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An Experimental Study of Hot Water Consumption on the Thermal Performance of a Horizontal Mantle Tank

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Abstract: The aim of this experimental study is to show the effect of mixing factor on the performance of thermal behavior of a horizontal cylindrical storage tank. Five inflow rates with four draw-offs have been carried out in this study. The experiments show that hot water consumption with highest flow rate has more influence in degradation of thermal stratification and by analyzing the influence of the amount of inlet mass flow rate on the degree of thermal stratification during an unloading process we found that it has less effect in thermal stratification. Results show that turbulent mixing factor caused by discharging is the most significant item in the performance of thermal stratification in storage tank.

Key words: Storage tank · Thermal stratification · Solar water heater

INTRODUCTION

In recent years, investigation of the thermal stratification in storage tanks has become one of the most important subjects for solar energy systems. In this case many experimental and numerical studies have been carried out by several authors. In most investigations, only the effect of forced convective heat transfer has been studied whereas the natural convection is important too. It is ignored. By looking carefully in these studies we can find that the performance of a thermal stratification in storage tanks is influenced by many factors such as the thermal capacity of the fluid used, the design and geometry of the inlet and outlet ports, the operating temperature range of collector and tank, thermal losses from the storage tank, inlet velocities and temperature, the mixing introduced during charge and discharge and the degree of thermal stratification maintained in the tank. All of these studies have shown that by improving thermal stratification inside the tank, the efficiency of whole system will be increased.

Loss or degradation of thermal stratification in storage tanks is caused by several heat transfer mechanisms (Zurigat *et al*., [1]; Shyu *et al*. [2]). These mechanisms are forced convection flow through the tank, heat loss to the ambient, thermal mixing at the inlet and outlet, natural convective flow induced by conduction within the tank walls and heat diffusion inside the tank due to the vertical temperature gradient within the fluid.

Shyu *et al*. [2] in their experimental study showed that conduction in the tank wall and heat loss to the ambient had influenced the decay of thermal stratification in a vertical cylindrical storage tank. By comparing the results with the numerical analysis they showed that thermal diffusion through the water in the tank is not a significant parameter.

A few investigations were focused on thermal performance of horizontal cylindrical tanks; one of these studies was done by conversant with Alizadeh [3]. Four sets of experiments have been carried out where cold water was injected into the bottom of the tank with three different initial thermal fields. The first one is the tank with initial thermal stratification with bottom temperature the same as the inflow temperature. The second set is the tank with the initial thermal stratification, such that the bottom being at a relatively higher temperature than the inflow temperature. The third set is an initially heated isothermal tank and the fourth set is the same as the first set of experiments except that the straight tube inlet nozzle is replaced by a 30° downward bent divergent conical tube. The above experiments show that better thermal stratification can be obtained using the divergent conical tube as the inlet nozzle due to the diffusion effect of the nozzle. Also a slight improvement in the tank performance was achieved in the second set of experiments.

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Young and Baughn [4] carried out experimental and numerical studies of the thermal behavior of a horizontal storage tank. They found that a fully mixed tank is left after each withdrawal with thermal stratification being completely degraded. By employing a manifold diffuser on the inlet, it was shown that the extent of mixing reduced. The experiments were compared with the numerical results and fair agreement was obtained at the top of the tank.

Shah and Furbo [5] showed that the temperature stratification in the inner tank for vertical mantle is not destroyed by the mantle fluid, because the fluid descends in the mantle gap until it reaches the thermal equilibrium level with water in the inner tank.

Ghaddar *et al*. [6] by examining the one dimensional problem showed that the turbulent mixing factor is extremely dependent on the flow rate, the inlet port design and the thermocline location in the tank.

As mentioned above, Stratification is affected by several factors, which have been investigated by different authors. Andersen and Furbo [7] investigated destratification during hot water discharge in a solar tank with different inlets. They found that mixing during hot water draw-offs decreased the yearly thermal performance of the solar system.

The purpose of the current investigation is to predict the effect of mixing factor on the thermal behavior of a horizontal cylindrical storage tank.

