

# A NUMERICAL AND EXPERIMENTAL STUDY ON THE MIXING CHARACTERISTICS OF STRATIFIED THERMAL STORAGE

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**Abstract** : A series of numerical and experimental works are performed for the determination of important design parameters and enhancement of the thermal storage efficiency with a bench scale facility. To this end a 2-D axi-symmetric computer program is developed. For this, a control-volume based finite-difference method is used with the Patankar's SIMPLE algorithm and power-law scheme for the interpolation of convection term.

The calculated temperature profiles with time along the vertical line of storage are compared with the measured ones. The temperature profiles are in general in good agreement especially at the early stage of hot water loading. Further the calculated flow characteristics are analyzed with the aid of the dye visualization experiment, which is injected in charging water. The mixing front shows quite stable and flat for the case of hot water charging from upper inlet, while the front movement of cold water charging from the bottom inlet is quite irregular. This observed difference of mixing front could be well explained by the significant difference of calculated streamlines of two cases.

In general the calculated results with major parameters such as inlet velocity, diffuser shape and diameter, baffles to control flow were physically acceptable and consistent. Further study is recommended to provide optimal determination of design parameters and operating condition for the case of full-scale storage.

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**Key Words** : diffuser, SIMPLE, thermal storage tank, thermal stratification

## INTRODUCTION

Energy storage by thermal stratification is known to be one of the most efficient methods to store surplus energy for later usage and thereby to reduce any possible thermal pollution problem in incineration system. In most cases in practice, a vertical cylindrical tank with a hot water inlet (outlet) at the top and a cold water inlet (outlet) at the bottom is used. The hot and cold water in the tank usually are stratified initially into two layers, with a mixing layer in

between. A properly designed thermal storage system may increase the overall system efficiency significantly. Therefore, it is important for the designers to pay more attention to the thermal performance of the storage tank in system design. The performance of a thermal storage tank is affected by a number of factors. The main ones are tank size, the aspect ratio of tank, inlet and outlet shape of diffuser, and baffle shape to control flow pattern inside storage. Further, the parameters related with operating conditions covers inlet flow condition such as flow velocity and/or momentum, operating temperature range, and loading time. Since many important parameters are associated in this

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process, a series of numerical investigation have been made to minimize the time consuming and expensive experimental works.

Even if a numerical approach by Navier-Stokes equation is able to simulate effectively the flow and temperature distribution in the storage tank to figure out the physical insight of mixing mechanism controlled by the thermal buoyancy and convective mixing, a rather limited research effort are reported in open literatures. Sagara et al.<sup>1)</sup> made a numerical approach to show that this method is effective in examining the outline of the mixing process with many computational penalty due to very fine grid numbers employed in calculations. A two-equation model extended to non-isotropic turbulent flow due to buoyancy was used as the turbulent model. Nakahara et al.<sup>1)</sup> also made a numerical approach to examine the mixing process of the stratified tank, in which Reynolds stresses and turbulent heat fluxes are given with algebraic equations. Ghajar and Zurigat<sup>2)</sup> investigate the numerical accuracy together with the effect of inlet geometry on stratification in thermal energy storage. More recently Al-Najem et al.<sup>3)</sup> develop a general analytical solution for two-dimensional dynamic thermal stratification for variable eddy conductivity with varying inlet temperature. Al-Najem<sup>4)</sup> further investigated the thermocline decay in storage systems. It was found that heat loss to ambient is basically the main destructive item among several loss factors.

In this study, a series of numerical calculation together with experimental work have been made to figure out the physics of design process together with the determination of operating condition in the actual scale-up storage tank.

## MATHEMATICAL MODEL

### Governing Equation

The basic gas-phase conservation equations for mass, momentum, and energy quantity can be expressed, in Eulerian cylindrical framework, as,<sup>5)</sup>

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \cdot (\rho u\phi) = \nabla \cdot (\Gamma \nabla \phi) + S_\phi \tag{1}$$

where,  $\phi$  denotes general specific dependent variables expressed as a physical quantity per unit mass. Further,  $u, v, \rho, \Gamma_\phi,$  and  $S_\phi$  standard for  $x, y$  velocity components, density, diffusion coefficient, and source term corresponding to  $\phi,$  respectively. Table 1 summarizes the diffusion coefficient,  $\Gamma_\phi,$  and source term,  $S_\phi,$  used in this study. The solution of governing equations is done by a control volume based finite difference method used with the Patankar's SIMPLE algorithm and power-law scheme for the interpolation of convection term.<sup>5)</sup>

