tests, with the discharge cycle in operation, increase in ΔT_0 results in a greater stabilizing effect on the thermoclines, due to an increased density difference between hot and cold fluid layers. However, the deterioration of thermoclines is faster due to increased heat loss, and hence the enclosed water body tends to be isothermal faster. The thermoclines also degrade faster at increased flow rates as higher velocities of fluid enhance the chances of mixing of hot and cold fluid zones.

In the discharge cycle the experimental results are shown in terms of thermocline thickness, d_T. Thermocline thickness is defined as the length of the water body in the tank where $T_0/T < 70$[6]. This has been calculated in the present investigation as the thickness of the region in which the temperature of the water body varies from T_U to T_L, where

$$T_U = ((T_1 + T_2) + 0.9\Delta T_0)/2 \quad \text{and} \qquad (1a)$$

$$T_L = ((T_1 + T_2) + 0.9\Delta T_0)/2 \qquad (1b)$$

and the values obtained compare well with those of Abdolly.

Figure 3a is a plot between the thermocline thickness and flow rate. The degradation is the highest in the Al tank. Tanks with a higher modified Biot number have prolonged stratification.

In the discharge cycle, the extraction efficiency defined as $\eta = Q_L \times t^*/V$ decreases with increased flow rates (Fig. 3b). Both t^* and characteristic time, t_1, decrease with increased flow rate, but the rate of decrease in the value of t^* is larger than in t_1. The extraction efficiency which is the product of the inverse characteristic time and t^* decreases faster with increase in flow rates. The degradation of thermoclines is due to the combined effect of mixing and heat losses.

The thermoclines degrade faster as time progresses and also with increase in the δ/D ratio for the same material. Also, the stratification decays faster in geometrically similar storage tanks with increase in the thermal conductivity of the tank material (Fig. 3c).

The extraction efficiency increases with increase in inlet and outlet water temperature difference (ΔT_0) due to greater stabilizing effect of the thermoclines (Fig. 3d).

Similar trends are observed in a simultaneous charging and discharging cycle with the flow rate through the load loop being less than the rate of flow through the collector cycle. The results are given in Table 1, which gives the values of thermocline thickness and percentage heat recoverable (PHR) for various temperature differences when $Q_C > Q_L$. PHR is a measure of the performance of stratification and is defined as[6],

$$\text{PHR} = (H_{RT}/H_{RO}) \times 100$$

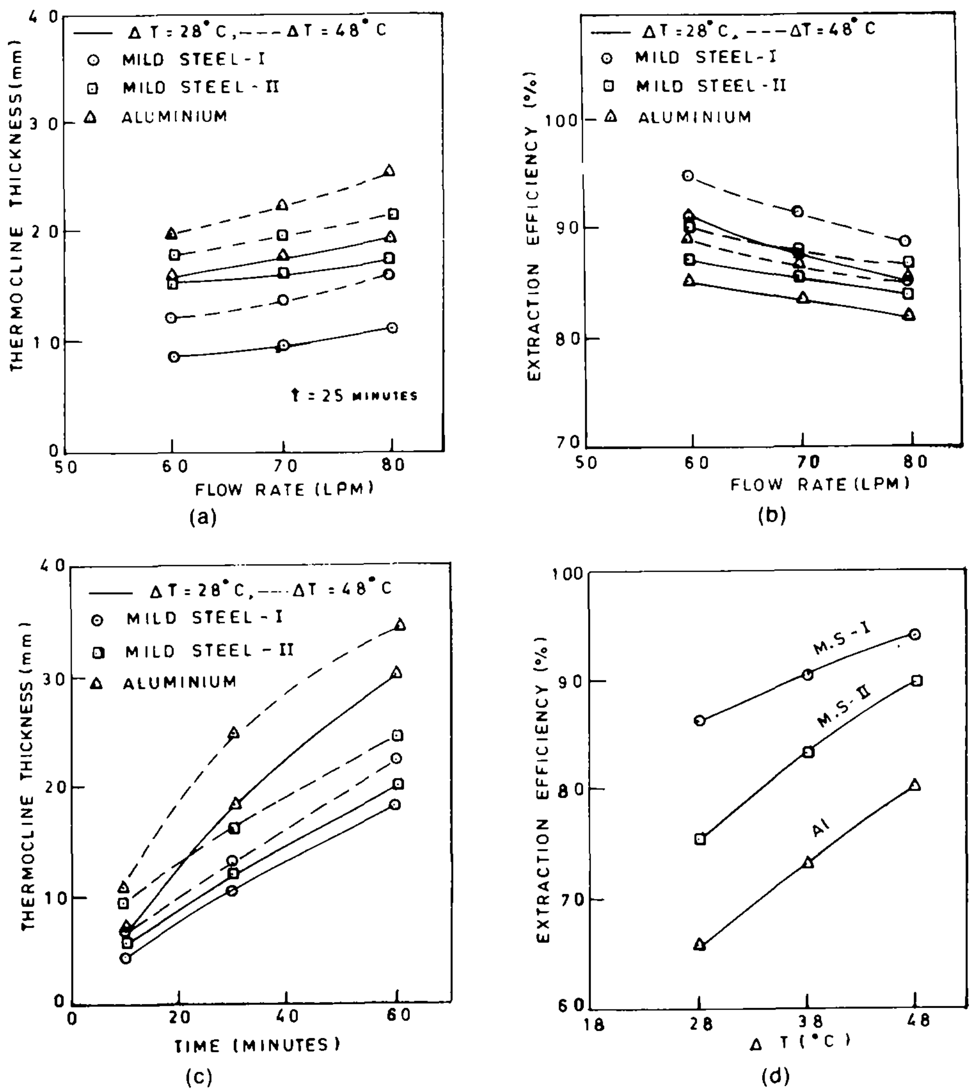

Fig. 3. (a) Variation of thermocline thickness with flow rate; (b) variation of extraction efficiency with flow rate; (c) variation of thermocline thickness with time; (d) variation of extraction efficiency with ΔT.

