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Designing and Characterization of a High Reynolds Number Stratified Chilled Water Thermal Storage Tank with Perforated Damper

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Abstract

In air conditioning system electrical demand is more which leads to expansion of thermal power plant to meet this peak demand, which goes unused most of the time. A proper designed thermal storage tank can offset this demand and used for load shifting purpose. A new idea of using perforated dampers near greater extent of mixing occurs is investigated that high Reynolds number flow greater than designed value can be introduced which gives near about FOM as given by designed data value. The important operating parameters are considered in ranges of: r/R= 0.2 to 0.4, r/h_i= 5 to 10. The results indicate that the thermal storage tank stratifies well without any disturbance. It is investigated that the perforation technique gives 67.1 % FOM which can be increased by more improved perforation. The mixing of chilled and warm water at start of charging or discharging affects the shape of thermocline and heat conduction through walls of tank and thermocline causes widening in thermocline.

Keywords: Thermal storage system, Stratification, Charge- discharge cycle, Thermocline thickness, Perforated plates

1. INTRODUCTION

Chilled water thermal storage systems remove heat from storage during off peak cooling demand period and later used it to fulfill air conditioning load during peak hour cooling demand period. The main purpose of this thermal storage tank is load shifting. This natural stratified storage has become the technology of choice because of its simplicity, low cost and retrofitting property.

In naturally stratified thermal storage tank chilled and warm waters are stored without any physical barrier. Stratification is a natural technique used to separate chilled water from warm water by means of horizontal layer formation due to density difference of chilled and warm water. The transition zone which separates chilled and warm water is called as thermocline. Denser chilled water is stored below less dense warm water. To achieve this, during a charge cycle chilled water is introduced at the bottom of tank through diffuser designed to minimize mixing and warm water is removed at the same rate through similar diffuser at the top of the tank and during discharge cycle the process is reversed. The tank remains full at all times while the interface called thermocline moves upward and downward during charge and discharge cycles respectively. Figure 1 explains charge and discharge cycle.

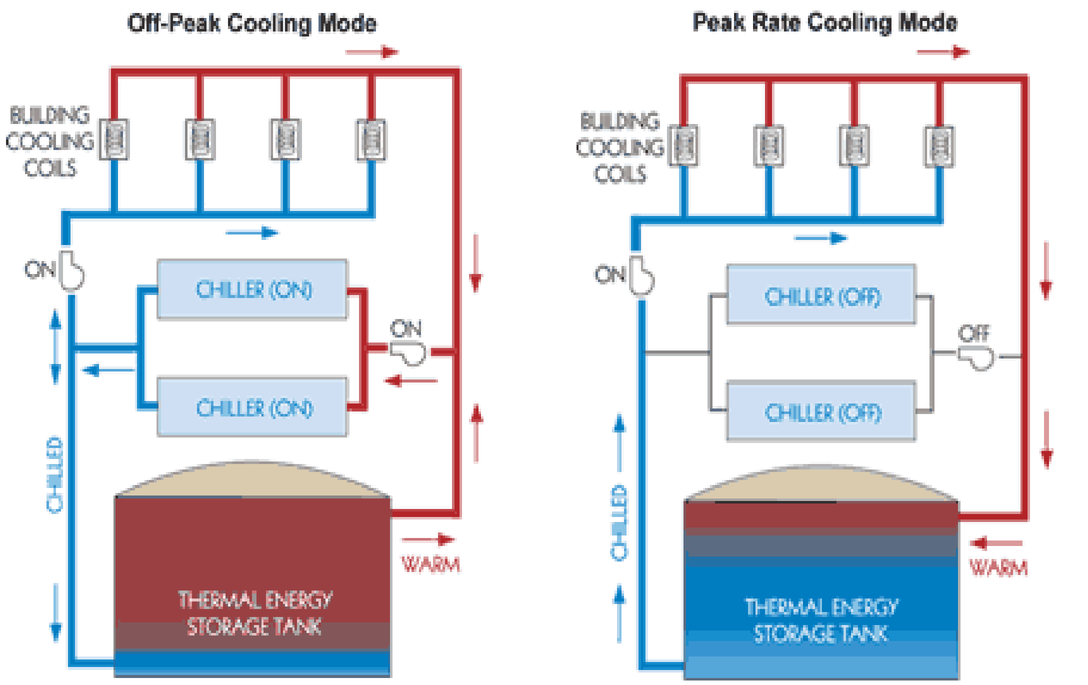


Figure 1. Charge and discharge cycle [1]

As per ASHRAE guidelines some fundamental design considerations of thermal storage system are given below:

1. The temperatures at which chilled water storage are typically charged are 4^0C and 7^0C.
2. For temperature differentials of 6^0 to 11^0 C the chilled water storage volume is generally between 5.9 and 11.3 kWh/m^3.
3. To maintain the temperature differential of 17^0C, the required storage volume is reduced up to 17.7 kWh/m^3.