Experimental Set up: A horizontal galvanized steel storage tank with diameter of 0.45 m, length of 1.1 m and capacity of 175 L was used for this study. The walls were thermally insulated with rock wool of approximately 80 mm thickness to minimize heat loss to the ambient air. The collector is simulated with a rectangular tank which contains three electrical heating coils producing 4.4 kW of power totally. The simulated collector loop flow enters the mantle through an inlet port at top of the tank and exists from another port at the bottom of the tank. The inlet port having a diameter of 12.7 mm and directs the flow into the annulus along the horizontal axis, so that the entering flow is parallel to the wall of the inner tank. The temperature of inlet port of annulus was controlled between 50-55°C. At each end of the tank there is one 19.05 mm internal diameter (I.D.) for inlet and outlet of water, Fig 1. Cold water is injected at the one end of the tank and 30 mm above the bottom and hot water is discharged from the other end of the tank and 30 mm lowers than the top.

There are three Copper-Constantan (T-type) thermocouple stands placed on the inside centerline of the tank and are used for monitoring the temperature distribution of water in the tank. A total of 17 thermocouples (4 on each stand, 2 in the inlet and outlet port for annulus and 3 on the inner surface of the tank) are used and they were distributed on the distance of 3, 16, 29, 42 mm from the bottom of the tank. For the temperature of the inlet and outlet nozzle, two encased mercury thermometers are used.

Temperature signals were collected from the test tank using a data logger interfaced to a personal computer. The temperature distribution through the storage tank was recorded at regular time periods of 15 sec. The data logger used was made by Campbell Scientific model CR10X having 16 channels and increased to 64 channels by an AM416 relay multiplexer.

Experiments were carried out for five different inflow rates, 0.417, 0.35, 0.3, 0.2 and 0.15 kg/sec, approximately with four draw-offs in each test namely, 30, 50, 80 and 110 L. The storage tank was initially filled with water having a uniform temperature of 22°C and after achieving the desired stratification; the cold water was injected into the tank.

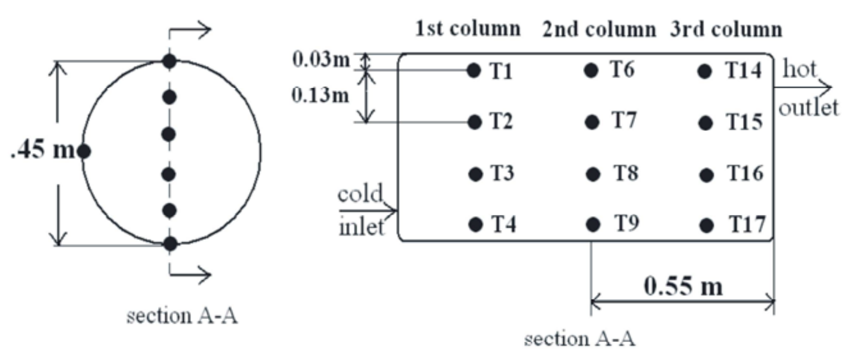

Fig. 1: Dimension of horizontal storage tank with the position of thermocouples.

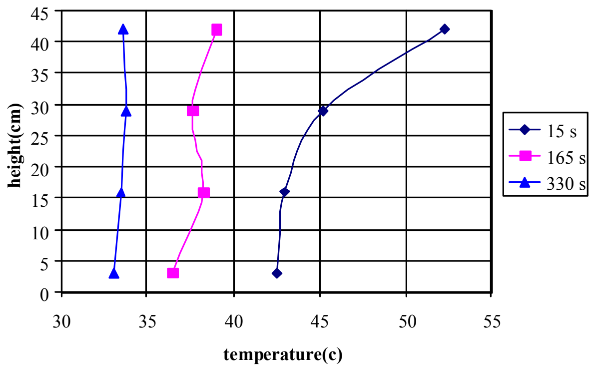

Fig. 2: Transient vertical temperature inside the initially stratified tank for flow rates of 25 l/min, 110 L unloading, near the outlet nozzle.

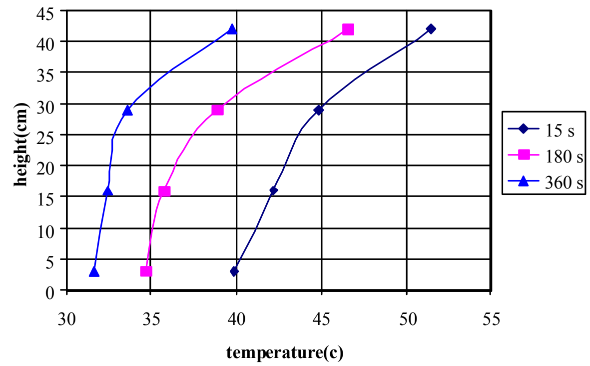

Fig. 4: Transient vertical temperature inside the initially stratified tank for flow rates of 18 l/min, 110 L unloading, near the outlet nozzle.

