ABSTRACT

It is difficult to evaluate the performance of air-conditioning systems with thermal energy storage tanks, and there are many systems without seeing whether they realize the expected performance or not. The objective of this study is to estimate the performance of water thermal energy storage tank of multi-connected complete mixing type. Measured data was compared with results of simulation using a physical model under ideal conditions in order to detect some faults in the thermal energy storage tank. In this paper, measured data was replaced with generated data by simulation considering influence of buoyancy in order to find an index for detecting faults. The detection method was applied to a real thermal energy storage system and the dead water zone which causes the lower performance of the storage tank was detected.

1. INTRODUCTION

Air-conditioning systems have become increasingly more complex with the progress of technology. When the air conditioning systems have faults, it is difficult for system operators to deal with them. This situation can cause the inefficient energy usage and an uncomfortable indoor environment, and can result in the system breaking down. Even if designers aim to realize an appropriate indoor environment without waste of energy, the highest performance of the system will not be achieved without appropriate system operations.

The objective of this study is to estimate the performance of water thermal energy storage system with water storage tank of multi-connected complete mixing type by using a simplified simulation under ideal conditions. The authors have been trying to detect the faults such as abnormal water level and insulation damage of tank wall by using simplified simulation (Sagara 1997). In water thermal energy storage tank of multi-connected complete mixing type, there can be a large temperature difference between inflow water and tank water. If inflow water is not mixed with tank water, temperature stratification can be generated in the divided tanks, and the dead water zone can appear. In this paper, the detection method of the dead water zone which causes the lower performance of the storage tank is presented. Assuming the simple system consisting of a heat pump, an air-handling unit (AHU) and a water storage tank, the detection method using a physical model for water storage tank was investigated. Then, the detection method was applied to the measured data in a real building and the size of the dead water zone was estimated.
2. PHYSICAL MODEL UNDER IDEAL CONDITIONS

The type of water thermal storage tank is roughly classified into two types; the multi-connected complete mixing type and the temperature-stratified type. The former type is more popular in Japan because it is easy to construct and have a long history, though storage performance is lower than the latter type. Many buildings in Japan have a space under basement floor which is divided by high tie beams for protection against earthquakes. The divided space has been used for water thermal storage tank of the multi-connected complete mixing type. In this study, the measured temperature data are compared with the simulation result by using the physical model under ideal conditions in order to detect fault conditions in the multi-connected complete mixing type.

The assumptions in modeling are as follows.
1. Water is mixed completely in each divided tank.
2. Heat gain and loss through tank wall are neglected.
3. Water density and specific heat are constant regardless of water temperature.

Under these ideal assumptions, water temperature in the $i$th tank is calculated with the following equation (see Figure 1).

$$\rho c_p V_i \frac{d\theta_i}{dt} = \rho c_p q_{in} \left( \theta_{in} - \theta_i \right)$$

The temperature in each divided tank is calculated by a finite difference method in which the calculation time step is 1 second, and the input temperature to the lower/higher temperature end tank is assumed to be equal to output temperature from heat pump/air-handling unit.

3. THE DETECTION METHOD OF THE DEAD WATER ZONE

The detection method of the dead water zone was investigated by using the simulation result. The thermal storage system for this study is composed of a water thermal storage tank of the multi-connected complete mixing type, a heat pump and an air-handling unit. The storage tank is divided into 26 sub-tanks connected in series and its total volume is 400 m$^3$. Operating condition of this system is listed in Table 1. The thermal storage system is shown in Figure 2 schematically, and the plan of thermal energy storage tank is shown in Figure 3. The connecting holes through the tank 1 to the tank 6 are located at lower part near tank bottom in order to generate the dead water zone intentionally.

In the thermal storage tank, the ceiling, bottom and outer wall adjacent to soil are insulated, but the partition walls between divided tanks are not insulated. The water to the heat pump is pumped up from the lower and higher temperature end tank, and chilled water is put into the lower temperature end tank as shown in Figure 2. The water to the AHU is pumped up from the lower temperature end tank and returns to the higher temperature end tank.

