THERMAL STRATIFICATION IN STORAGE TANKS

M.A. Alsaad and N.J. Rabadi
Department of Mechanical Engineering
Faculty of Engineering and Technology
University of Jordan
Amman, Jordan

ABSTRACT

This paper investigates the effect of storage tank aspect ratio on thermal stratification. The experimental results obtained confirmed that flow rate and the inlet location are the decisive factors in maintaining stratification. The effect of aspect ratio is shown to change depending on the residence time of hot water or the withdrawal rate from storage tank. For short residence time stratification is greater at low aspect ratio; at longer residence time this tendency changes and stratification becomes greater at high aspect ratio.

INTRODUCTION

Since solar radiation as an inherently time-dependent energy resource, storage of energy is essential if solar radiation is to meet energy needs at night or during periods of could cover. Storage provides a reservoir of energy which can adjust for phase differences between local solar energy supply and the load demand. Furthermore, storage is essential if solar is to meet a large fraction of total energy needs for many such applications[1,2].

Several researchers [3-8] predict significant improvement in the performance of solar heating and cooling systems if thermal stratification can be maintained in storage tanks, Various experimental, numerical, and analytical models of stratified tanks have been developed to show the benefits of stratification and how it can be maintained [9,10]. The concept of the critical Richardson number as the governing parameter of stratification described in references [11,12] and experimentally verified in reference[11] implies that stratification is possible if the Richardson number, Ri, is greater than 0.25. From the definition of Richardson number, $Ri = 9\ \beta L \Delta T / U^2$, where g is the gravity constant, β is the volumetric coefficient of thermal expansion, L is the water depth, ΔT is the difference between water temperature at top and bottom of the tank, and U is the inlet velocity. It is evident that this concept ignores the effect of aspect ratio on thermal ratification.

The objective of this study is to examine experimentally the effect of storage tank aspect ratio, AR, mass flow rate and fluid inlet location on thermal stratification. In order to isolate the effect of inlet temperature on stratification, the incoming water was always kept at a temperature higher than the storage tank temperature high extreme.

THE EXPERIMENTAL ARRANGEMENT

A schematic of the experimental arrangement used in this study is shown in Figure (1). It consists of a rectangular stainless steel tank of dimensions 0.75 x 0.75 x 1.80 m and 3mm wall thickness. The tank water volume is 1012.5 liter and the tank mass is 150 kg, yielding a heat capacity ratio of 62. The tank has a glass window on its front side with dimensions (1.48m x 0.135m) to provide for inside visualization. L shape steel flanges are welded longitudinally on the tank outer surface to provide stiffening. The tank has six fixed inlet ports and six fixed withdrawal ports. The inlet port location are at 50, 150, 230, 350, 480, and 530 mm from the top of the tank. Two more openings are located near the bottom of the tank, one to provide for circulation of water to the heating system and the other for make up water. The tank is insulated using 30 mm thick fiber glass sheets wrapped around it.

Changing the aspect ratio is achieved by filling the tank with water to different levels. The largest aspect ratio available was 2.4. An infinite number of smaller aspect ratios can be obtained by merely changing the level of water in the tank, however only two other aspect ratios (2.13 and 1.87) have been considered here. The water level in the tank is maintained through controlling the outlet flow from the bottom of the tank relative to a desired fixed inlet flow near the top of the tank. The resulting mass flow rate is recorded using a variable area-type flow meter in Figure (1).

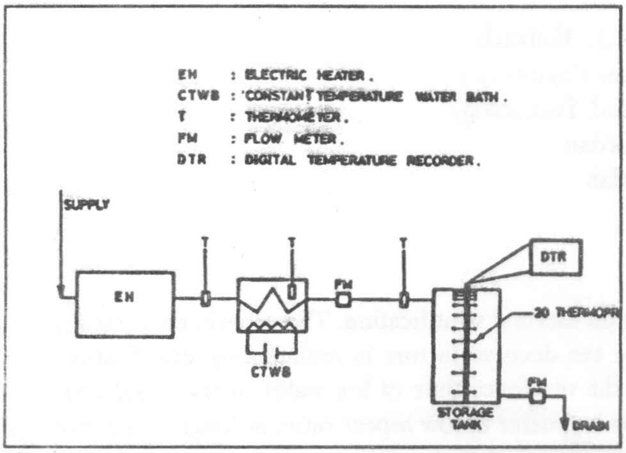

Figure 1. Schematic of experiment.

