Study on Air Mixing Limit in Vertical Inlet/Outlet Diffuser of Temperature-stratified Water Thermal Energy Storage Tank by Three-dimensional CFD

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Water Thermal Energy Storage (TES) system is used to cut down heating and cooling cost in the daytime. In the temperature-stratified water TES tank, a diffuser is used as an inlet/outlet for mixing restrain. The upper diffuser in water tank sucks water near water surface in a storage mode of chilled water, and can entrain air from near water surface. Water could not flow through pipe system smoothly under air-mixing condition. This study aims to show a limit condition of air mixing in vertical inlet/outlet diffuser of water TES tank and to provide a design procedure on the safe side.

1. Introduction
A water thermal energy storage (water TES) system has been introduced in many buildings in Japan. Thermal energy required in the next daytime is generated and stored during nighttime using cheaper nighttime electric power and is supplied for cooling and heating in daytime. The TES system can contribute to electric-load leveling as well as water supply for emergency in disasters in case of water TES, which was especially focused on after the Great East Japan Earthquake on March 11, 2011.

The thermal storage tank of water TES is classified into two types; a labyrinth type and a temperature-stratified type. In the temperature-stratified water TES tank, different temperature water is stored without mixing by its density difference, and a diffuser is used as inlet/outlet for mixing restrain of water in tank. A lot of papers discuss about computational fluid dynamics (CFD) simulations of water TES tank

In this paper, a vertical inlet/outlet diffuser which can be installed at low cost is studied. One diffuser is settled near the tank bottom and another diffuser is settled near the water surface, and the smaller depth from water surface results in the better performance of thermal storage (Yu et al. 2010). However, the upper diffuser sucks water near water surface in a storage mode of chilled water, and may entrain air from near water surface. Water could not flow through pipe system smoothly under air mixing condition.

This study aims to show a limit condition of air mixing in vertical inlet/outlet diffuser of water TES tank and to provide a design procedure on the safe side. In this paper, a theoretical study was conducted by using a dam hydraulics theory, and the prediction accuracy of theoretical limit condition derived from dam theory was verified by unsteady three-dimensional CFD analysis.

2. Theoretical study
A theoretical study was conducted, and the relationship between water flow rate flowing into diffuser over its edge in suction mode and diffuser depth from water surface was introduced by using a dam hydraulics theory

For simplicity in theoretical approach, a cylindrical diffuser edge was regarded as an annular dam as shown in Figure-1. Water flow rate flowing into diffuser over its edge is introduced from dam theory as the following equations:

\[ Q = CA \sqrt{2gH_d} \]
\[ A = \frac{W}{H_u - \frac{1}{3}H_d} \]

where \( Q \) [m³/s] is water flow rate flowing into diffuser over its edge, \( H_u \) [m] is water level difference between upper stream and downstream of diffuser edge, \( H_d \) [m] is diffuser depth from water surface, \( W \) [m] is circumference of diffuser edge, \( C \) [-] is flow coefficient and \( g \) [m/s²] is gravitational acceleration.

Water flow rate flowing into diffuser over its edge become larger, as water level difference in both sides of diffuser edge become larger. However, there is a limit to the water flow rate flowing into diffuser, and water flow rate reaches the limit when \( H_u \) equals to \( H_d \). When the upper diffuser tries to suck more water over the limit, there is a possibility to cause air mixing. Therefore, this flow rate was defined as theoretical limit of flow rate flowing into diffuser over its edge. The relationship between water level difference in both sides of diffuser edge and flow rate flowing over diffuser edge is shown in Figure-2.

The relationship between theoretical limit of flow rate and diffuser depth from water surface is derived as the following equation:

\[ Q = \frac{2}{3} CW \sqrt{2gH_u^3} \]
3. Validation of Theoretical Limit by CFD

3.1 CFD analysis domain

This theoretical limit of flow rate was validated by using computational fluid dynamics (CFD) analysis. The temperature-stratified water TES tank in unsteady three-dimensional CFD analysis is schematically shown in Figure-3, in which $r$ is the radius of diffuser, and the radius of analysis domain is four times of the diffuser radius.