In order to minimize mixing of chilled and warm water so as to prevent degradation of thermocline thickness and to achieve well thermal stratification, efforts has been made by several researchers. ASHARAE recommends that the water entering to the tank should be at a low velocity so that it can create buoyancy forces and maintain the thermocline.

Baines et al. and Guyer et al. [2, 3] have studied various types of inlet systems investigated by many authors to accomplish thermal stratification in storage tank.

Cole et al. and Bellinger et al. [4] have investigated that for cylindrical tanks, radian disk and circular diffusers are suitable and for rectangular and square tanks, slotted and H-type diffusers are suitable. In this study radial disk diffuser is used.

M.A. Karim et al. [5] has experimentally investigated that the formation of thermocline can be ensured by designing the diffuser with Froude number = 1 and equal pressure drop. Lower Froude number causes unequal pressure drop and unequal flow from different openings. Froude number is defined as the ratio of the inertia force to the buoyancy force acting on a fluid.

Mackie et al. and Reeves at al. [6] reported that for a Froude number of 1 or less, the buoyancy force is greater than inertia force while for higher Froude number it is vice-a- versa which causes jet formation at the downstream of inlet and results in mixing.

$$Fr = \frac{q}{(g\beta hi^3)^{1/2}}$$

Where, q = inlet flow rate per unit length of diffuser

hi = diffuser inlet height

g = gravitational acceleration

β =$\Delta\rho/\rho$, Δ ρ is density difference of chilled and warm water and ρ is water density at ambient.

Musser et al. and Bahnfleth et al. [7] defined that for radial diffuser, h_i is the width between diffuser plate and spreading surface. For lower diffuser spreading surface is tank floor and for upper diffuser is water free surface. Froude number is used to calculate inlet diffuser height whereas Reynolds number is used to determine whether the flow is laminar or turbulent. Reynolds number is defined as the ratio of inertia force to viscous force.

$$Re_i = \frac{q}{\nu}$$

Where q is defined as above and ν is kinematic viscosity of working water. Unlike Froude number criteria for Reynolds number is controversial (Dorgan and Elleson, 1993).

Musser et al. and Bahnfleth et al. [8] have investigated that for very short tanks, recommended design values of Re_i is near about 200 and for large tanks having depth greater than 40 ft. (12.2 m) is about 2000. However some report suggests that all tanks with Reynolds number on the order of 10,000 stratify well and experience good performance of diffuser.

2. PROBLEM DESCRIPTION

To characterize low capacity and high Reynolds number chilled water thermal storage tank. A single cylindrical tank is designed to take care 20% of total cooling load of 200 TR of a system for duration of 60 minutes. This is insulated from outside to prevent any heat exchange. The storage capacity is 9.36 m^3 and Re_i is 660. Cold water and hot water enters/leaves at 4°C and 17°C respectively. Two identical radial diffusers have been used. ASHRAE guidelines recommend that the Reynolds number of such system should be around 200. So during the operation of such chilled water thermal storage tank, there is a probability of destruction of thermocline due to high Reynolds number. Therefore system needs certain internal modification at the exit of diffuser to prevent the destruction of the thermocline. Refer figure (2).