The temperature field inside the tank is measured through a network of locally assembled thermoprobes as shown in Figure (2). A teflon rod of 20 mm diameter has twenty copper tubes mounted on it. Each tube holds one thermocouple wire which protrudes at the tip and carries the temperature signal to a digital temperature reader (Comark Electronics, Microprocessor Thermometer).

The teflon rad length can be adjusted to provide for different water depths in the tank. When the water level is lowered, The teflon rod must be lowered to keep the closely located thermoprobes in the water. The system gives temperature data at twenty different points with ten different levels in the field. The locations of the thermoprobes are always made at 10, 30, 50, 110, 190, 290, 430, 610, 830, and 1245 mm from the top water level in the tank. The distances between thermoprobes increase as they get further away from the top water level. This is to accommodate for the expected temperature profile in stratified fields.

The inlet flow temperature to the tank is controlled using a series of electric heaters set to automatically maintain the temperature to within ± 0.5 °C. Inlet flow temperature is measured by glass mercury thermometer. All experimental tests were performed with fixed inlet temperature of 60 °C.

RESULTS AND DISCUSSION

In order to properly present the results obtained from the numerous experiments performed. the following definitions are made:

1. Aspect ratio AR; is defined as the ratio of the depth of water inside the tank to the characteristic length of the tank horizontal-cross-section(diameter for cylindrical tank and base side length for rectangular tank).

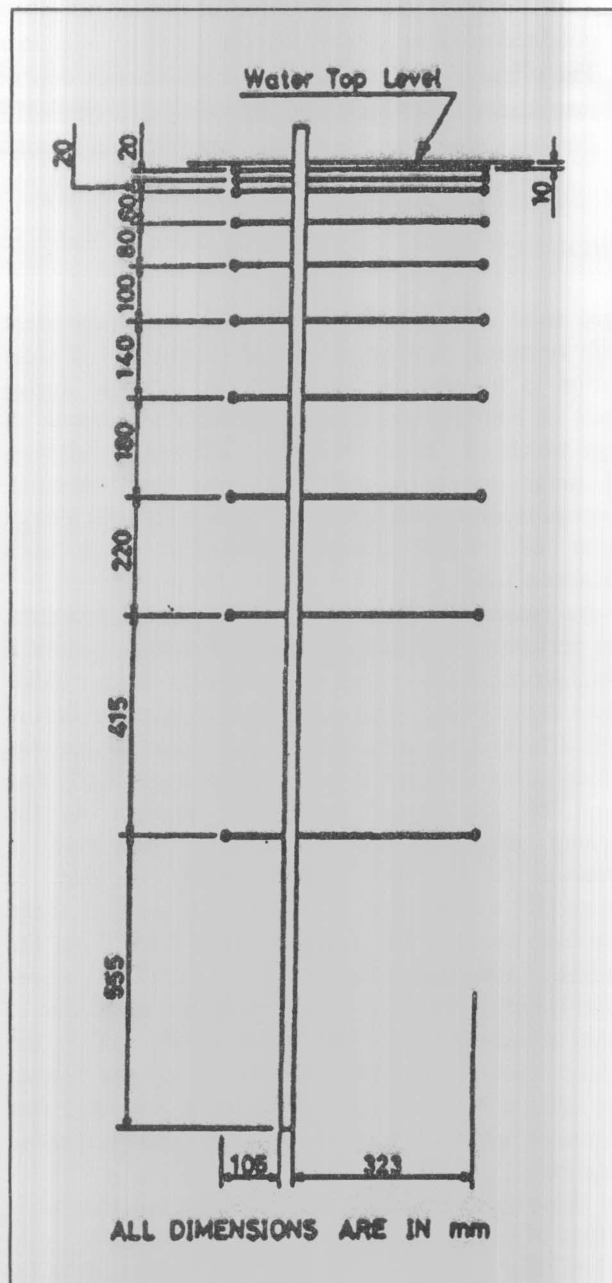

Figure 2. Thermocouple network.

2. Dimensionless temperature θ; is defined as follows:

$$\theta = \frac{T - T_o}{T_i - T_o}$$

where, T is the temperature at any point inside the tank at any time t. T_o is the temperature at the same point at time zero(start-up time of the experiment). T_i is the temperature of the water entering the tank (fixed at $60^\circ c$).

