*J*ournal *of A*pplied *F*luid *M*echanics, Vol. 14, No. 2, pp. 429-438, 2021.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.47176/jafm.14.02.31450

Effect of Diffuser Height on Thermocline in Stratified Chilled Water Storage Tank

F. M. Hasan† and M. A. Theeb

Department of mechanical engineering, Mustansiriyah University, Baghdad, Iraq

†*Corresponding author Email: firasalazawi76@gmail.com*

(Received February 7, 2020; accepted August 3, 2020)

ABSTRACT

Chilled water energy storage using thermal stratification technique currently used in the vast area because it contributes to reducing energy consumption and refrigeration capacity as well as its maintenance, operating and capital costs are low. In this paper, experimental tests were carried out on a small-scale vertical cylindrical storage tank equipped with an elbow-type conventional diffuser at inlet heights of 20, 170, 320 and 470mm for flow charging rates from 1.5-7.5l/min. in order to obtain a good thermal separation. The degree of stratification was estimated by means of temperature distributions and performance metrics, which involve thermocline thickness, the half-cycle figure of merit and equivalent lost tank height. The results show that the decrease in diffuser height above the tank floor tends to the steep thermocline or satisfactory thermal separation, the stratification and thermal performance were obtained at diffuser height of 20 mm within the limiting volume flow rates 1.5-4.5 l/min. better than those at volume flow rates ranging from 5.5-7.5l/min. and much better than at diffuser heights of 170, 320 and 470mm for various flow rates.

Keyword: Cool thermal energy storage; Stratification; Thermal performance; Diffuser height; Inlet diffuser.

1. INTRODUCTION

Peak electrical loads usually occur in hotter days with low or high relative humidity in consequence of using air conditioning systems. The large cooling systems often operated in industrial and office buildings at day time, during the daylight hours, the peak cooling energy happens out of the blue for short hours of the day and exceeds the average designed cooling system energy, thence, leading to a power outage, this problem can be solved by replacing the cooling system over the peak period with cool thermal energy storage (CTES) system, this significantly contributes to shifting the maximum cooling electrical energy from on-peak period to off-peak period, for this reason, concern for the applications of the cool thermal energy storage by electric utilities began in growth since 1970 in North America (Dorgan and Elleson, 1993) and spread in Asia, Europe and South America since 1995 (Hasnain, 1998).

CTES can be defined as a technology that stores the cool medium in reservoir to be employed after a while, CTES can be stored in two different ways, sensible CTES that stores energy with decreasing medium temperature such as water, rocks and others, latent CTES that stores energy with a change of phase of the medium at constant temperature such as melting and freezing water, the current research presents sensible chilled water CTES. There are multiple techniques whose mission is to separate the chilled water region from the hot water region, these are stratification, membrane, empty tank and baffle tank techniques. Thermal stratification technique compared with others is far better because of using a single tank, no need to physical barrier, a lower surface area to volume ratio, maintenance and capital costs is lower (Dorgan and Elleson, 1993). Based on the comparison, the stratification system is considered one of the most commonly used in practical applications because it aims to reducing electrical load and thereby reducing electrical utility bills, for instances, the electrical utility bill charges in army facility at fort Jackson spent by 51% of total bills or equivalent of $5.3 million during peak electrical demand every year, hence, 2.28 million-gallon stratified chilled water storage tank has been added to cooling system to management of electrical load, the saving rate after adding this system was about $430 thousand annually over on-peak electrical demand (Sohn *et al.* 1998). The decreasing the inlet air ambient temperature leads to increasing the gas turbine efficiency and power output. Evaporative-type cooling is the common option to cool inlet air because it is cheap and efficient, but it is inappropriate in hot climates. Alternative option of evaporative cooling is the chiller where the chiller permits to inlet air cooling more than evaporative cooling, however, it requires huge capitals as well as extra electrical load. The best alternative option is the thermal energy storage, which shifts the chiller load to off-peak period and takes its place during on-peak period. Also, it can economically be considered much better than evaporative cooling (Cole *et al.* 2014).

Generally, natural stratification is formed thermally due to the density difference, which arises from the temperature difference between the warm tank water and chilled water coming from the chiller. Stratification primarily creates three vertical layers having different densities, the high-density cold water remains at lower tank, low-density warm water remains at upper tank and density gradient or temperature gradient can be represented as insulated natural thermal barrier, which locates between warmer and colder water to prevent the mixing between them as shown in figure1, this layer is called a thermocline.

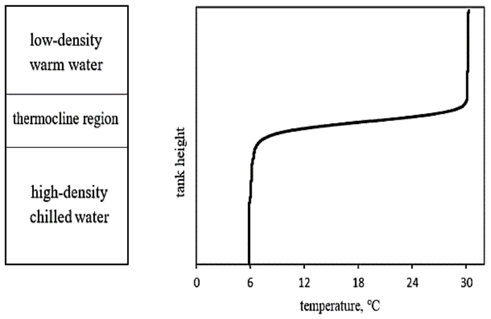

Fig. 1. Density and temperature distributions along the tank height.

There are two cycles of stratification system, the charge and discharge cycles. During the charging cycle, the chilled water enters the lower tank to merge with warm water to form the thermocline after passes of time, the thermocline after formation moves upwards until it disappeared, this cycle continues till the tank is charged completely. The chilled water during the discharging cycle withdraws from the storage tank into the building and then returns into the upper tank as warm water to merge with chilled water to create the thermocline, which moves downward until it disappeared also, this cycle continues till the tank is discharged fully as illustrated in Fig. 2.