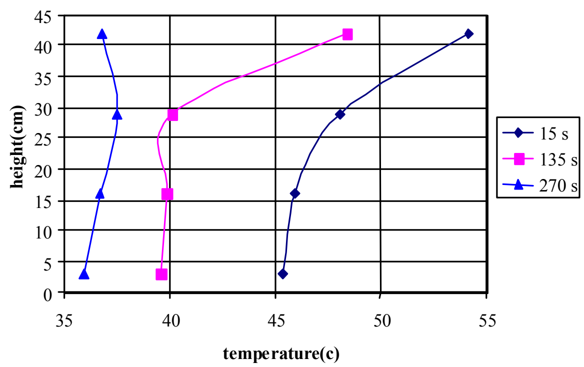

Fig. 3: Transient vertical temperature inside the initially stratified tank for flow rates of 21 l/min, 110 L unloading, near the outlet nozzle

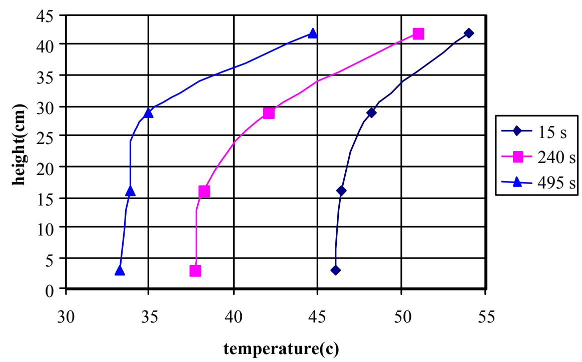

Fig. 5: Transient vertical temperature inside the initially stratified tank for flow rates of 12 l/min, 110 L unloading, near the outlet nozzle.

Experimental Results: The test tank initially contains a body of stable stratified water with hot top layers and cold bottom layers. The time needed for achieving stratification inside the tank in all tests is about 140 minute. In all sets of experiments, the initial stratification is induced such that the temperature of the bottom of the tank increased with respect to the cold inflow temperature.

In Figs 2, 3, 4, 5, 6 the effect of the injected cold water into the bottom of the thermally stratified tank, using the straight tube as the inlet nozzle are presented in the form of transient vertical temperature distributions in the tank for five different injected cold water flow rates. At this time cold water injected into the tank and simultaneously hot water is discharged from the tank. The presented graphs show the thermal behavior of water near the outlet nozzle during discharge. From Fig. 2, for flow rate of 25 lit/min, we can see that after 15 sec the temperature of outlet water, T14, from Fig.1, is about 53°C, whereas the temperature of water at the bottom of the tank in column3, T17, is about 43°C.

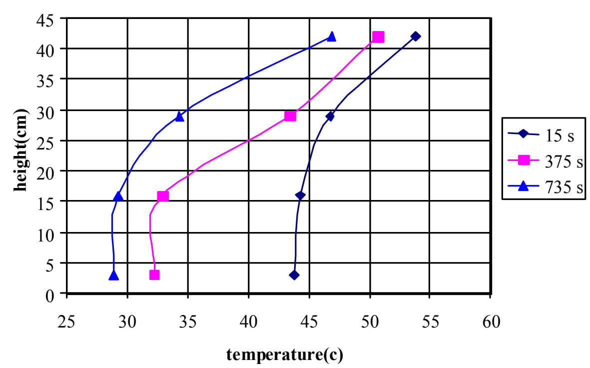

Fig. 6: Transient vertical temperature inside the initially stratified tank for flow rates of 9 l/min, 110 L unloading, near the outlet nozzle.

After 165 sec the temperature of third column will be more uniform and in the last time of discharge the whole water has a uniform temperature so that the difference between T14 and T17 is very small.

In lower flow rates the results showed that the difference in temperature of column3 near the outlet nozzle

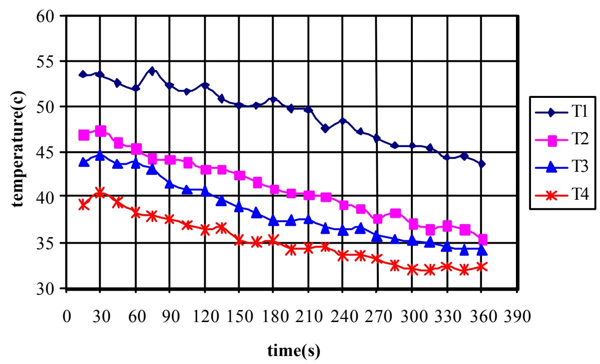

Fig. 7: Temperature distribution inside the tank for flow rates of 18 l/min, 110 L unloading, near the inlet nozzle,1st column