Table 1.  $\phi$  and  $\Gamma_\phi$  expression for 2-D cylindrical coordinate

Variables	$\phi$	$\Gamma_\phi$	$S_\phi$
Axial momentum	$u$	$\mu$	$\frac{\partial}{\partial x} x \left( \mu \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial u}{\partial x} (\mu r \frac{\partial v}{\partial x}) - \frac{\partial p}{\partial x} - (\rho - \rho_{ref})g$
Radial momentum	$v$	$\mu$	$\frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \mu r \frac{\partial v}{\partial r} \right) - 2\mu \frac{v}{\partial r} + \frac{\rho \omega^2}{r} - \frac{\partial p}{\partial r}$
Tangential momentum	$w$	$\mu$	$-\left( \frac{\mu}{r^2} = \frac{\rho v}{r} + \frac{1}{4} \frac{\partial \mu}{\partial r} \right) w$
Temperature	$T$	$\frac{\mu}{\sigma_T}$	

### Temperature and Density Calculation

It is necessary to consider influence of physical variables that depend on temperature at each grid point. In the case of  $v$  momentum, it is very important to calculate the density exactly because it is included buoyancy force  $-(\rho - \rho_{ref})g$  as in Table 1) in source term. As Eq.(3) indicates, the density calculation is made by polynomial curve fitting.

$$\rho(T) = \rho_{ref} * (0.63420 + 0.19547 \times 10^{-2} \times T + 0.12593 \times 10^{-6} \times T^2 - 0.87217 \times 10^{-8} \times T^3) \tag{3}$$

where,  $\rho_{ref}$  is the density at reference temperature at K.

**Boundary Condition**

Figure 1 represents the experimental setup and schematic diagram of a thermal storage tank employed in this study. The left part of storage tank with wall B.C. is to treat the pipe wall of pumping water via the central part of storage. The right wall of storage tank is considered as an insulating material.

The basic dimensionless parameters which commonly used for the design of thermal storage tank are Reynolds No.( $Re_i$ ) and Froude No. ( $Fr_i$ ). These parameters are introduced as for discussion.

$$Re_i = q / \nu_i \tag{4}$$

$$Fr_i = q / [hi^3 g \Delta \rho / \rho_i]^{1/2} \tag{5}$$

Where,  $q$  is the flow rate per unit length of circumferential direction of diffuser and  $hi$  is the slot height of diffuser. Although much research efforts have been made on the thermal storage tank, the exact range of  $Re_i$  and  $Fr_i$  is still unknown for optimum storage efficiency. Nevertheless general range of these parameters employed are in the range of  $Fr_i \leq 2$  and  $Re_i \leq 800$  available in open literature.<sup>6,7)</sup> Using these definitions, the calculation of basic parameters could be made as follows:

$$q = v, Re_i, h_i = (q / Fr_i)^{2/3} / (g \Delta \rho_i / \rho_i)^{1/3} \tag{6}$$

$$L = Q / q, d_i = L / \pi, A_c = L \times h_i, V = Q / A_c$$

where,  $L, di, Ac,$  are length of circumferential direction, diffuser diameter, injection area of diffuser.

**RESULTS AND DISCUSSION**

The thermal stability and storage efficiency are dependent on various design parameters such as flow rate (inlet velocity), diffuser shape and diameter, slot height of diffuser, inlet condition and so on. In this study, inlet conditions are fixed as volume flow rate  $Q = 11.0$  L/min, slot height  $h_i = 8$  mm, diffuser diameter  $d_i=150$  mm, hot water temperature  $T = 60^\circ\text{C}$  and cold water temperature =  $20^\circ\text{C}$  for most cases of this work. The storage tank diameter is 0.29 m and height is 0.92 m, respectively.

**Temperature Profile Comparison of Hot Water Charging**

The developed computer code is evaluated against experimental data. The comparison results of temperature profiles are shown in Figure 2 for the first 12 min after injection of hot water charging. It represents the temperature distribution along the vertical line at the middle location from the centerline of storage. In more specific hot water ( $60^\circ\text{C}$ ) enters in the upper portion of the tank when storage tank is initially filled with cold water ( $20^\circ\text{C}$ ). As shown in Figure 3, the temperature profiles are in

- ① disk for water inlet
- ② hot water flow line
- ③ wall
- ④ cold water flow line
- ⑤ Insulation material

Figure 1. The experimental setup and schematic diagram of thermal storage tank.