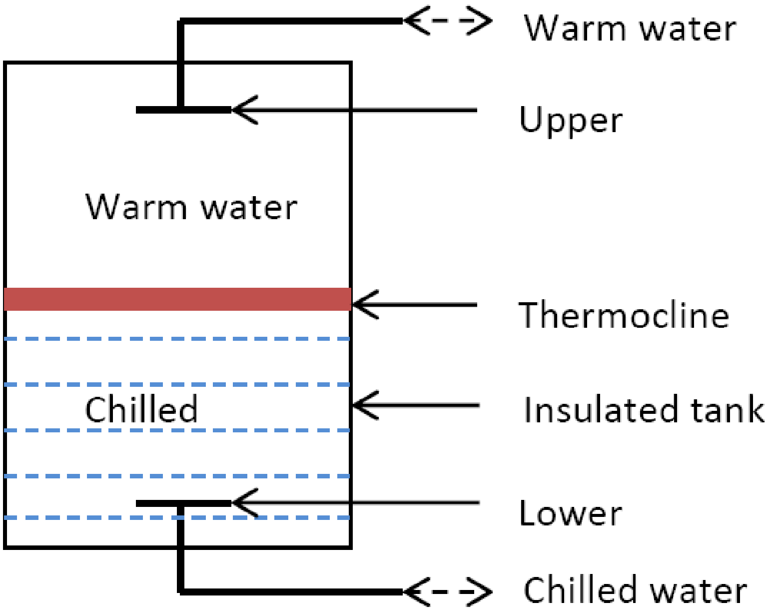


Figure 2. Schematic diagram of storage tank

The objective of present work is to design and characterize the storage tank under high Reynolds number operating condition. To complete the investigation the work is proposed to be executed in three parts:

Part I - Theoretical calculations for tank and diffuser design

Theoretical calculation for mass flow rate, height and diameter of tank, diffuser diameter, diffuser inlet height, Froude number and Reynolds number are carried out.

Part II - Numerical analysis for steady and transient state thermal stratification

Temperature distribution in full scaled tank and thermocline thickness are analyzed.

Part III – Investigating the flow structure evolving inside the tank while using perforated damper

Methodology

In order to decide the size the of the storage tank, the theoretical analysis (part-I) is presented first which is followed by numerical analysis of the remaining two parts. The numerical work is executed by using commercial software i.e. 'ANSYS Fluent'.

Theoretical Analysis:

Part I - Theoretical calculations for tank and diffuser design

a. For tank design

As mention in problem definition 20% stand by unit of 200TR is 40TR for which tank has designed. Mass flow rate is calculated by using equation,

$$20\%\ of\ 200\ TR \times 3.5 = \dot{m} \times Cp \times (T_h - T_c)$$

Where T_h is warm water temperature and T_c is chilled water temperature. From calculated mass flow rate, diffuser exit velocity and velocity in pipe is calculated. A full scaled 3D tank volume is considered to fine tank diameter and height by assuming height to diameter ratio 1.5.

$$\dot{m} = A_1 \times v_1 \times \rho \ \ and \ \ A_1 v_1 = A_2 v_2$$

Here, A_1 is tank area, A_2 is diffuser area, v_1 is velocity in pipe, v_2 is diffuser exit velocity and ρ is density of water. Diameter of tank is D and height is H.

$$V = \frac{\pi}{4} D^2 H$$

b. For diffuser design

For effective thermocline diffuser design must be proper. From Froude number inlet diffuser height is calculated. Following are the parameters of tank and diffuser on which performance of the system is depend:

1. Inlet mass flow rate, $\dot{m}$ (Kg/s)

2. Diffuser exit velocity, v_2 (m/s)

3. Tank radius, R (m)

4. Diffuser radius, r (m)

5. Diffuser inlet height, h_i (m)

6. Kinematic viscosity of working fluid, ν (m^3/s)

The above parameters are studied and investigated from reference of A Musser and W P Bahnfleth [7]. Parameter ranges taken are as follows: r/R from 0.2 to 0.4 and r/hi from 5 to 10. The calculated values are listed in Table 1 below:

Table 1. Tank and diffuser parameters

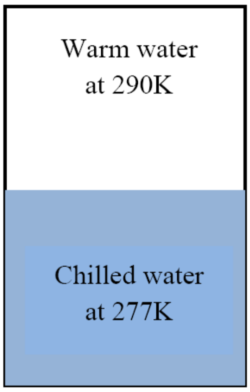
Parameters	**Value**
Froude number, Fr_i	0.97
Inlet Reynolds number, Re_i	660
Inlet flow rate per unit length, q m^2/s	1.0346×10^{-3}
Inlet diffuser height, h_i, m	0.04
Diffuser radius, r, m	0.2 to 0.4
Diffuser exit velocity V_2, m/s	0.0515
Distance between lower parallel plate and tank floor, m	0.1
Diameter of pipe, D_P, inches	2
Mass flow rate, Kg/s	2.6 (156 L/min)