3.1 Measured Data Generated by Simulation

Since generated data by simulation considering influence of buoyancy could well simulate the measured data (Kitano and Sagara 2000), we use simulated data as measurement one to find
an index for the detection. This simulation is based on the mixing model for the temperature-stratified thermal storage tank. Here, vertical one-dimensional diffusive and convective heat transfer was assumed. Heat gain/loss through tank wall is taken into account in order to study the effect of heat gain/loss on the fault detecting method. Inflow water from inlet connecting hole is mixed with the tank water in a certain region of the tank. The region is called mixing region in this paper. The depth of the mixing region depends on the inflow conditions and vertical temperature distribution in the tank.

Equation (2) is the governing equation of the mixing model.

$$\frac{\partial \theta}{\partial t} = \kappa \frac{\partial^2 \theta}{\partial z^2} - U_j \frac{\partial \theta}{\partial z} + \frac{\Phi}{A_j} \left( \theta_{in} - \theta \right) + \sum_{k=1}^{6} \frac{A_{W,k} h_k}{\rho c_p V_i}$$

(2)

where $\Phi$ is inflow rate per unit vertical depth in the mixing region. Both integrated values of $\Phi$ and $\Omega$ from 0 to $L_n$ are equal to inflow rate, $q_{in}$.

Heat transfer in concrete tank wall and ambient soil is assumed to be governed by the one-dimensional heat conduction equation.

<table>
<thead>
<tr>
<th>Energy Storage Tank</th>
<th>Operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of energy storage tank</td>
<td>400 [m$^3$]</td>
</tr>
<tr>
<td>Number of divided tanks</td>
<td>26</td>
</tr>
<tr>
<td>Capacity of heat pump</td>
<td>146 [kW]</td>
</tr>
<tr>
<td>Flow rate in heat pump</td>
<td>25 [m$^3$/h]</td>
</tr>
<tr>
<td>Output temperature of heat pump</td>
<td>6 [degC]</td>
</tr>
<tr>
<td>Input/output temperature difference of heat pump</td>
<td>5 [degC]</td>
</tr>
<tr>
<td>Input temperature limit of heat pump</td>
<td>10 [degC]</td>
</tr>
<tr>
<td>Input/output temperature difference of AHU</td>
<td>7 [degC]</td>
</tr>
</tbody>
</table>

Table 1: Operating condition

Figure 1: Schematic diagram of the divided tank

Figure 2: Studied thermal storage system

Figure 3: Floor plan of thermal storage tank

Figure 4: Input temperature, chiller output and cooling load
dimensional unsteady heat conduction equation. Temperature in concrete and soil was calculated with a finite difference method for each wall of divided tank under constant soil temperature at 1m distance from concrete wall. Generated data are the data in the 8th date of simulation started initially with 11 deg C uniform temperature in the whole storage tank. The change of heat pump output, cooling load, and output temperature from heat pump and AHU are shown in Figure 4. In this thermal storage system, heat pump is operated from 0:00 to 12:00 and from 16:00 to 24:00. AHU is operated from 8:00 to 18:00 as shown in Figure 4.

In this simulation, the temperature measurement point is located at the center of each divided tank.

3.2 Temperature Change Rate

Since the dead water zone cannot store thermal energy, the water volume which is effectively used for thermal energy storage in each divided tank becomes less than designed water volume. The less water volume causes the more rapid temperature response. Therefore, the temperature change rate can be an index of temperature response changed by the dead water zone of each divided tank. The temperature change rate is defined as equation (3). This rate is non-dimensional number, and the effect of each tank volume on temperature response can be neglected.

