International Journal of Heat and Technology
Vol. 43, No. 1, February, 2025, pp. 39-46
Journal homepage: http://iieta.org/journals/ijht

Heat Transfer Analysis of Stratified Chilled Water Storage Tank for District Cooling Systems

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https://doi.org/10.18280/ijht.430105

Received: 6 October 2024
Revised: 29 November 2024
Accepted: 13 December 2024
Available online: 28 February 2025

Keywords:
district cooling system, figure of merit, stratification, thermocline, thermal energy storage

ABSTRACT

The cooling demand is rising exponentially across the globe due to adverse environmental conditions, Thus, needs more energy-efficient solutions for commercial and residential applications. District Cooling System (DCS) is a cost-effective method for providing comfort to consumers from a central plant through a distribution network improving the efficiency for reliable solutions in densely populated areas. The research work included designing, developing, and fabricating a DCS system for a 0.5 TR refrigeration system for learning thermal stratification in terms of thermocline thickness, figure of merit, and equivalent lost tank height for different volume flow rates of water. The system can perform experiments for charging and discharging operations to study district cooling systems. The system consists of three sections such as chiller, heating, and stratification. The stratification tank has centrally located ten temperature sensors to measure the temperature drop between the cold and warm water to measure the mixing intensity. It is found that the thermocline thickness is 0.175 m, the figure of merit for half-cycle is 0.9, and the equivalent lost tank height is 0.07 for a water flow rate of 100 LPH. Thus, with the DCS system, energy is saved over the conventional cooling methods with less impact on the atmosphere in terms of CO_2 and GWP for sustainable growth. The CFD simulations of the thermal stratification phenomenon are performed with ANSYS to predict the performance during charging and discharging operations. CFD results are validated with the actual experimental observations for different flow rates. The relationship between mixing intensity and incoming flow is established to study thermal energy storage by stratification. It is found that a stratified chilled water storage system eliminates shortcomings of conventional ice bank storage systems due to higher power consumption for lower evaporating temperatures. Indian industry has now started using the concept of DCS system over other conventional methods as an energy conservation approach for residential and commercial heating, ventilation, air conditioning and refrigeration applications.

1. INTRODUCTION

In district cooling and heating systems, the colony of buildings are air-conditioned as against central air conditioning where only one building is maintained at comfort conditions. The chilled water is produced with a large chiller and supplied to different buildings through the pipe network. DCS systems avoid the initial cost of installing chillers and cooling towers. Thus, the chilled water is supplied as a utility like electricity, water, and gas.

District cooling systems are gaining momentum in India considering the large demand for comfort and commercial applications with environmental solutions. A stratified chilled water storage system eliminates shortcomings of conventional ice bank storage system which is high power consumption due to lower evaporating temperature. District cooling plants are used due to less fixed cost and decarbonization. Thermal Energy Storage (TES) tanks work as a reservoir that can sustain peak load easily [1]. The TES tank reduces the need for using chillers at its peak capacity, fulfilling the disparity between demand and supply of energy. The DCS systems can offer large prospects for energy-saving, energy efficiency, and societal benefits in terms of climate change. In India, at Gujarat International Finance Tec-City (GIFT), the DCS system used is 180,000 TR against the capacity of 270,000 TR. The chilled storage tank is designed in such a way that they are charged during an off-peak period whereas discharged in peak time minimizing electrical demand from 240 MW to 135 MW as per the district cooling guidelines, India. Thus, there is a tremendous saving in energy and environment. The substantial advantage of the DCS is to reduce the required capacity of the chilling plant as systems are designed based on average demand rather than peak demand. TES with a district cooling system provides many advantages over fluctuating refrigeration needs.

It is found that TES reduces around one-third of peak load along with peak electricity demand by 10% to 20% [2]. The thermal energy in the TES is stored in either latent heat or sensible heat. The warm water and cold water coexist in the stratification tank due to the proper design of diffusers. The stratification is observed when the mixing of water, thermal losses, and thermocline thickness is at a minimum. The stratified tank consists of three zones at the bottommost of the tank as chilled water zone, the top, the warm water zone, and the intermediate zone as thermocline region separating chilled and warm water.