Numerical Investigations:

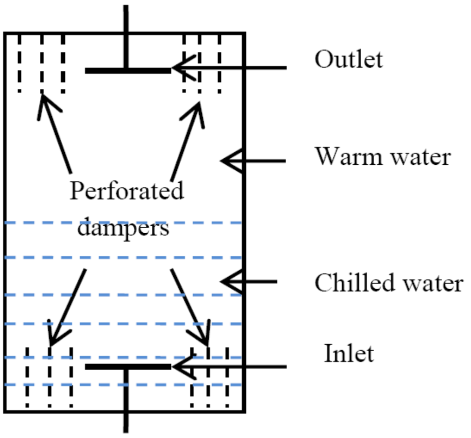
To execute the investigation the proposed thermal storage tank is completely filled with chilled water at bottom and warm water at top of the tank. To damp the flow perforated dampers are placed vertically at bottom and top floor of tank.

Computational domain:

In order to investigate temperature distribution in steady and transient state Fig.3 (a) domain is designed and to investigate the effect of perforation Fig.3 (b) domain is designed.



(a)



(b)

Figure 3. Tank domain

Computational domain size:

A full scale tank of dimension 2m × 3m is created in ANSYS Design Modeler. Whole domain is discretized using MultiZone and Quad/Tri elements.

Mathematical models

Stratification in storage tank depends on mixing of chilled and warm water means directly depends on its density. Froude number plays important role in diffuser designing which decide efficiency of the system. The flow introduces to be of low velocity with less turbulence. The flow parameters can be captured mathematically by using energy, mass and momentum balance considering steady/ transient, incompressible flow with negligible body force.

Continuity equation,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Momentum equation,

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = \rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)$$

Energy equation,

$$C_p = [\frac{\partial T}{\partial t} + \left(\vec{V} \bullet \nabla\right)T] = k\nabla^2 + S$$

Where S is a source term

Turbulence model,

It is observed from the literature review that the physics of such stratified thermal storage has been successfully captured by using K-ε turbulence model.

Turbulent Kinetic Energy (k) Equation:

$$\frac{\partial}{\partial t}(\rho k) + div(\rho k U) = div\left(\Gamma_k grad\ k\right) + G_k - \rho\varepsilon$$

$\Gamma_k = \mu + \frac{\mu_T}{\sigma_k}$ is turbulent diffusion coefficient of kinetic energy

$G_k = \mu_T\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}$ is rate of generation of turbulent energy

Dissipation rate is given by following transport equation:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + div(\rho\varepsilon U) = div\left(\Gamma_\varepsilon grad\ \varepsilon\right) + C_{\varepsilon 1}G_k\frac{\varepsilon}{k} - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}$$

$\Gamma_\varepsilon = \mu + \frac{\mu_T}{\sigma_\varepsilon}$ is turbulent diffusion coefficient of dissipation rate.

Boundary conditions,

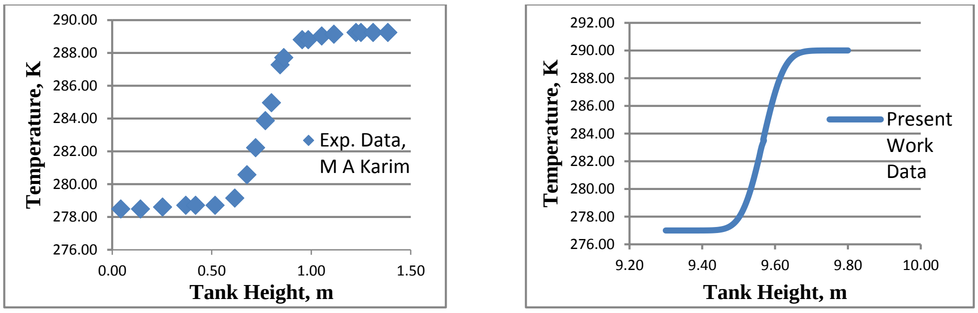
Boundary conditions applicable to present investigation are as given below:
Inlet- Velocity inlet
Outlet- Pressure outlet
Tank- Wall with no slip condition
Other- Interior

Solution method:

Material properties of water at 277K and 290K are taken for investigation, using Energy model, Multiphase-volume of fluid (VOF) model and k- ε Realizable, Standard wall function Turbulence model, variation in pressure and velocity is treated by PISO algorithm. Second order upwind scheme is used to treat the convective effect of momentum, turbulent kinetic energy and turbulent dissipation rate. The convergence criterion is set to be 10^{-3}. Investigated results are analyzed in CFD post.