Experiments on thermal stratification were performed by a group of researchers for obtaining high efficiency and high cooling capacity with little thermocline thickness. (Yoo *et al.* 1986) showed, based on their experiments, that the gravity current travelling over the tank floor is the main mechanism in thermocline formation and the inlet densimetric Froude number is the key parameter to control thermocline formation, and they showed also that the lower diffuser opening should coincide with thank floor and the inlet densimetric Froude number of 2 is the maximum value in design of inlet diffuser. (Mackie and Reeves, 1988) presented a study to determine allowable range of volume flow rates per diffuser length for two inlet diffusers, linear and nozzle diffusers corresponding to Froude number of unit, they demonstrated that the limited range from 0.14-1.86l/min./m are the primary criterion to design the inlet diffuser for stratified storage tank. (Wildin, 1996) investigated experimentally the effect of diffuser height and inlet Reynold number defined by inlet flow rate on thermocline formation during charging cycle, his results demonstrated that the thermocline formation is good with decreased diffuser height and inlet Reynold number. (Musser and Bahnfleth, 1998) proposed a method to evaluate the thermocline thickness defined from temperature distribution profiles obtained from the stratified chilled water storage tank during charging-discharging cycle by means of dimensionless cut off point temperature, 5% to 15% of cutoff point temperature is limited by them to specify the thermocline thickness, they confirmed, based on their results that the thermocline thickness at different heights for cutoff point temperature of 15% cannot be estimated because the values of the thermocline thickness at this cutoff point are approximately equal. Therefore, they selected 10% of cutoff point temperature as a standard for comparing at different heights and different flow rates. (Li *et al.* 2012) experimentally assessed the effectiveness of stratification using three inlet diffuser, direct inlet diffuser, perforated pipe inlet diffuser and slotted pipe inlet diffuser in a hot water rectangular storage tank by means of discharge efficiency for different flow rates, they showed that the discharge efficiency regardless of inlet diffuser decreases with increasing flow rate, moreover, the discharge efficiency of perforated diffuser gives higher efficiency than slotted pipe diffuser, and much higher than direct inlet diffuser. Furthermore, the turbulent mixing was significantly restrained utilizing perforated diffuser compared to slotted and direct inlet diffusers. On the other hand, they compared between perforated and direct inlet diffusers in terms of electrical consumption, they revealed that the perforated diffuser reduces the electrical consumption less than direct inlet diffuser. (García-Marí *et al.* 2013) used two typical examples of inlet diffusers, sintered bronze conical diffuser and elbow diffuser for minimizing flow rate entering into hot water cylindrical storage tank with little mixing between the hot and cool water, they evaluated the tank with inlet diffusers by performance measures, stratification efficiency, thermocline thickness and temperature profiles, they proved that the sintered bronze conical diffuser for various flow rates decreases the chaotic waves during the mixing in the tank leading to produce good stratification, whereas the elbow diffuser increases the turbulent waves during the mixing leading to produce good destratification. (Farmahini–Farahani, 2012) studied numerically the influence of inlet and outlet flow positions in the formation of the thermocline, he found that the thermocline decays or broadens in thickness when the inflow and outflow positions move away from the bottom and top of the thank.

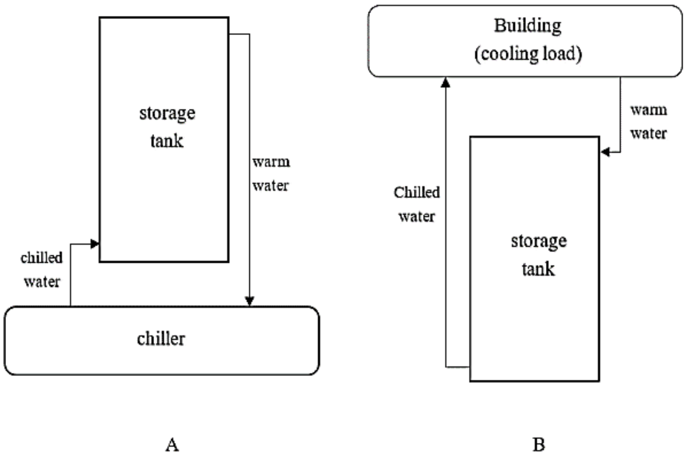

Fig. 2. (A) Charging and (B) Discharging cycles of a stratified chilled water storage system.