3.2 CFD analysis condition

To shorten time required for calculation, three-dimensional analysis was conducted by using symmetry boundary condition. Mesh interval near the diffuser and water surface was 0.5 mm, and it became gradually rougher as it became far from the diffuser and water surface. Analysis conditions in three-dimensional CFD are listed in Table-1.

In this unsteady calculation, a volume of fluid (VOF) method is used, in which a behavior of water and air is calculated as multi-phase flow at the same time. The VOF method can model two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each fluid throughout the domain. Typical applications include the motion of liquid after a dam break, the prediction of jet breakup, the motion of large bubbles in a liquid, and the steady or transient tracking of any liquid-gas interface. In this study, it was defined that a cell was full of air when the volume fraction of cell was 1, and a cell was regarded as water surface when the volume fraction of cell was between 1 and 0.

3.3 CFD analysis cases

Analysis cases in three-dimensional CFD are listed in Table-2. Three cases of different diffuser diameter are studied. For each case, seven conditions of suction flow rate were tested, and included the theoretical limit flow rate and 10%, 20%, 30% plus/minus flow rates from the theoretical limit. Thirty observation points were set above the initial water surface and sixty observation points were set under the initial water surface at 1mm interval on the central axis of diffuser. Volume fraction values were observed at these points and were saved as calculation results at every time step.

4. Result and Discussion

Air mixing situation was examined by observing visualized images of calculation result. In this study, air mixing was judged to occur when air bubbles in diffuser were visually recognized. In all cases, there was significant difference in the state of air mixing when suction flow rate exceeded the theoretical limit. As an example of visualized images, all results of Case B (diffuser diameter: 0.2m) are shown.
in Figure-4, and some results of Case A and B are shown in Figure-5 and Figure-6. In the case in which the suction flow rate was lower than theoretical limit, little air mixing was occurred. Conversely, in the case in which the suction flow rate was larger than theoretical limit, air mixing can be recognized visually. In three-dimensional CFD analysis, each state of air mixing in two sections which were defined as symmetry boundary condition was different from one another. However, there was little difference of them when water flow rate was lower than theoretical limit. According to these results, theoretical limit, which was derived from the dam theory, was appropriate as a condition of air mixing limit.

Volume fraction values were observed and saved every time steps at ninety-one observation points set on the central axis of diffuser, and the water level on the central axis was detected by using these observed data of volume fraction value. Relationships in each case between a relative displacement of water level from initial level and the time for two seconds after the start of suction were shown in Figure-7.

Theoretically, air mixing occurred when the relative displacement of water level from initial level equaled to diffuser depth from water surface. Overall trends indicated that water level did not move down to the level of diffuser edge in the condition of lower flow rate. Additionally, the relative displacement of water level became larger, as water flow rate became larger. These results shows that the limit condition of air mixing can be theoretically predicted with sufficient precision regardless of diffuser diameter.

According to all results, it was found that air mixing did not occur and water level did not move down to the level of diffuser edge when water flow rate was theoretical limit-30%. Therefore, it was concluded that theoretical limit-30% was appropriate water flow rate when temperature-stratified water TES tank with vertical inlet/outlet diffuser was designed on the safe side.
5. Conclusions

This study aims to show a limit condition of air mixing in vertical inlet/outlet diffuser of water TES tank and to provide a design procedure on the safe side. In this paper, a theoretical study was conducted by using a dam hydraulics theory, and the prediction accuracy of theoretical limit condition derived from dam theory was verified by unsteady three-dimensional CFD analysis. It was confirmed by the CFD analysis that the limit condition of air mixing could theoretically predicted with sufficient precision and water flow rate under theoretical limit-30% was appropriate for designing a vertical inlet/outlet diffuser in water TES tank on the safe side.

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