The researchers showed that for proper diffusers and height of the tank, stratification efficiency is over 90%. They used cylindrical and radial diffusers in the study of stratification to find out thermocline thickness and found that radial diffusers are better over cylindrical diffusers for Froude number (Fr) of two. They compared the performance of small and large diffusers with octagonal diffusers and found that octagonal diffusers produced minimum mixing for Fr=1. The performance of stratified cooled water storage systems serving in hot, humid regions presented quantitative information about performance [3-5]. It is observed that due to higher daytime ambient temperature than night, 65% more demand for electricity in the daytime [6-8]. They found that TES could save energy, operation, maintenance, and initial costs. In the DCS system, smaller air handling units and ducting are needed due to more temperature difference. The lower the thermocline thickness, the better the stratification and FOM [9-11]. It is observed that the stratification phenomenon is dependent on the MIX Number, stratification coefficient, and exergy loss. They studied that exergy efficiency is an important frame of reference than energy efficiency [12]. They proved that with DCS, waste heat application has improved from 77% to 96% with carbon dioxide reduction by 8% considering environmental conditions [13]. Energy consumption has significantly increased due to population, modernization, and economic development in different countries. The solar and wind energy resources are synchronous [14, 15]. District heating systems are useful for thermal energy consumption in residential and commercial buildings. They developed the Modelica library to study DCS with charging and discharging operations. Thus, they saved the time needed for district heating/cooling system testing and analysis [16, 17].

The CFD simulations are performed for thermocline thickness in a storage tank with different cylindrical openings and diameters. They studied flow patterns with the simulation during charging and discharging operations [18]. They studied thermal energy systems and the parameters affecting the stratification with CFD. They considered five tank dimensions with varying diameters to study the outcome of velocity at the inlet and aspect ratio of the tank for thermocline thickness calculation [19]. They studied the stratification phenomenon and validated it with CFD [20]. Thus, different researchers studied the stratification in district cooling for residential and commercial applications. In the existing research, the experimental setup is designed, fabricated, and developed to conduct trials at different flow rates for charging and discharging operations.

2. EXPERIMENTAL SETUP

The DCS system with stratification tank is developed for 0.5 TR chiller capacity with 150-litre tank storage capacity. The main intentions are to study the conservation of thermal energy, stratification phenomenon with thermocline, figure of merit, and equivalent loss tank height measurement, investigate the relationship between mixing intensity and incoming water flow rate, and carry out CFD simulations during the charging and discharging process. During the charging process, cold water at a temperature of about 4°C to 7°C is pumped into the tank from the bottom diffusers. At the same time, warm water which is relatively lighter than chilled water remained at the top and is finally removed from the tank from the upper diffusers. It is observed that due to the difference between cold and warm water, there is a layer that has a steep temperature gradient region called a thermocline. The thermocline travels in the upward direction in the charging phenomenon while downward during the discharging operation. In discharging, chilled water leaves from the lower diffuser while warm water enters the tank from the upper diffuser [21]. The entire setup is divided into three parts chiller section, reservoir, and stratification. The chiller section consists of a compressor, condenser, expansion valve, and evaporator coil with measuring instruments. The reservoir section consists of a water tank with a controlled heater supply for the preparation of hot water. The stratification system contains a stratification tank with 10 thermocouples along the axis to measure temperatures for thermocline measurement, a flow meter, pumps, and control valves with lower and upper diffusers. Figure 1 shows the schematic diagram of the entire TES by stratification [22-27]. After the chilled water tank is filled with the required temperature of the water, the process of charging in the stratified water tank starts. The valve V2 is kept on so that chilled water from tank 1 goes into the stratified tank. Valves V4 and V5 are designed to control the water flow rate with a flow meter from 50 LPH to 350 LPH. Double circular diffusers having circular holes on their surface of 6 mm are used in the setup.