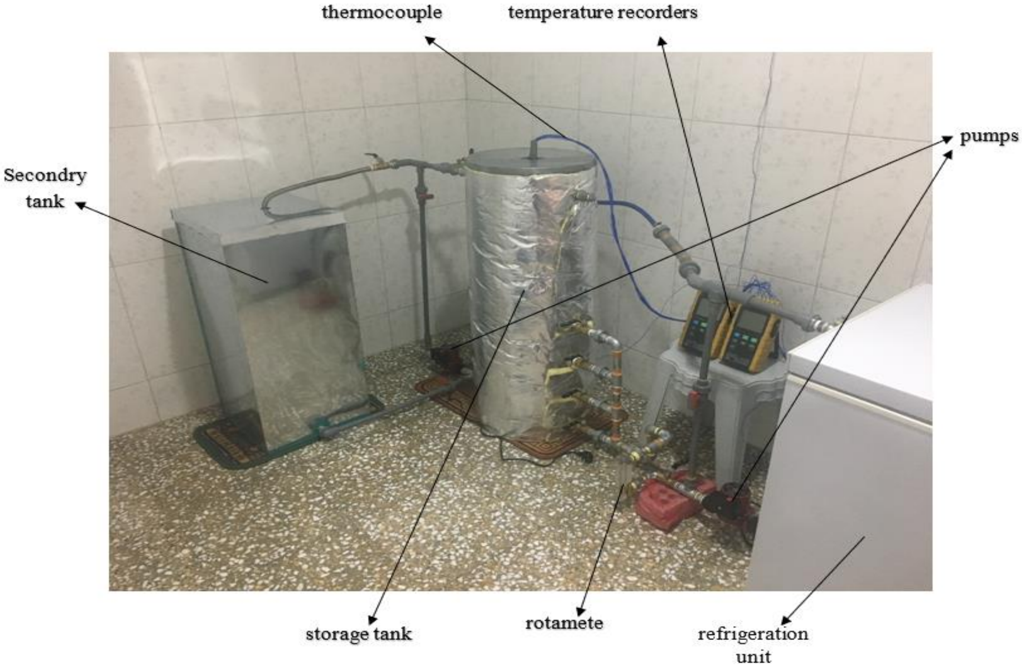

Fig. 3. Stratified chilled water storage test system.

This paper aims at finding the best thermocline by positioning the elbow diffuser and volume flow rate using temperature distributions and performance metrics.

2. EXPERIMENT SETUP

2.1 Components

A stratified test system as shown in Fig. 3 is made up of three main components, a storage tank, secondary tank and refrigeration unit. A test storage tank is a vertical cylindrical galvanised iron tank having dimensions of 400 mm internal diameter, 1100 mm height and 1.5 mm thickness, and contains water, which uses as a storage medium with depth up to 1000 mm. The external wall, bottom and top of the tank are insulated with 50 mm of fibre-glass. A secondary tank is a vertical rectangular galvanised iron tank has bottom dimensions of 400×400 mm and height of 900 mm and holds 144 litter, it employs to receive the water from a storage tank, then leave to a refrigeration unit. Air-Cooled refrigeration unit utilizing a reciprocating compressor has a capacity of 0.5 kW (0.15 ton). Figure 4 illustrates the schematic diagram of the experimental stratified chilled water storage system.

2.2 Inlet Diffuser

The inlet diffuser equipped in a storage tank at different heights is an elbow-type diffuser. The elbow diffuser consists of a single opening of 19 mm internal diameter with a 90° bending angle. It connected inlet pipe joined with the tank wall. The elbow opening is oriented downwards through which the flow enters vertically. The elbow diffuser is

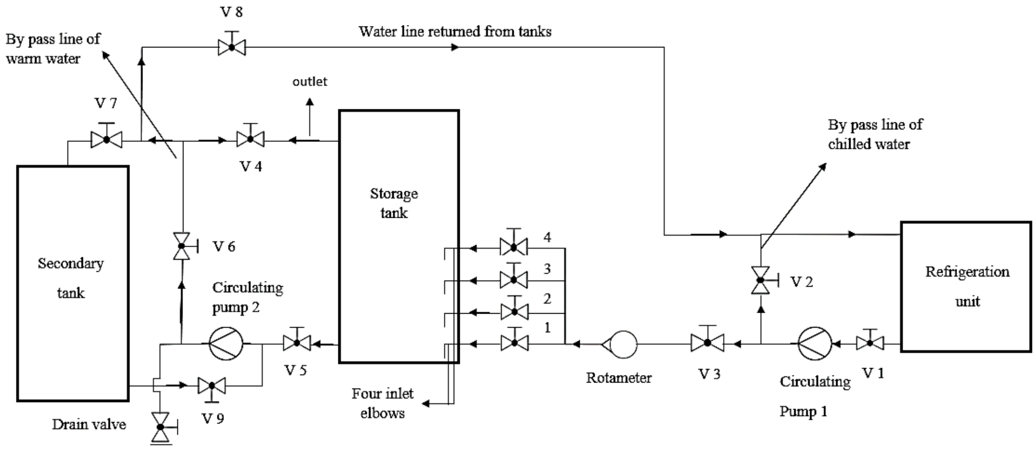

Fig. 4. Schematic diagram of stratified chilled water storage test system.

installed at heights of 20, 170, 320 and 470 mm respectively from the tank floor. The outflow pipe is installed at height 1000 mm away from the tank floor in addition to that the outflow pipe is not connected to the elbow diffuser because it does not have a significant effect on thermal stratification. Additionally, the test process is charging. The outline of the elbow diffuser fitted out in a storage tank is illustrated in Fig. 5.

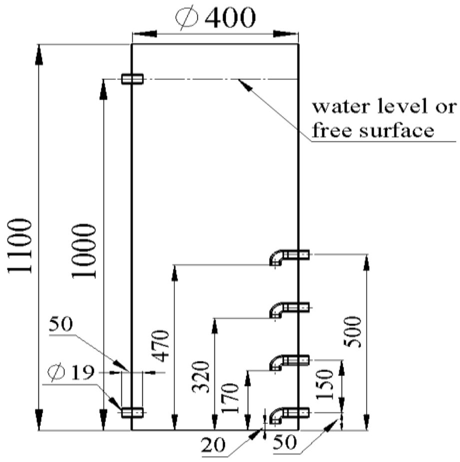

Fig. 5. Storage tank with elbow diffuser distributed at different heights, all dimensions in mm.