\[
\frac{\Delta \theta^{*}}{t^*} = \frac{V_i}{q_{in}} \left( \frac{\theta_i^{*+1} - \theta_i^*}{\Delta \theta_{AHU}} \right)
\]  

where \( t^* = q_{in} t / V \), \( q_{in} = (q_{in}^{*+1} + q_{in}^*) / 2 \) and \( \Delta \theta_{AHU} \) is the designed input/output temperature difference of AHU. Vertical temperature profiles in the tank 1 to the tank 6 are shown in Figure 5. In this case, chilled water is put into the tank 1, and it flows through the tank 1 to the tank 26. Lower temperature water flows along the tank bottom and almost never flows upward in the tank 2 to the tank 5. This is because lower temperature water has larger density than warmer tank water and the connecting holes are located at lower part near tank bottom through the tank 1 to the tank 6. As a result, the warmer tank water is not mixed with the chilled water and stays at upper part of the tank 2 to the tank 5. The measurement points in the tank 2 to the tank 5 are located within the dead water zone as shown in Figure 5. The temperature change
rate of the simulation result under ideal conditions is compared with that of the measured data generated by a simulation in Figure 6. In the tank 3, temperature change rate of the measured data keeps approximately zero because the dead water zone spreads to the middle of the tank where measurement point is located. In the tank 6 and the tank 16, temperature change rate of the measured data is larger than the simulation result, and the time of extreme value is earlier than the simulation result. The appearance of the dead water zone enlarges the extreme value and quickens the time of the extreme value.

3.3 Difference and Time Lag of Extreme Value

Figure 7 shows the difference of extreme value (see Figure 6, $|E_{\text{mea}}| - |E_{\text{sim}}|$) and the time lag of extreme value (see Figure 6, $T_{\text{mea}} - T_{\text{sim}}$) in all divided tanks under three conditions; (a) the dead water zone are enlarged to the middle part of tank from beginning to end, (b) the dead water zone are scaled down from the middle part to upper part of tanks, (c) the dead water zone are appearing only in the upper part of tanks. In each condition, the difference of extreme value takes large positive value and the time lag of extreme value takes large negative value in the tank 6 located at the downstream side of the tank including the dead water zone. In addition, these values are proportional to the size of the dead water zone because the larger the dead water zone causes the more rapid temperature response. The dead water zone is appearing in divided tanks located at the upstream side of the tank having the maximum difference of the extreme value as shown in Figure 7. Thus it was shown that the difference of extreme value could be used as an index to detect the dead water zone in this study.

4. APPLICATION TO MEASURED DATA IN REAL BUILDING

The detection method shown above was applied to the measured data in a real building. The thermal storage system of this building is composed of a water thermal storage tank of the multi-connected complete mixing type, a heat pump, an air-handling unit (AHU) and fan coil units (FCU). The storage tank is divided into 18 sub-tanks connected in series and its total volume is 329 m³. Operating condition of this system is listed in Table 2. The thermal storage system is shown in Figure 8 schematically. The plan of the thermal energy storage tank and temperature measurement points are shown in Figure 9. In this storage tank, the temperature measurement points are located at the center of the each divided tank except the tank 10 and the tank 11.

4.1 Detection in Charging Mode

The data measured from 20:00 on 25th to 11:00 on 26th of Aug. 2006 were used for the detection of the dead water zone. Input/output temperature of heat pump and flow rate through heat pump in charging mode are shown in Figure 10.

![Figure 7: Difference and time lag of extreme value in each divided tank](image-url)
The difference of extreme value in each divided tank is shown in Figure 11. As shown in Figure 11, the difference of extreme value has the maximum value in the tank 3. According to the results shown in previous chapter, it was expected that the dead water zone was appearing in the tank 2. In order to estimate the size of the dead water zone in the tank 2 in the simulation, the dead water zone ratio of the tank 2 is changed, and its results is compared with measured temperature data. As a result, the temperature difference between the measured data and the simulation result becomes the minimum when the dead water zone ratio in the tank 2 is set as 0.5, and the temperature profiles in the whole tank are shown in Figure 12. The temperature profiles without the dead water zone are shown in Figure 13. As shown Figure 12 and Figure 13, the simulation result changing the dead water zone ratio is similar to the measurement data if compared with the simulation result without the dead water zone. The measured vertical temperature profile shows that the dead water zone was appearing about the upper half of the tank 2 (see Figure 14).