3. RESULT AND DISCUSSION

The results of Part-I are already mentioned above. Before executing the investigation of remaining two parts the computational model is authenticated by an experimental data collected by doing investigation on similar work done by M A Karim et.al. [5]. He performed a flow visualization test experimentally for the same temperature limit of 4^0C and 17^0C in a transparent tank of dimension 0.8m × 0.8m × 1m. Figure 4 shows temperature distribution profile for experimental data of 5.28 L/min flow rate (Fig.4a) and present work data of 156 L/min flow rate (Fig.4b). From Figure 4, thermocline thickness for experimental data is 0.3m and for present work data is 0.25m.



(a) (b)

Figure 4. Temperature distribution profile

Part II - Numerical analysis for steady and transient state thermal stratification

In this part thermal stratification in full scale storage tank at steady and transient state has analyzed in 2D. Fig.5 shows that if a well stratified thermal storage tank is kept in non-working condition for a longer period then the chilled and warm water inside the tank will come across at same temperature and that water will be of no use for any air conditioning applications. This steady state investigation proceeded for further present work study.

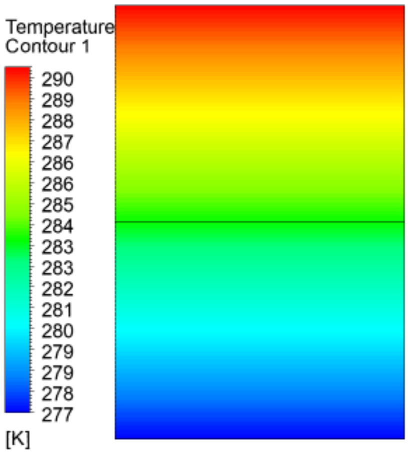


Figure 5. Stratification at steady state

After getting authentication from thermal stratification at steady state, the next part of the investigation of analyzing thermocline thicknesses at various intervals of time are shown in Fig.6. The data presented in the graph below is considered for five time intervals i.e. from 5 min to 5 hrs and accordingly spreading of thermocline thickness is analyzed.