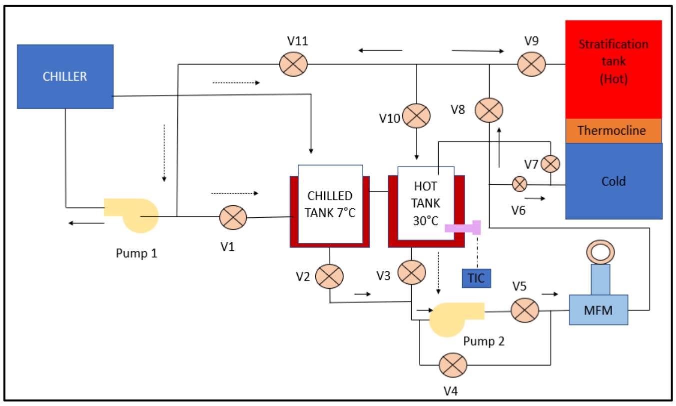

Figure 1. Schematic diagram of TES by stratification

The diffusers are designed such that laminar flow is maintained without mixing cold and hot water in stratified tanks. The chilled water with 7°C temperature moves upward with the flow and warm water escapes from the top diffuser. Through thermocline thickness, actual conduction of heat takes place between hot and cold water during the charging cycle. Schematic diagram 1 shows the components used in the test rig such as cylinders, heaters, chiller, water pumps, valves, and piping arrangement along with measuring instruments. The steel water tank with 40.5 cm diameter, and 111 cm height with 1.5 cm thickness is used to study stratification. The chiller capacity is 1.75 kW to produce chilled water. The secondary tank of 150 Litre capacity is used as a reservoir with water heaters to study the discharging phenomenon. The system consists of two water pumps, one for the chiller and the other during the stratification. The rotameter is provided to measure water flow rate and 10 PT100 thermocouples are employed to measure temperatures along the axis. The rotameter is calibrated with the uncertainty of ±10 LPH. Temperatures are measured across the center of the tank during charging and discharging operations with ±0.3°C accuracy. Thus, during the charging operation, chilled water is produced at around 4 to 7°C and sent to a stratified tank such that valves V2, V4, and V6 are opened with the second pump ON with the flowmeter. The temperature at various points along the centre line in the stratification tank is measured with thermal sensors. The equations are used for calculating thermocline thickness, figure of merit, and equivalent lost tank height for the performance of stratification in DCS.

Figure 2 shows the mechanical architecture of the stratification tank. Table 1 shows the performance parameters for a water flow rate of 100 LPH. The components used in the stratification system are shown in Table 2 and Table 3 show the specifications of components used in the experimental model.

Initially, cold water at 7°C is prepared in the chiller section, and the storage tank is with normal water at ambient temperature. Water flow rates are varied from 100 LPH to 300 LPH. During the charging, chilled water enters the tank from bottom to top producing thermocline thickness between chilled and warm water.

Figure 3 shows the test rig developed with inner and outer details to find thermocline thickness, equivalent loss tank height, and FOM to study charging and discharging operations, consisting of three sections: A chiller section, reservoir, and stratification tank. The chiller is used to produce chilled water up to 4°C, a reservoir section, and a water heater section are provided to study discharging operations, and a stratified tank with thermal sensors is offered to calculate mixing intensity in terms of thermocline thickness.

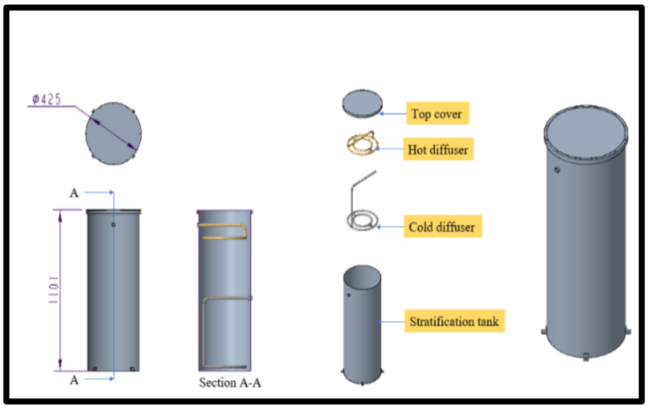

Figure 2. Mechanical architecture of stratification tank (All dimensions are in mm)

Table 1. Performance parameters for a water flow rate of 100 LPH

Temp	Start (min)	End(min)	Interval(min)	Flow(ltr)	Volume (m^3)	Thermocline Thickness (mm)	Equivalent Lost Tank Height m	Figure of Merit
T1	2.5	15.75	13.25	22.0833	0.02208	175.82	0.0739	0.926087
T2	5.25	25.25	20	33.333	0.03333	265.39	0.0739	0.926087
T3	8.75	31.5	22.75	37.9166	0.03791	301.88	0.0739	0.926087
T4	16.25	42.5	26.25	43.75	0.04375	348.33	0.0739	0.926087
T5	22	52	30	50	0.05	398.09	0.0739	0.926087

Table 2. Components used in the setup

Sr. No.	Component	Actual Picture	Sr. No.	Component	Actual Picture
1	Compressor		4	Pressure Gauges	
2	Condenser Fan		5	Water Tanks	
3	Evaporator Coil		6	Water Pumps	