Figure 2. Comparison between the calculation and experimental temperature data for 12 min after loading.

general in good agreement especially at the early stage, but the discrepancy of temperature profiles becomes more visible with time. The reason of this difference was considered due to the combined factors of experimental inaccuracy and numerical error accumulation by more than 200,000 time-step calculations. One of the experimental parameters for this difference considered is by the unsteady charging of hot water pumping. But the exact reason of this difference is not known yet.

### Streamline Analysis of Hot Water Charging

Figure 3 shows a calculated streamline contour for the case hot water ( $60^{\circ}\text{C}$ ) charging in the upper inlet of the tank when storage tank is filled with cold water ( $20^{\circ}\text{C}$ ). As shown in Figure 4, up to 10 min from the initiation of charging, there is no visible evidence of recirculation region and most part of the storage tank remains as a plug-type flow. But at 25 min after hot water loading there show two large recirculations formed in the upper half section of storage tank, which may be quite detriment to thermal stratification.

Figure 4 shows the contour of isothermal lines, in which the isothermal lines are quite flat and parallel to horizontal lines for the cases of 10 and 25 min together. The first case can be explained due to the relatively simple plug-type

Figure 4. The calculated temperature contour plots with time (hot water front).

flow but for the latter case the flat temperature profiles, even if it has strong recirculation in flow, can be explained in that the recirculation occurs after the thermal stratification region as shown in Figure 4.

### Calculation of Cold Water Charging at Bottom Inlet

Figure 5 shows streamline and temperature contour plots for the case of cold water ( $20^{\circ}\text{C}$ ) charging at the lower portion of the tank when storage tank is filled with hot water ( $60^{\circ}\text{C}$ ). As shown in Figure 5, the streamlines are very much complex with many recirculating flows, as compared to Figure 3. The reason why this kind of flow pattern forms is not quite clean at this stage, but it is considered partly as the effect of strong entrainment from the immediately above for the lower injection case. This situation is clearly different with the case of hot water charging, in which the upper boundary condition is considered as free surface. As a consequence of this kind of strong entrainment and thereby flow character of many local recirculation with height, the interface of stratified layer is also unstable as shown in Figure 5. The irregular face of mixing front was also clearly shown and confirmed qualitatively by dye visualization experiment.

Figure 3. Streamline contour plots with time with time (hot water front)

Figure 5. Streamline and temperature contour plots after 10 min (cold water front).

### Parametric Study of Inlet Velocity Change

In Figure 6, contours of streamline and isothermal line are presented with the increase of inlet velocity from 0.15 m/sec to 0.225 m/

sec. As show figures, with increase of the inlet velocity the formation recirculation becomes more significant which is known to be detrimental to the thermal stability. Further the thermal gradient in a thermal stratification region becomes less with the increase of velocity, which stands for the enhancement of mixing between cold and hot water.

### Parametric Study of Diffuser Type

Figure 7 shows the calculation results of different diffuser shape, say, plate type and curve type. The streamline of curved type looks better than the one of flat one especially for the case of high flow rate within the limited flow rate range of this study. However in order to make a more reliable conclusion, a more systematic parametric investigations are recommended.

Figure 6. Distribution of streamline and temperature contour plots the change of inlet velocity ; (a)  $V_{in} = 0.15$  m/sec (b)  $V_{in} = 0.225$  m/sec).

Figure 7. Comparison between the plate type diffuser and curve type diffuser ; (a) plate type (b) curved type.

### Baffle Effect

In order to improve the storage efficiency, investigation is made to control storage flow by the proper set up of baffles. Two different types of baffles are tested as shown in Figure 8. The installment of a new baffle at the location of recirculation formation is tested but is not quite successful. This is because there is another formation of recirculation region due to the effect of new baffle. Considering the unsteady phenomena of storage tank, it is strongly recommended some sort of moving baffles which moves toward the region of high speed flow induced by the decrease of pressure.

be drawn as;

(1) In general, the performance of developed computer program is compared successfully against experimental data of temperature profiles and dye injection flow. It shows that the program is a viable tool for the design of thermal storage tank.

(2) The mixing front shows quite stable and flat for the case of hot water charging, while the cold front is quite irregular. The unstable mixing interface of cold water charging is explained by the strong entrainment of the flow from the immediately above cold water injection.

(3) The performance of the curved-diffuser shows better than the flat one especially for the case of low flow rate. And in general, the increase of inlet velocity causes instability of thermal stratification.

Further systematic parametric study is strongly recommended for the design of scale-up thermal storage.

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Figure 8. Distribution of streamline contour plots with installation baffles ;  
(a) a baffle (b) two baffles.

### CONCLUSION

Based on a series of numerical and experimental investigation, some important results can

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