2.3 Instruments

K-type thermocouple and rotameter-type flowmeter measuring devices are used in the experiment with uncertainties of ± 0.88°C and ± 0.11 l/min. Nine of the eleven thermocouples are placed in the centreline of the storage tank as vertical positions with 10 cm apart from the tank floor to measure the temperature behaviour along the tank height as shown in Fig. 6. Two other thermocouples are installed at the exit outlet of the refrigeration unit and storage tank in order to measure the chilled or inlet and outlet water temperatures. The rotameter is installed between the refrigeration unit and storage tank to measure the desired volume flow rate through the pipe conveying chilled water.

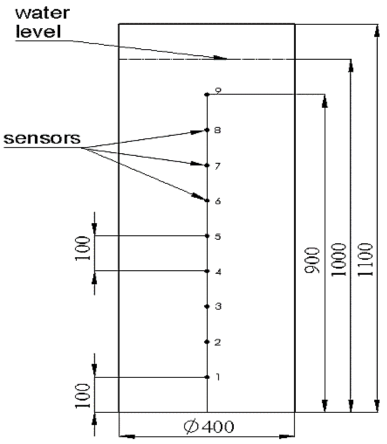

Fig. 6. Temperature sensors distributed along the vertical centreline of the storage tank, all dimensions in mm.

3. PROCEDURE

1. The storage tank initially contains warm water at uniform water temperature of 30°C. The inlet temperature is roughly constant at 4.1°C during the charging process. The charging flow rates are varied from 1.5 to 7.5 l/min with an increment of 1 l/min at each inlet diffuser height. Temperature data is recorded in real-time at 5 second intervals by means of temperature recorder.
2. At the beginning, the chilled water is charged from the refrigeration unit into a storage tank at operating flow rate through elbow diffuser. During the charging process, the warm water enters the secondary tank continually until the process is finished when the tank temperature reaches steady or uniform final temperature. After the end of the process, the water in the secondary and storage tanks leave the

refrigeration unit to be cooled again for testing. This process is repeated seven times for flow rates at each inlet diffuser height.

4. EVALUATION OF STRATIFIED STORAGE TANK

The following variety of metrics are used for measuring the performance of the stratified tank:

4.1 Thermocline Thickness

Thermocline thickness is determined using dimensionless cut-off point temperature (Θ), the dimensionless temperature is defined by (Musser and Bahnfleth, 1998) as given in the following equation:

$$\Theta = \frac{T - T_c}{T_h - T_c} \qquad (1)$$

Where T is the measured temperature sensor located in the storage tank at a vertical position, T_c according to their definition is the average inlet chilled water temperature, T_h is the warm water temperature sensor in the storage tank. In this paper, T_c is utilized as cold-water temperature sensor in the storage tank. For the charging cycle, the Θ varies from a value of 1 at warm water (initial) temperature to value of zero at cold water (final) temperature. A range of 0.05 to 0.15Θ is the limiting values estimated by them to define thermocline zone. In this study, the thermocline region lies at endpoints 0.15-0.85Θ and holds 70% of the temperature change. The thermocline thickness is specified by intersecting two cut-off points temperatures 0.15 and 0.85 (Θ-axis) with thermocline line of temperature profile, then intersects with Z-axis to define the thermocline thickness as illustrated in Fig. 7.

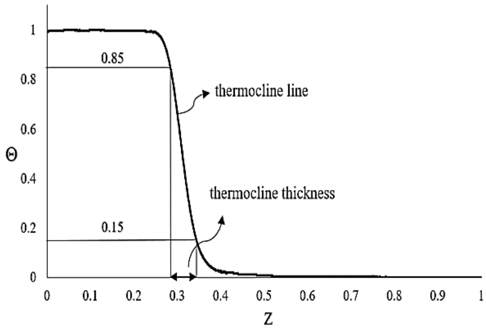

Fig. 7. Defining thermocline thickness from temperature profile.

4.2 Half-Cycle Fig. of Merit

The term half-cycle figure of merit (*FOM½*) of charging cycle for a single tank was proposed by (Bahnfleth and Musser, 1998) to refer to the integrated capacity to the maximum capacity ratio.

$$FOM_{1/2} = \left.\frac{C_{int}}{C_{max}}\right|_{single\ tank} \qquad (2)$$

Maximum capacity (C_{max}) for one tank volume defines the maximum energy measured between average initial tank water ($T_{ave,initial}$) and average inlet water temperatures ($T_{ave,inlet}$) before the mixing occurs.

$$C_{max} = \rho\ A\ H\ c\ (T_{ave,initial} - T_{ave,inlet}) \qquad (3)$$

Where ρ, A, H and c are water density (m^3/kg), tank area (m^2), usable tank height (m) and specific heat (kJ/kg °C) respectively.