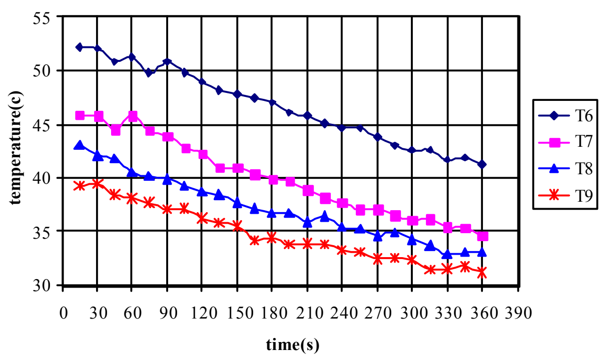

Fig. 8: Temperature distribution inside the tank for flow rates of 18 l/min, 110 L unloading, centerline of tank,2nd column

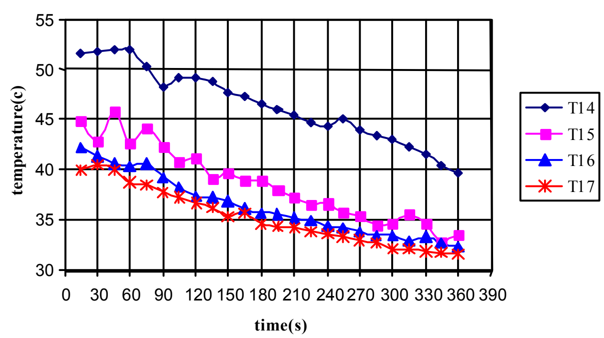

Fig. 9: Temperature distribution inside the tank for flow rates of 18 l/min, 110 L unloading, near the outlet nozzle,3rd column

will be greater, for example for flow rate of 9lit/min, Fig. 6, we can see that the T14 and T17 temperature difference is very large so that the temperature of T17 is closer to the inlet flow rather than other temperatures. For this reason we can say that in high flow rates, graphs showed that mixing aggravates as the amount of inflow rate is increased. This phenomenon causes a distortion in the shape of thermo cline. Although the temperature of the inflow is lower than the bottom of the tank, it causes strong mixing in this region. Mixing has an intense influence in degradation of thermal stratification because the cold water injected into the tank and by unloading the hot water the temperature of water is decreased in short time but in lower flow rates mixing can not influence the temperature loss of water inside the tank, severely. As we can see from Fig.6, the temperature of outlet water for T14 is about 54°C after 735sec.

In order to establish a good thermal stratification, we must have a good thermo cline region. In these graphs it is shown that in all flow rates at the beginning of draw-offs we have a good thermo cline region. In high flow rates in spite of the fact that the short time is needed for discharging 110L of hot water but at this short time, the distortion of thermo cline region is very high. By decreasing the flow rate we can achieve the accepted thermo cline region and the result of that is having a good amount of hot water inside the tank.

In Figs 7, 8, 9 only the test results of one inflow rate, 18 lit/min is presented in the form of temperature distribution in the tank for every node of thermocouples during draw-offs. The time of draw-offs of 110L in this flow rate is about 360sec. The graphs show that we have an area with sufficiently hot water after discharging from the tank, it is seen in Fig. 7.

And the last temperature, T1 after discharging is about 44°C, whereas the last temperature of T14 nears the outlet nozzle, Fig.9, is about 39°C. By comparing these graphs we can see that there is a large slope in temperature loss of 3rd column near the outlet and this is because of the effect of mixing inside the tank during draw-offs.

CONCLUSION

Experimental investigation for different unloading process has been carried out to predict the thermal stratification behavior inside horizontal cylindrical storage tank. Five inflow rates 0.417, 0.35, 0.3, 0.2 and 0.15 kg/sec with four draw-offs in every test 30, 50, 80 and 110 L have been set where cold water was injected into the bottom of the tank. In all the experiments, the tank was initially filled with water having a uniform temperature of 22°C, approximately and after achieving the desired stratification, the cold water was injected into the tank. In this study the collector is simulated with a rectangular tank equipped with three heaters and only the load flow loop has been considered. Results show that the turbulent mixing during draw-offs has a significant effect on the thermal performance of mantle tank systems which causes degradation of temperature as it gets higher, then that is very important to avoid mixing in the solar tank during draw-offs.

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