3. Dimensionless water depth D: is defined as the ratio of the depth of the point at which temperature is measured to the maximum depth of water in the tank.

Investigation of the inlet flow rate, inlet location, and aspect ratio effects on thermal stratification in the storage tank is the objective of this study. In order to study the effect of each of these parameters alone, all other parameters were fixed. Thus, for example, if the effect of the incoming water flow rate was studied, a number of experiments were performed for different flow rates while keeping all other parameters constant. Although, keeping the water initial temperature constant was difficult in practice, yet using the dimensionless temperature defined above negates the discrepancy of variable initial conditions.

The effect of flow rate on thermal stratification is shown by Figure (3) where temperature profiles for flow rates of 0.02,0.03 and 0.04 kg/s are drawn at durations 3,2 and 1.5 hours, respectively, to ensure equivalent heat input to the storage tank. AS Figure (3) shows, thermal stratification for the flow rate of 0.02 kg/s is closer to perfect stratification than that for the flow rates of 0.03 and 0.04 kg/s. It is evident that of the three rates used in this work, stratification is always greatest for the flow rate of 0.02 kg/s irrespective of the value of the aspect ratio. It is observed that the thermal stratification is improved as the flow rate is decreased and a more uniform temperature profile is obtained when the flow is introduced just below the water level. This result is verified for different aspect ratios and different inlet locations as indicated by Figures (4), and (5). It is believed that as the inlet flow rate increases, the degree of turbulence increases, hence increasing the mixing within the tank which impedes stratification.

The effect of inlet location on thermal stratification is shown in Figure (6) for fixed mass flow rate of 0.021 kg/s and a fixed residence time of three hours where three temperature profiles corresponding to the inlet locations 2.3 and 4 are shown on the same plot. Experimental data presented in Figure (6) indicates that better thermal stratification was achieved with inlet location 2. The results of the present work agree with the more general finding of reference [8] that inlet flow should be introduced into the tank at a level where the temperature of the incoming flow and tank fluid match.

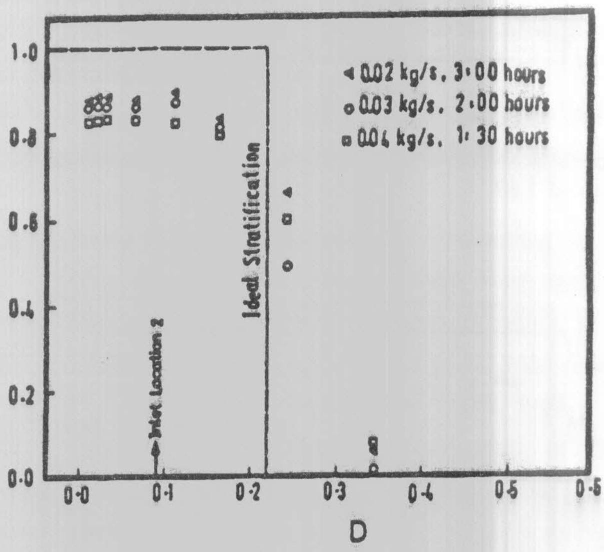

Figure 3. Effect of flow rate on stratification for aspect ratio of 2.40.

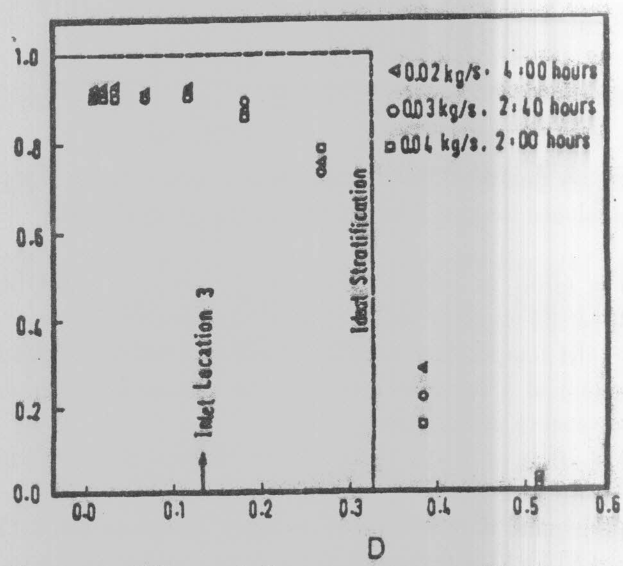

Figure 4. Effect of flow rate on stratification for asppect ratio of 2.13.