Integrated capacity (C_{int}) for one tank volume is the useful energy measured between average initial tank water and average final tank water temperatures ($T_{ave,final}$).

$$C_{int} = \rho\ A\ H\ c\ (T_{ave,initial} - T_{ave,final}) \qquad (4)$$

By inserting Eqs. (3) and (4) into Eq (2), to obtain:

$$FOM_{1/2} = \frac{T_{ave,initial} - T_{ave,final}}{T_{ave,initial} - T_{ave,inlet}} \qquad (5)$$

4.3 Equivalent Lost Tank Height

Equivalent lost tank height (*ELH*) as defined by (Musser and Bahnfleth, 1999) is the ratio of lost capacity existed in a storage tank that cannot be eliminated to the maximum capacity per lost depth of water.

$$ELH = \left.\frac{C_{lost}}{\rho\ A\ c\ (T_{ave,initial} - T_{ave,inlet})}\right|_{\substack{single\\ tank}} \qquad (6)$$

Lost capacity (C_{lost}) is the lost water energy that is calculated in the area between average final temperature and average inlet temperature.

$$C_{lost} = \rho\ A\ H\ c\ (T_{ave,final} - T_{ave,inlet}) \qquad (7)$$

5. RESULTS AND DISCUSSION

Temperature data collected from the storage tank along the vertical height divided into 9 layers are presented in the form of dimensionless temperature (Θ) versus dimensionless tank height (Z) to reveal the degree of stratification. The degree of stratification can be determined based on the following parameters:

5.1 Temperature Distributions

Figure 8 shows temperature distributions at different depths within the storage tank at diffuser height of 20 mm above the tank floor for various flow rates. It is seen that the mixing intensity between warm and incoming chilled water for flow rates falling within the range of 1.5-4.5 l/min is weak. However, the mixing intensity for flow rates from 5.5-7.5 l/min is strong as a result of high inertia of incoming water. Furthermore, the tails on the inlet side of the thermocline are on the same level at flow rates range of 1.5-4.5 l/min, while the tails for flow rates of 5.5-7.5 l/min. at the beginning of the charging process displace upwards. Consequently, the thermocline at flow rates of 1.5, 2.5, 3.5 and 4.5 l/min. respectively is steeper than that at flow rates of 5.5, 6.5 and 7.5 l/min. respectively. On the other hand, it is observed that when the thermocline regardless of diffuser height and flow rate moves up, the thermocline thickness increases with the continuation of charging process, the reason is due to the heat transfer by conduction across a thermocline.

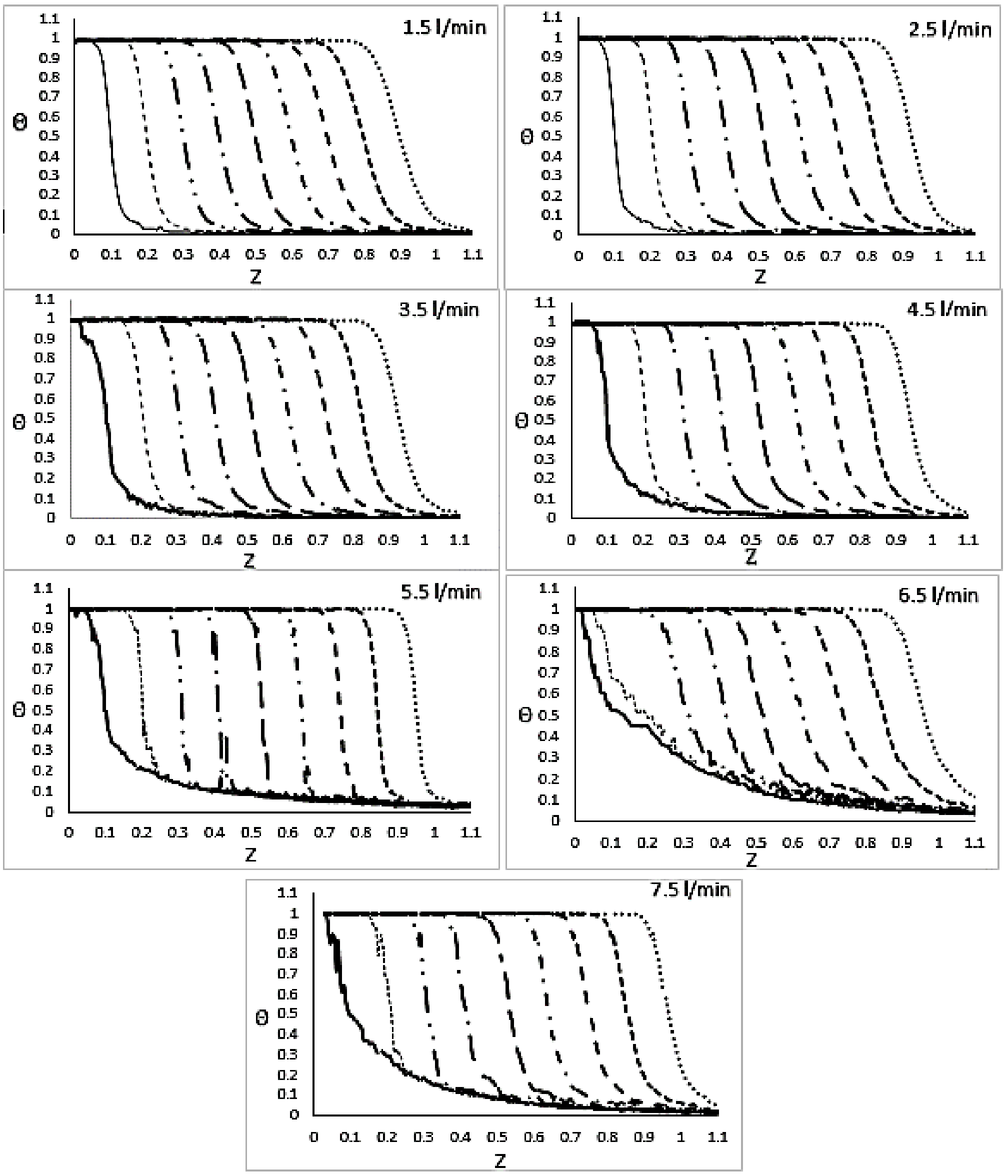

Fig. 8. Transient temperature distribution within vertical storage tank at various sensors of different flow rates for inlet diffuser height 20m.