Table 3. Specifications of components used in the experimental model

Sr. No.	Part Name	Part Details	Quantity
1	Compressor	Make: Emerson Make	1
2	Condenser	Air Cooled	1
3	Evaporator coil	12×12 Feet, Tube in tube Type	1
4	Water pump	Make: Luxmi Lada, Model: -J45 Mono block 0.50HP, 1Ph, 230Hz.	2
5	Rotameter	Make: Eureka, Model: PC, Fluid: Water 50 to 500 LPH	1
6	Suction pressure gauge	Make: Wika, 0 to 300 PSIG	1
7	Discharge pressure gauge	Make: Wika, 0 to 500 PSIG	1
8	Expansion valve	Capillary Size: 0.050"×10’×01	1
9	Sintex water tank	Model No: CV 15-01, Capacity: 50 Ltr, Size: 570 mm×490 mm×900 mm	2
10	Ms water tank	Size: 400 mm (Dia), Height: 1100 mm, Capacity: 144Ltr,	1
11	Condenser fan	Make: Hicool, Air Flow: 300CMH, 8" Axial Flow	1
12	Drier	Make: Dryall, ¼’’ DN 50	1
13	Gasket	Size: 25×03 mm	1
14	Ball valve	Size: ¾" (Pump suction)	10
15	Globe valve	Make: Leader, Size: ¾"	2
16	Ball valve	Size: ½"(For drain)	3
17	Water piping	CPVC	1
18	Diffusers	Size: ¾"Copper pipe	2

(a)

(b)

Figure 3. (a) Inner details of the test rig, (b) Test rig developed for experimentation

3. RESULTS AND DISCUSSION

3.1 Thermocline formation in stratification tank

In a stratified storage tank, warm and chilled water coexist at the same time due to the proper design of upper and lower diffusers. Heat transfer by conduction is observed between warm and chilled water through the thermocline section. Thermocline thickness formation is a significant contribution to the stratified tank. The highly stratified system is inversely proportional to the thickness of the thermocline. Thus, a high stratification system has a narrow thermocline and minimum temperature difference. Thermocline thickness (T_H) measures mixing intensity in a stratification tank as shown in Figure 4.

$$T_H = \frac{T - T_C}{T_h - T_C} \tag{1}$$

where, T_c: inlet water temperature, T_h: initial temperature of water in TES tank.

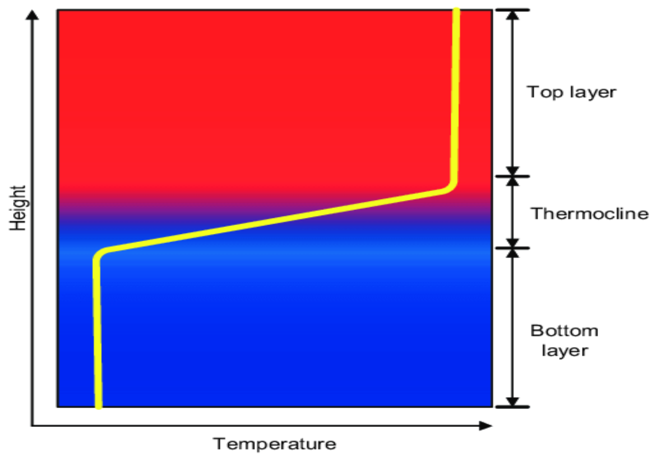

Figure 4. Thermocline in storage tank

It is observed that the dimensionless temperature ratio varies from zero to one. Thus, thermoclines give a clear indication of mixing intensity. The small stable thermocline is a better sign of stratification. It is observed that thermocline thickness depends on natural convection between the outside wall and ambient temperature, mixing of water due to high velocity through the diffusers, diffusion and conduction properties of fluids, and aspect ratio of the stratified tank. Thermocline thickness in the experimental trial was found to be 0.175 m for 100 LPH water flow rate. Figure 5 shows the actual diffusers designed and developed for the storage system at the bottom and top of the stratification tank with 10 holes inside and outside the ring. Thus, thermocline gives a clear indication of mixing between warm and chilled water as shown in Figure 6. Figure 7 represents the temperature of water is different from inlet to outlet.