4.2 Detection in Discharging Mode

The data measured from 7:30 to 20:00 on 28th of Aug. 2006 were used for detection in discharging mode. Input/output temperature of heat pump, flow rate through heat pump and flow rate from AHU and FCU in discharging mode are shown in Figure 15.
The difference of extreme value in each divided tank is shown in Figure 16. As shown in Figure 16, the difference of extreme value has the maximum value in the tank 16, and it was expected that the dead water zone was appearing in the tank 17. The temperature profiles in the whole tank are shown in Figure 17. This figure shows that the simulation result is close to the measured data. The connection holes from the tank 14 to the tank 18 are located at the lower part near tank bottom and the higher part near water surface alternately as shown in Figure 9, and the tank water in each tank is expected to be mixed enough. Figure 18 shows the vertical temperature profiles and the dead water zone was not appearing in the tank 2, 9, and 14. However, the temperature data of the tank 17 was measured only at the center of tank and the appearance of the dead water zone in the tank 17 cannot be confirmed.

In order to figure out the temperature distribution in the storage tank, CFD analysis was...
conducted. Figure 19 shows the temperature distribution at section A-A’ (see Figure 9) at 12:20 when the temperature change rate of the tank 16 has the maximum value. As shown in Figure 19, it was found that the warmer inflow water from the tank 18 to the tank 17 flows up near water surface and it is not mixed enough in tank 17. Consequently, the dead water zone is appearing near the bottom of the tank 17. In addition, the warmer water in the upper part of the tank 17 flows into the upper zone of the tank 16. Temperature stratification is formed in the tank 16, and the temperature change rate of the tank 16 is found to become large when the temperature stratification passes across the measurement point at the center of tank.

In this case, the simulation result agreed with the measured data, and tank water was expected to be mixed enough. However, from the result of CFD analysis, the dead water zone was estimated to be appearing in the tank 17 and the appearance of the dead water zone was detected by using the difference of extreme value, which shows that the difference of extreme value is useful as the detection index of the dead water zone.

5. CONCLUSION

In this paper, the detecting method of the dead water zone using simplified simulation under ideal conditions was investigated. Aiming to confirm the temperature response, the temperature change rate was considered to be an index of temperature responses which is changed by the dead water zone of each divided tank. The appearance of the dead water zone enlarges the extreme value and quickens the time of the extreme value. In this study, the difference of extreme value of the temperature change rate between the simulation results and the measured data was proposed to be a detection index of the dead water zone. The detection index was applied to measured data in a real building and the appearance of the dead water zone was detected and its size was estimated.

REFERENCES


NOMENCLATURE

\( h \) : heat gain through tank wall [W/m\(^2\)]
\( q \) : flow rate in thermal energy storage tank [m\(^3\)/s]
\( \theta_i \) : temperature of \( i \)th divided tank [deg C]
\( \theta_{m} \) : temperature into a divided tank [deg C]
\( \theta_{g,m} \) : temperature into a heat pump [deg C]
\( \Delta \theta_{a} \) : designed input/output temperature difference of AHU [deg C]
\( U \) : velocity in horizontal cross section of tank [m/s]
\( \Phi \) : distribution of inflow rate in a divided tank [(m\(^3\)/s)/m]
\( \Omega \) : distribution of outflow rate of a divided tank [(m\(^3\)/s)/m]
\( \kappa_{t} \) : thermal diffusivity of water in thermal storage tank [m\(^2\)/s]
\( A \) : horizontal sectional area of tank [m\(^2\)]
\( A_{w} \) : area of tank wall [m\(^2\)]
\( L_{m} \) : water depth [m]
\( l_{i} \) : position of inflow [m]
\( l_{m} \) : depth of mixing area [m]
\( V \) : volume of a divided tank [m\(^3\)]
\( c_{p} \) : specific heat of water [J/kgK]
\( \rho \) : water density [kg/m\(^3\)]

SUBSCRIPT

\( i \) : tank number
\( j \) : time step
\( k \) : wall number in the divided tank