Figure 9 portrays the temperature distributions at inlet diffuser heights of 170, 320 and 470 mm respectively for various flow rates. It is observed that the thermocline broadens as the diffuser moves away from the tank floor, that is to say, the thermocline at inlet height of 470 mm is larger than that at inlet height of 320 mm and much larger than that at inlet height of 170 mm and very much larger than that at inlet height of 20 mm. In addition, the tails on the inlet side of the thermocline at inlet diffuser heights of 170, 320 and 470 mm for different flow rates displace upwards as a result of diffuser height far away from the tank floor and the inlet flow at inlet height of 170, 320 and 470 mm respectively collides the tank water directly causing turbulent mixing, this will lead to formation of non-steep thermocline while the inlet flow at inlet height of 20 mm collides and moves horizontally along the tank floor resulting in formation of steep thermocline. It can be observed also from Fig. 9 that the temperature profiles obtained from temperature sensors below and near to diffuser opening at inlet heights of 170, 320 and 470 mm respectively are nearly matched because of the diffuser height as mentioned previously in addition to the temperature sensors placed below the inlet flow will give temperature profiles differ from the temperature profiles of temperature sensors placed above the inlet flow. Therefore, the temperature sensors have no significant effect below inflow opening because the temperature data of temperature sensors are almost the same.

The comparison of different inlet diffuser heights can be seen in Fig. 10, temperature profiles are taken at 600 mm away from the tank floor for flow rate of 1.5 l/min. It is found that the thermocline increases with

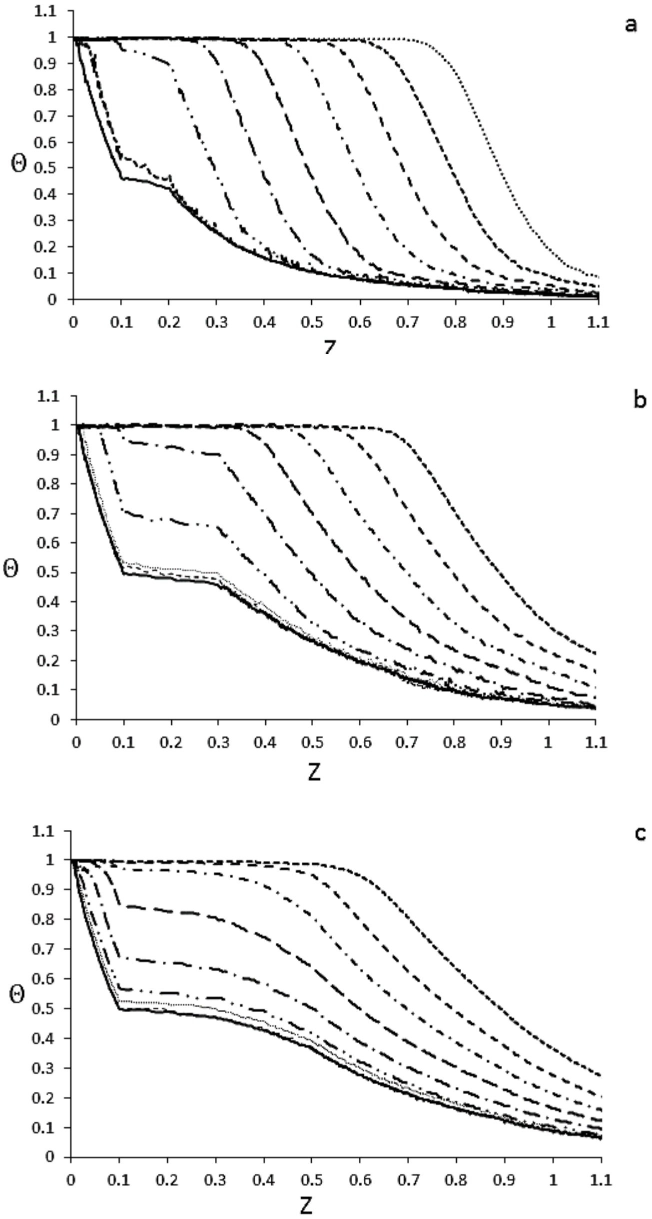

Fig. 9. Temperature distribution in a vertical storage tank at various sensors of different flow charging rates for inlet diffuser heights: (a) 170mm, (b) 320mm and (c) 470mm.

increasing diffuser height, this increase considers not good because the increase in thermocline size tends to reduce the cooling volume. Thus, it is concluded that the thermal separation between warmer and colder water is better when the diffuser inlet height is very close to the tank floor.

5.2 Performance Metrics

The previous section has shown the thermal behaviour inside the storage tank at different inlet diffuser heights for various flow rates and proved that increase in diffuser height tends to deteriorate thermocline. The performance of the stratified tank can be quantified using thermocline thickness (h_t), the half-cycle figure of merit ($FOM_{1/2}$) and equivalent lost tank height (*ELH*). Figure 11 presents the values of the thermocline thickness taken at 900 mm tank height in different diffuser heights for various flow rates. It can be seen that the thermocline thickness at diffuser height of 20 mm is thinner than that at diffuser height of 170 mm and much thinner than that at diffuser height of 320 mm and very much thinner than that at diffuser height of 470 mm. These findings are consistent with findings illustrated in Fig. 10.