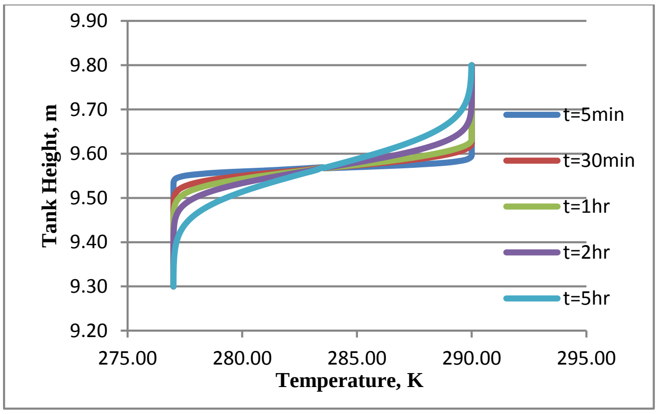
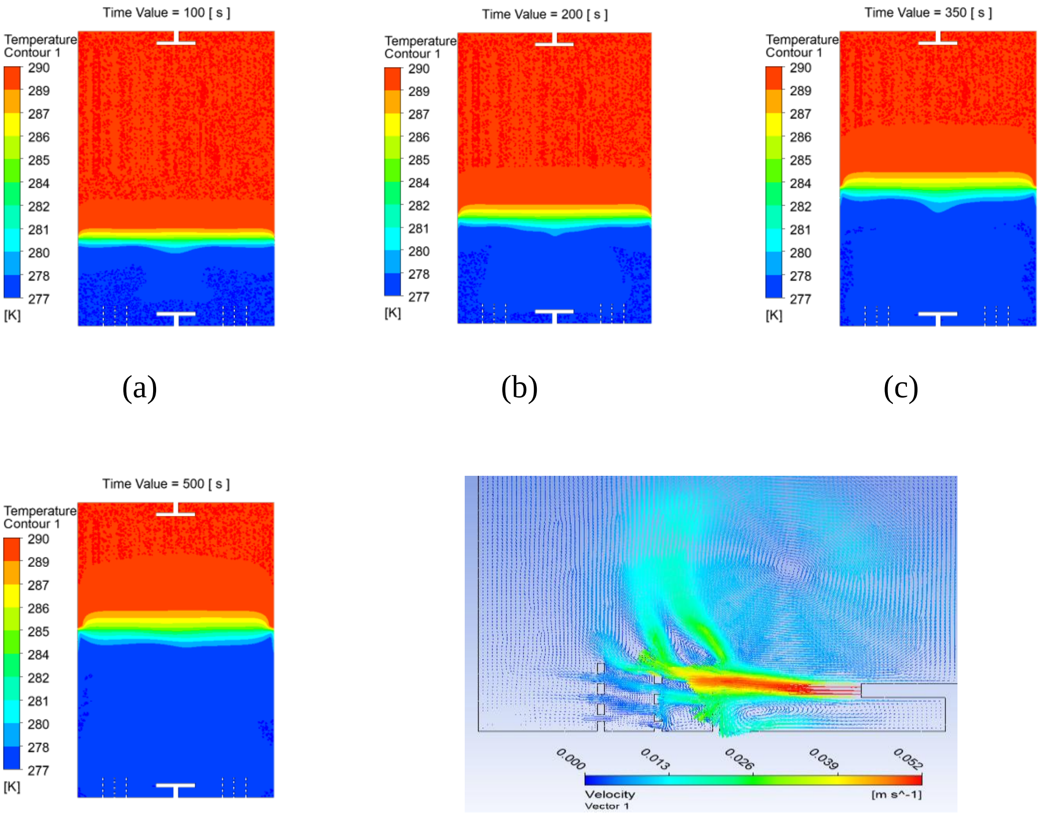


Figure 6. Thermocline thickness

Part III – Investigating the flow structure evolving inside the tank while using perforated dampers

In this section of investigation a new idea of using perforated dampers to damp the flow of high Reynolds number is introduced. Perforated dampers are placed vertically parallel to the wall of tank in such a way that the flow coming out from inlet diffuser will strike on first damper only and then the flow coming out from first damper will strike on second damper only and similarly it goes on (Fig. 7e). It causes the breaking of intensity of flow at bottom region only and do not disturb the thermocline. Hence instead of forming jets the flow gets stabilized at bottom. Even though some jets are formed they are of low intensity and after some height do not disturb the thermocline. Fig. 7 shows case of 0.4m diffuser diameter for charging in which thermocline is moving upward without any physical barrier.



(d)

Figure 7. Effect of perforated dampers on thermocline

Now assuming uniform filling of tank by fixing radius of tank for the same full scaled storage tank (3D) and calculating the interested volume of storage which will be useful for the application. To minimize the meshing and further calculation time, the perforation is carried out for charging only and assumed that the same result is obtained for discharging. The total volume of tank required to fill in one hour is 9.36 m^3 and the interested storage volume calculated for the above case is 6.28 m^3. Hence by linear relation this 6.28 m^3 of volume can be used for 40 min for 40TR cooling load.

To investigate the effectiveness of the system of 0.4m diffuser diamer, figure of merit (FOM) of the system is calculated as 67.1%. FOM is defined as the ratio of instantaneous capacity to total absolute capacity of given volume.

$$FOM = \frac{Area\ A}{Area\ A + Area\ B}$$

Where, Area A= Usable volume

Area B= Unusable volume

Area A + Area B= Total volume.

It is reported in literature that FOM can be up to 80% to 90% for designed values of Reynolds number and Froude number. This 67.1% FOM can be increased by further improvisation in perforation and can reach up to the mark.

4. CONCLUSION

Theoretical calculations of part-I concluded the tank and diffuser design for given operating conditions. In part-II from flow visualization and full scaled 2D numerical simulation it is clear that thermal storage tank stratifies well without any physical barrier. Diffuser design has great influence on thermocline and it should be designed based on Froude number equal or less than one. Part-III concludes that the high Reynolds number flow can be introduced in tank with the provision of perforated dampers. Perforation breaks the intensity of flow and stabilizes it at bottom region without affecting the thermocline.

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