where

$$H_{R_i} = \sum m_j Q_j$$

$$Q_j = 0 \quad \text{if} \quad (T_j - T_{10})/(T_{20} - T_{10}) < 0.8$$

and

$$Q_j = 4.18(T_j - T_{10})$$

$$\text{if} \quad (T_j - T_{10})/(T_{20} - T_{10}) \geqslant 0.8.$$

Table 1. Thickness of thermoclines and PHR

		$Q_c = Q_L$ = 60 LPH						Q_c = 40 LPH, Q_L = 70 LPH					
		Mild steel tank-I		Mild steel tank-II		Aluminium tank		Mild steel tank-I		Mild steel tank-II		Aluminium tank	
ΔT(°C)	Time (min)	38	48	38	48	38	48	38	48	38	48	38	48
Thermocline thickness (mm)	30	6.5	8.50	7.5	9.5	8.5	11.0	12.0	13.0	14.0	16.0	23.0	27.0
	60	—	—	—	—	—	21.0	23.0	23.0	24.0	33.0	—	—
	120	12.5	18.00	18.0	25.0	20.0	28.0	—	—	—	—	—	—
PHR (%)	30	91.2	93.04	89.0	90.1	87.1	88.3	68.8	69.7	57.4	60.5	47.6	48.4
	60	—	—	—	—	—	—	33.0	35.3	21.3	24.3	6.7	7.6
	120	88.0	90.0	82.0	80.0	72.3	75.2	—	—	—	—	—	—

When the flow rates through the collector cycle and the load cycle are equal ($Q_C = Q_L$), the stratification is prolonged, and hence the PHR is high. (PHR = 0.88 in the case of the MS-I tank after 2 h.) The PHR values for MS-II and Al are low for the same time interval. High values of PHR are obtained when the initial temperature difference is increased, and this is due to increased stabilization of thermoclines.

When the flow rate through the load cycle is more than the collector cycle, the thermocline degradation increases due to increased rate of extraction of stored energy, and hence there is a steep fall in PHR.

It is noted that PHR decreases with time due to the degradation of thermoclines and decreases faster in the case of storage tanks whose axial conductance is greater.

5. CONCLUSIONS

1. These experiments have once again established the conclusions of the earlier investigators that it is possible to store both hot and cold fluids in the same enclosure.
2. The degradation of thermoclines is due to radial heat losses, axial wall conduction and thermal diffusion within the fluid between hot and cold fluid zones. The exterior insulation helps in reducing the heat losses to the environment through the lateral surface of the tank, but it does not prevent degradation of thermoclines due to enhanced heat leakage through the conducting metallic wall. However, the reduction in the radial heat losses helps in obtaining stratification in the tanks in spite of the heat losses due to axial conduction.
3. The higher the modified Biot number the better the stratification. A storage tank made of material of low thermal conductivity and lower wall-thickness-to-diameter ratio will have prolonged stratification due to reduction in the heat loss from axial wall conduction.
4. In the discharge cycle thermal stratification can be prolonged by using moderate flow rates and moderate initial temperature differences between hot and cold water.
5. In the simultaneous charging and discharging cycle the stratification can be prolonged when the flow rate through the load cycle is either equal to or less than the flow rate through the collector cycle.
6. Insulating the tank by lining the interior of the tank with rubber or any low thermal conductivity material compatible with stored fluid may improve the stratification.

Acknowledgments—The authors gratefully acknowledge the financial support received from the Council of Scientific and Industrial Research, New Delhi (Project No. 23 [149]/83-EMR.II). Authors express their sincere thanks to the Principal, Regional Engineering College, Warangal, India, for providing the facilities to carry out this work.

NOMENCLATURE

- Al aluminum tank with 1 mm wall thickness (insulated)
- Bi modified Biot number $hL^2/K\delta$
- D diameter of tank, mm
- d_T thermocline thickness
- h average wall heat transfer coefficient, $W/m^2 \cdot K$
- H_{R0} recoverable heat at time, $t = 0$
- H_{Rt} recoverable heat at any time, t
- K thermal conductivity of tank wall, $W/m \cdot K$
- L length of tank, mm
- MS-I mild steel tank with 1 mm wall thickness (insulated)
- MS-II mild steel tank with 2.4 mm wall thickness (insulated)
- PHR percentage of recoverable heat
- Q_C collector cycle flow rate
- Q_L load cycle flow rate
- T axial temperature of water body at any position and time, °C
- T^* nondimensional temperature: $(T - T_a)/(T_H - T_a)$
- t^* time corresponding to 10% drop in initial temperature difference, ΔT_0
- T_a ambient air temperature, °C
- T_H temperature of hot water at inlet, °C
- T_J mean temperature of region "J" in the water body
- t_1 characteristic time, V/Q_1
- T_1 cold water temperature at time t in the tank, °C
- T_2 hot water temperature at time t in the tank, °C
- T_{10} cold water temperature initially in the tank, °C
- T_{20} hot water temperature initially in the tank, °C
- V volume of tank, L
- Z axial coordinate, mm
- Z^* nondimensional coordinate, Z/L
- ΔT temperature drop per cm in the water body
- ΔT_0 initial temperature difference of hot and cold water, $T_{20} - T_{10}$
- δ wall thickness, mm
- η extraction efficiency

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