Figure 12 exhibits the values of the half-cycle figure of merit at different positions of elbow diffuser versus different flow rates, it is observed that the most values of $FOM_{1/2}$ exceed 90%, which means that the thermal performance is good. The higher $FOM_{1/2}$ lies at diffuser height of 20 mm for flow rates ranging from 1.5-4.5 l/min. Figure 13 displays the equivalent lost tank height at different diffuser heights as a

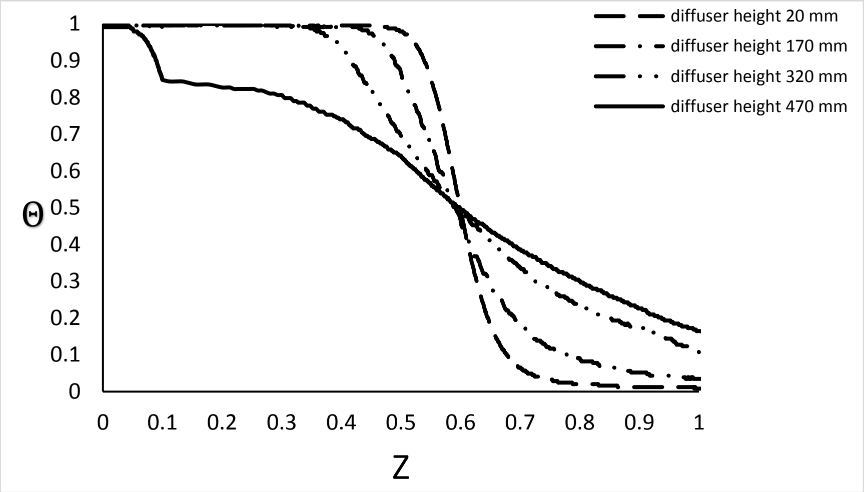

Fig. 10. Comparison of temperature profiles at different inlet diffuser heights with a distance of 600mm away from the tank floor for a flow rate of 1.5 l/min.

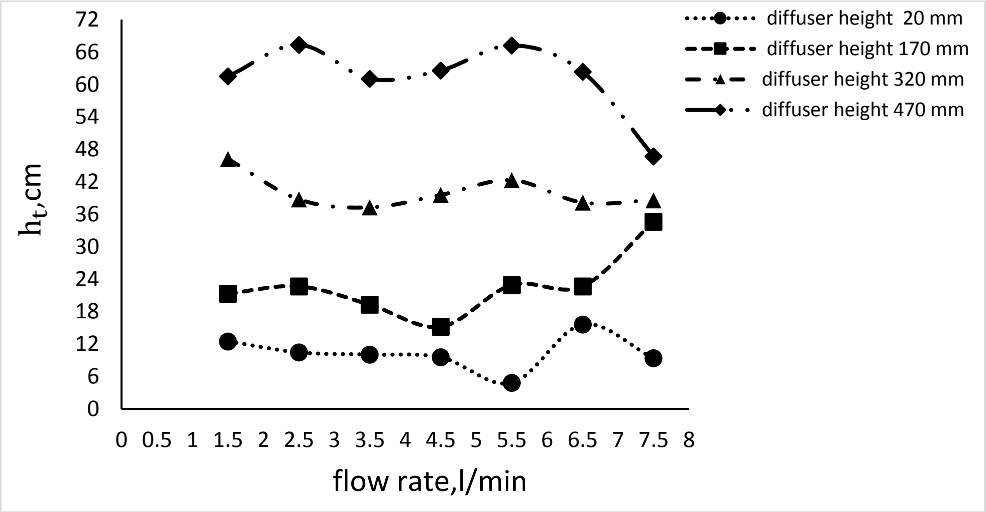

Fig. 11. Measurements of thermocline thickness at different inlet diffuser heights for different flow rates.

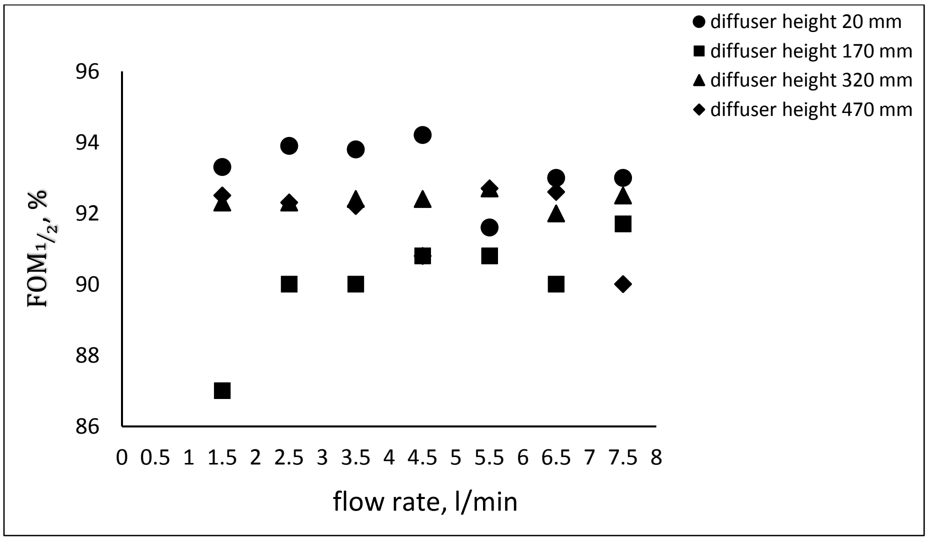

Fig. 12. Measurements of half-cycle figure of merit versus different flow rates at different diffuser heights.