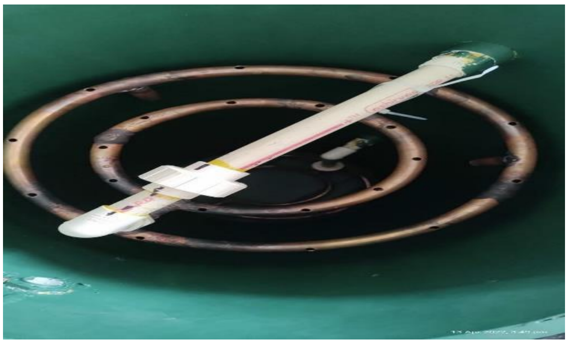

Figure 5. Diffusers used in stratification tank

Thermoclines are plotted for different flow rates such as 100 LPH, 150 LPH, and 200 LPH. It is observed that mixing intensity is proportional to incoming flow. Thermocline thickness increases with an increase in flow rate and hence badly affects the stratification. Thermocline thickness increases with time while charging the tank due to disturbance in the water. Figures 6, Figure 7, and Figure 8 show thermocline formation at 100 ltr/hr, 150 ltr/hr and 200 ltr/hr respectively.

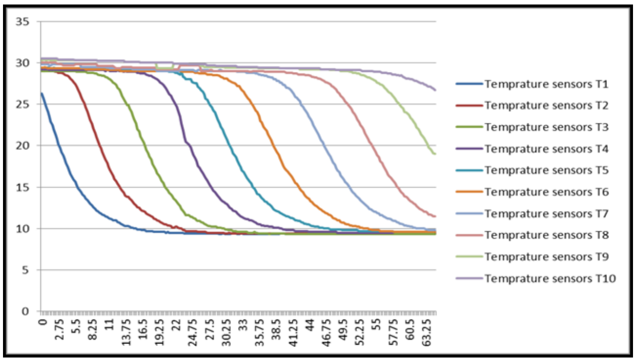

Figure 6. Thermocline for a flow rate of 100 ltr/hr

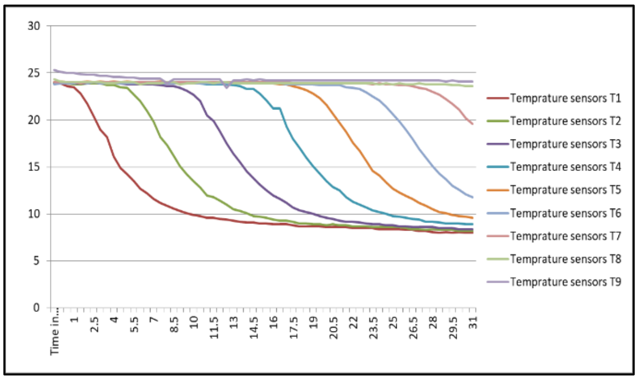

Figure 7. Thermocline for a flow rate of 150 ltr/hr

ANSYS Fluent 2022 is used to simulate a stratified tank with 2D surface model. All quad mesh with a total of 15421 cells, 31107 faces, and 15687 nodes with unsteady state, first order implicit laminar model is used. The boundary conditions given are inlet, outlet, wall, hot water, and cold water. The energy equation is used to assign temperature conditions. The material used is water as liquid with different boundary conditions using standard initialization and assigned different temperature water conditions to hot and cold-water zones. The laminar model in Fluent 2022 is used for simulation for 10000 iterations with an inlet velocity of 0.097 m/s. Figure 9 shows the temperature profile developed during the charging operation.