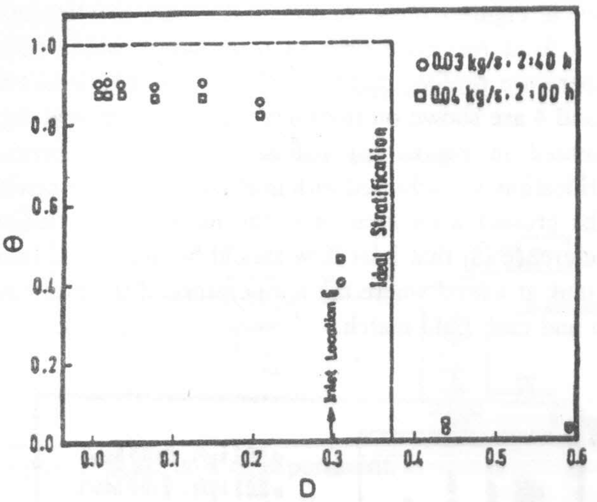

Figure 5. Effect of flow rate on stratification for aspect ratio of 1.87.

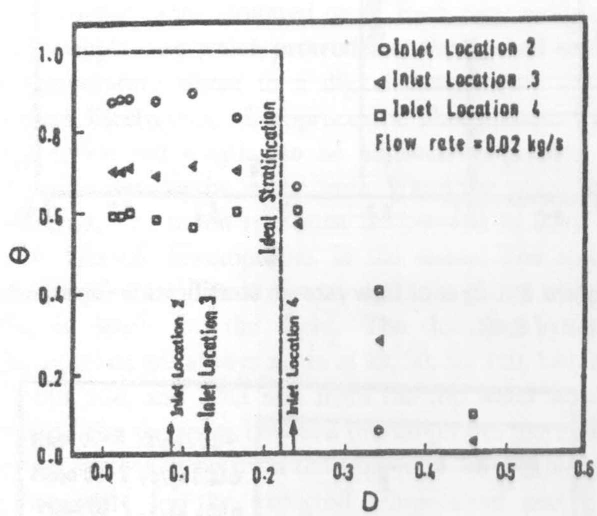

Figure 6. Effect inlet location on stratification for residence time of 3 hours and aspect ratio of 2.40.

The effect of inlet location on stratification must be considered together with the inlet temperature. However, the inlet temperature for all experiments was maintained constant at a value greater than the expected maximum temperature in the tank.

The effect of aspect ratio, AR, on thermal stratification is shown in Figures (7) and (8). Both figures present the experimental data obtained for aspect ratios of 2.4, 2.13 and 1.87 and for residence times of one and three hours. Figure (7) shows the temperature profiles obtained for flow rate of 0.02 Kg/s while Figure (8) shows the temperature profiles for flow rate of 0.03 kg/s. It should be noted that the inlet location distances from the water top surface were kept fixed for all aspect ratios investigated. The experimental data presented in Figures (7) and (8) indicate that the best performance is with longer residence time and better thermal stratification is achieved as the aspect ratio is increased. On the other hand, after one hour from feeding the hot water to the tank, thermal stratification is best for aspect ratio of 1.87 which is the smallest of the aspect ratios used.

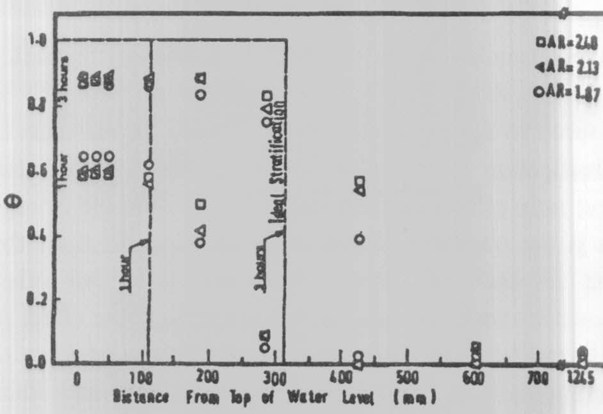

Figure 7. Effect of aspect ratio on stratification for flow rate of 0.02kg/s.