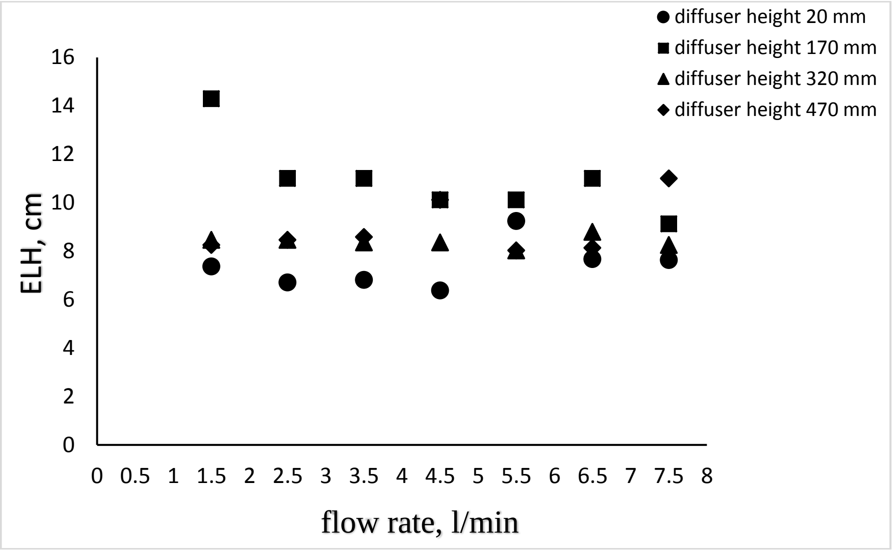

Fig. 13. Measurements of equivalent lost tank height versus different flow rates at different diffuser heights.

function of various flow rates, it is observed from the figure that the lost depth at diffuser height of 20 mm above the tank floor for flow rates 1.5, 2.5, 3.5 and 4.5 l/min respectively is significantly less than that at flow rates 5.5, 6.5 and 7.5 l/min respectively as well as diffuser heights 170, 320 and 470 mm respectively. Based on these results, it can be concluded that the performance of the stratified tank is superior when the diffuser height decreases or approaches the tank floor.

6. CONCLUSIONS

From the investigation of the effect of diffuser height on thermocline, the following findings can be concluded:

- Based on temperature distribution, the diffuser height close to the tank floor greatly improves the thermal separation or produces steep thermocline leading to increase in stored cooling capacity. Whereas the diffuser height away from the tank floor produces a deterioration of thermocline resulting in the reduction of stored cooling capacity.
- Based on performance metrics, the diffuser height closer to the tank floor provides satisfactory thermal performance compared to the performance of inlet diffuser away from the tank floor.
- The mixing between two water masses of different densities near the inlet diffuser close to the tank floor is little at low flow rates operating between 1.5-4.5 l/min. After that, the mixing is violent at high flow rates from 5.5-7.5 l/min.

ACKNOWLEDGEMENT

The authors wish to thank Mustansiriyah university (www.uomustansiriyah.edu.iq) and in particular college of engineering for the use of facilities in their labs.

REFERENCES

Bahnfleth, W. P. and A. Musser (1998). Thermal performance of a full-scale stratified chilled-water thermal storage tank. *ASHRAE Transactions* 104, 377.

Cole, W. J., J. D. Rhodes, K. M. Powell and T. F. Edgar (2014). Turbine inlet cooling with thermal energy storage. *International Journal of Energy Research* 38(2), 151-161.

Dorgan, C. E. and J. S. Elleson (1993). *Design guide for cool thermal storage*: ASHRAE Atlanta.

Farmahini–Farahani, M. (2012). Investigation of four geometrical parameters on thermal stratification of cold water tanks by exergy analysis. *International Journal of Exergy* 10(3), 332-345.

García-Marí, E., M. Gasque, R. P. Gutiérrez-Colomer, F. Ibáñez and P. González-Altozano (2013). A new inlet device that enhances thermal stratification during charging in a hot water storage tank. *Applied Thermal Engineering* 61(2), 663-669.

Hasnain, S. (1998). Review on sustainable thermal energy storage technologies, Part II: cool thermal storage. *Energy conversion and management* 39(11), 1139-1153.

Li, S., Y. Li, X. Zhang and C. Wen (2012). Experimental study on the discharging performance of solar storage tanks with different inlet structures. *International Journal of Low-Carbon Technologies* 8(3), 203-209.

Mackie, E. I. and G. A. Reeves (1988). *Stratified chilled-water storage design guide*: EPRI, Electric Power Research Institute.

Musser, A. and W. P. Bahnfleth (1998). Evolution of temperature distributions in a full-scale stratified chilled-water storage tank with radial diffusers. *ASHRAE Transactions* 104, 55.

Musser, A. and W. P. Bahnfleth (1999). Field-measured performance of four full-scale cylindrical stratified chilled-water thermal storage tanks. *ASHRAE Transactions* 105, 218.

Sohn, C. W., J. Fuchs and M. Gruber (1998). *Chilled water storage cooling system at Fort Jackson, SC.*

Wildin, M. W. (1996). *Experimental results from single-pipe diffusers for stratified thermal energy storage* (0001-2505).

Yoo, J., M. Wildin and C. Truman (1986). Initial formation of a thermocline in stratified thermal storage tanks. *ASHRAE Trans.;(United States),92*(CONF-8606125-).