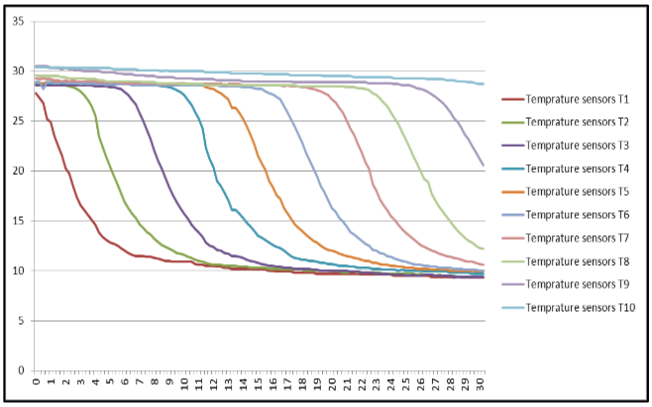

Figure 8. Thermocline for a flow rate of 200 ltr/hr

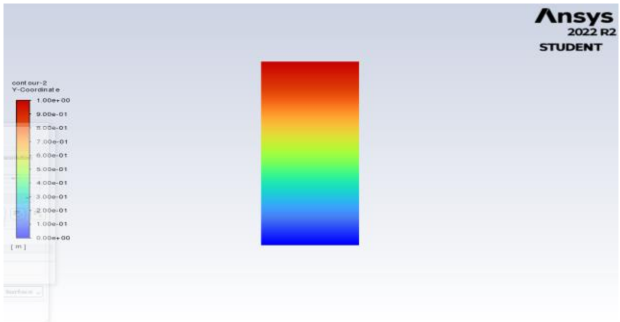

Figure 9. Temperature profile in tank

3.2 Aspect ratio

The aspect ratio is an indicator of tank height and diameter. A higher aspect ratio is better for stratification. Thermocline thickness is inversely proportional to the aspect ratio of the tank. In the experimentation, the aspect ratio of the tank used is 2.75. It is observed that the optimum design of a chilled water tank could help in better stratification along with control of temperature difference, fluid velocity, and thermocline region.

3.3 Flow rate of water

The flow rate of water that passes through a given surface per unit of time is important for mixing. The efficiency of stratification decreased for a large water flow rate. In the experimentation, trials are performed for volume flow rates varying from 50 LPH to 350 LPH.

3.4 Mixing coefficient

Richardson (*Ri*) and Reynolds number (*Re*) indicate the significance of stratification. Richardson number provides information on natural and forced convection while the Reynolds number is a measure of laminar or turbulent flow.

The mixing coefficient is the ratio of Reynolds number to Richardson number. The mixing coefficient of unity represents perfect stratification. It is observed that the Mixing coefficient is a direct measure of thermocline thickness. Reynolds number and Richardson number are expressed as:

$$Re = \frac{\rho v d}{\mu} = \frac{1000 \times 0.0010078 \times 1}{0.001427} = 706.23 \tag{2}$$

$$Ri = \frac{g\beta\Delta Th}{v^2} = \frac{9.81 \times 0.07333 \times 10^{-3} \times 8 \times 5}{(0.0010078)^2} = 28331 \tag{3}$$

The mixing coefficient Z can be expressed as:

$$\begin{aligned} Z &= 1.688 \times 10^4 \left(\frac{Re}{Ri}\right)^{0.67} \\ &= 1.688 \times 10^4 \left(\frac{706.23}{28331}\right)^{0.67} \\ &= 1422.82 \end{aligned} \tag{4}$$

3.5 Figure of merit (FOM1/2)

The Figure of Merit for Half Cycle ($FOM_{1/2}$) is a performance parameter during the charging and discharging cycle. It is the relative measure of discharge capacity to ideal capacity. It is an energy-based performance to calculate cooling capacity lost due to the conduction of heat in the thermocline. The lost capacity is determined when for exit temperature is at the highest temperature (Tlimit) [28-38]. For a charging cycle:

$$\mathrm{Cmax} = \rho\mathrm{AHc}\ (\mathrm{Th} - \mathrm{Tin}) \tag{5}$$

$$\mathrm{Cint} = \rho\mathrm{AHc}\ (\mathrm{Tini} - \mathrm{Tf}) \tag{6}$$

$$\mathrm{Clost} = \rho\mathrm{AHc}\ (\mathrm{Tf} - \mathrm{Tin}) \tag{7}$$

$$\mathrm{Cmax} = (\mathrm{Cint} + \mathrm{Clost}) \tag{8}$$

$$FOM_{1/2} = \frac{T_h - T_f}{T_h - T_{in}} \tag{9}$$

3.6 Equivalent lost tank height (ELH)

Equivalent lost tank height is the ratio of loss capacity to the extreme capacity of the tank. It is a measure of loss of energy in a storage tank due to a decrease in water height due to mixing and heat loss by conduction and convection.

$$\mathrm{ELH} = \frac{\mathrm{C_{LOST}}}{\rho\ \mathrm{c}\ \mathrm{A}\ (\mathrm{T_h} - \mathrm{T_{in}})} \tag{10}$$

where, A=tank projected area, ρ=water density, c=specific heat.