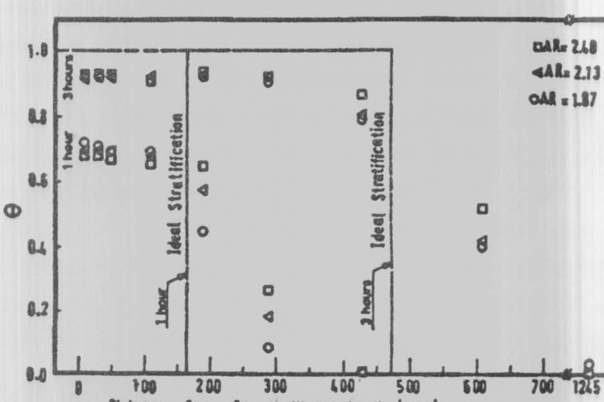

Figure 8. Effect of aspect ratio on stratification for flow rate of 0.03kg/s.

Since small aspect ratios are obtained by merely lowering the water level in the tank, hence generating air space inside the tank, free convection currents were throught to affect the heat loss from the water top surface. To minimize this heat loss, the water top surface was covered by a thick layer of floating tiny polystyrene spheres.

Also, changing aspect ratio was accompanied by a change in the volume of water while the tank mass stayed the same i.e the heat capacity ratio changes with aspect ratio. As the aspect ratio decreases the heat capacity ratio and the thermal losses from the tank decrease. The heat capacity ratio is considered as an important parameter in sustaining stratification. As the heat capacity increases the role the tank plays in smoothing the temperature profile becomes smaller. The effect of heat capacity ratio discussed here is believed to be hindered by the decrease of contact surface area between the water and tank since as aspect ratio decreases the surface area decreases. After three hours of operation, the effect of heat capacity ratio takes over and thermal stratification becomes best at aspect ratio of 2.4 which is the largest of the aspect ratios used. This result is consistant for the flow rates of hot water used as indicated in Figures (7) and (8).

CONCLUSION

A high degree of thermal stratification in a water storage tank can be achieved when the inlet flow is introduced into the tank at low rate. Thermal stratification can be further improved when hot water is introduced into tank at a location just below the water top level i.e where the temperature of the entering water and tank water match

The best thermal stratification obtained by the present set of experiments occured when both residence time and ratio were maximum. For short operation. i.e. short residence time of hot water in the tank, low aspect ratio is best for thermal stratification. On the long run, i.e. long residence time of hot water in the tank, the aspect ratio effect on thermal stratification in liquid storage tanks becomes minimal relative to the effect of heat capacity ratio.

ACKNOWLEDGEMENT

This work was supported by the Deanship of Research, university of Jordan, Amman-jordan.

REFERENCES

[1] LOF G.O.G. and Tybout R.A., Solar Energy 14,253, 1973.

[2] Shelpuk B., Joy P. and Crouthamel M., *Final Report, Energy Research and Development Administration*. Division of Solar Energy, 1976.

[3] Han S.M., Wu S.T., and Chrishtensent D.L., *Proceedings for the Fourteenth Southeastern Seminar on Thermal Sciences*, North Carolina State University, 1980.

[4] Sharp M.K., and Loehrke R.I., *ASM* aper 78-HT 94, and *AIAA/ASME Thermophysics and Heat Transfer Conference* 1978.

[5] Davis E.S., and Bartera R., Proceeding of the Workshop in *Solar Energy Storage Subsystems for Heating and Cooling of Buildings*, Virginia, 1975.

[6] Duffie J.A., and W.A. Beckman W.A., *Solar Energy Thermal proceses*, Wiley, New Yoork, 1980.

[7] Veltamp W.B., *Thermal Stratification in Heat Storages*, Martinus Nighoff publishers, The Hague, 1981.

[8] Koppen C.W.J.V, Internal Report, Eindhoven University of Technology, 1979.

[9] Sharp M.K., and Loehrke R.I., *Journal of Energy* 3, 106, 1979.

[10] Loehrke R.I., *Technical Report*, Colorado State University, 1977.

[11] Cole R.L., and Bellinger F.O., *Final Report, Argonne Notional Loboratory*, 1982.

[12] Cole, R.L. and Bellinger, F.O., Proceedings *IECEC, Intersociety Energy Conversion Engineering Conference*, 1982.