The experimentation is performed on fabricated DCS for different flow rates varying from 50 LPH to 350 LPH. The sample reading is shown below for reference. Water flow rate: 100 LPH, Chiller temperature: 7°C, Hot water temperature: 30°C, Suction pressure: 40 PSIG, Discharge pressure: 130 PSIG. Table 4 shows the instruments used in the experimental setup with the accuracy.

Table 4. Instruments used in the setup

Instrument	Range	Accuracy
Flow meter	0 to 350 LPH	± 0.5 LPH
Thermocouples	-80°C to 200°C	± 0.05°C
Pressure Gauges	0 to 300 PSIG	0.04 PSIG

The system parameters are studied by Hasan and Theeb [1], and the results are compared for different water flow rates. It is found that the results are in good agreement for performance parameters such as thermocline, figure of merit, and tank loss height.

4. CALCULATION

For Q=100 LPH=1.6667 LPM, Start time of 2.5 minutes, and end time equal to 15.75 minutes:

$$\begin{aligned} \text{Time Interval} &= \text{End time} - \text{Start time} \\ &= 15.75 - 2.5 = 13.25\ \text{min} \end{aligned} \tag{11}$$

$$\begin{aligned} &\text{Water passed through thermocouple} \\ &= \mathrm{Q} * \text{Interval} = 1.66 * 13.25 \\ &= 22.083\ \text{Litre} \end{aligned} \tag{12}$$

$$\begin{aligned} \text{Thermocline thickness} &= \frac{\text{Volume}}{\text{Area}} = \frac{0.022}{\frac{\pi d^2}{4}} \\ &= \frac{0.022}{\frac{\pi(0.4)^2}{4}} = 0.17582\ \text{m} \end{aligned} \tag{13}$$

$$[\mathrm{FOM}]\frac{1}{2} = \frac{\mathrm{Th} - \mathrm{Tf}}{\mathrm{Th} - \mathrm{Tin}} = \frac{30 - 9.4}{30 - 7} = 0.926087 \tag{14}$$

$$\begin{aligned} \text{Equivalent lost tank height} &= 1 - [\mathrm{FOM}]\frac{1}{2} \\ &= 1 - 0.926087 = 0.0739 \end{aligned} \tag{15}$$

5. CONCLUSIONS

Experiments are performed on fabricated test rigs for different water flow rates from 50 LPH to 350 LPH with linear diffusers in stratified thermal energy cylindrical tanks for charging and discharging operation and validated results with CFD simulation. The following conclusions are made from the analysis.

- TES tank is a thermal reservoir. Energy is stored in chilled water during off-peak time which can be used in peak time
- District cooling system reduces plant capacity due to energy stored in chilled water during off-peak time. The plant can run on 70% of rated capacity.
- In the case of central air conditioning, more units will be needed as standby for different buildings. In a District cooling system, one stand-by unit is sufficient which reduces operational and initial cost.
- Smaller refrigeration equipment sizes and costs apply to DCS as they are designed for average loads rather than peak loads.
- For a water flow rate of 100 LPH, the performance parameters such as thermocline thickness of 175 mm, half

Figure of Merit as 0.9 with equivalent loss tank height as 0.07 are observed.

- District cooling systems are superior to other air conditioning systems considering operating costs. The district cooling systems can be used as district heating systems in colder countries. Various chemicals can be used with the water to increase the specific heat of the water to increase the cooling energy storage capacity.
- The future research includes computational fluid dynamics study of thermal energy storage for stratification in district cooling systems with different simulation models.

ACKNOWLEDGMENTS

The authors are thankful to ASHRAE USA for providing funding of $5000 under the Equipment Project Grant and to ASHRAE Fellow member, Mr. M. S. Ranade for technical guidance.

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NOMENCLATURE

A	Area of tank (m^2)
C_{Lost}	Lost capacity (kJ)
d	Diameter of tank (m)
ELH	Equivalent loss of height (m)
$FOM_{1/2}$	Half cycle Figure of Merit
Q	Volume flow rate (LPH)
Re	Reynold number
Ri	Richardson number
T	Temperature (°C)
ΔT	Temperature difference (°C)
T_c	Chiller temperature (°C)
T_h	Hot temperature (°C)
T_f	Average temperature (°C)
Tin	Internal temperature (°C)
ρ	Density of water (kg /m^3)
v	Velocity of fluid (m/s)
μ	Dynamic viscosity (Ns/m^2)
β	Thermal expansion coefficient
Z	Mixing coefficient