Thermal performance of naturally stratified water storage tank in a power plant: a comparative study

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Abstract. Thermal storage is one of the key technology in the transformation of thermal power flexibility. A model of naturally stratified water storage tank is established, and CFD analysis of heat release process is made. As can be seen from experimental results in a power plant, in the thermocline thickness in the tank increased from 0.43 m to 0.66 m, with an average hourly thickness of 0.06m, which has well agreement with the CFD analysis results. The effective height of the tank is 29.836m, from which we can calculate that its thermal storage efficiency is as high as 96.7%.

1. Introduction
Cogeneration technology can bring environmental and economic benefits, and is one of the most efficient technologies for rational use of energy. When combined with cogeneration technology and water storage technology, it will reduce the gap between peak and valley of energy consumption and play an important role in reduce the non-renewable energy consumption.

Naturally stratified water storage tank mainly uses sensible heat of water to store thermal energy. Water is used as heat storage carrier. The storage and release of heat can be realized by the heat exchange between heat resource and the water stored in the naturally stratified water storage tank. A water distributor are arranged at the upper and lower parts of the tank to inject hot and cold water into the thermal storage tank as slowly as possible.

Naturally stratified water storage technology can be used in the following application scenarios:
1. Peak load regulating of cogeneration power plant.
2. The utilization of renewable energy (including wind power or photovoltaic power)
3. Urban heating/cooling services (solving urban heating and cooling problems)

Fragaki et al. used Energy PRO under the British peak-to-valley electricity price system to obtain a power plant with an annual heat load of 20,000 MWh. The most economical ratio is a gas turbine with a heat capacity of 3 MWe and one hot water storage tank with 7.8MWh heat capacity. Finally, a sensitivity analysis was made on the factors affecting the optimization results, such as unit efficiency and investment cost [1].

There are dozens of naturally stratified water storage tank projects which have been put into operation in the world. The Fyn thermal power plant in Denmark supplies hot water to Odense for urban heating with a heating capacity of 7700 TJ. There are two generating power unit in the power plant. The generating power unit 1 is 285 MW, the heating capacity is 325 MW, the generating power unit 2 is 400 MW, and the heating capacity is 450 MW. Two garbage incineration units are planned to be built and the hot water from the boiler is supplied to naturally stratified water storage tanks of
73,000 m$^3$. In winter, the maximum temperature of water supplied from power plant heating network is no more than 92 ℃. The height of the tank is about 40m, the diameter of the tank is about 50m, the heat storage capacity of the hot water storage tank is 13,500 GJ, and the heating capacity is 600MW [2].

2. Naturally stratified water storage tank used in the power plant

Naturally stratified water storage technology has many applications in power plants. First, The hot water stored in the tank is used to supply the urban heating load. Second, It also can support the separation of short-term thermal production and power production which is also called as thermoelectric decoupling. Third, it can be used as the deep load regulating of the power and heating load in cogeneration power plant.

2.1. The theory of thermocline in the naturally stratified water storage

The thickness of thermocline is the most important factor which can affect the thermal efficiency of naturally stratified water storage tank. In order to ensure the effective heating capacity of the naturally stratified water storage tank, corresponding measures should be taken to reduce the thickness of thermocline during the design and operation stages.

The thermocline is a natural temperature transition layer formed by thermal conduction between cold and hot water in naturally stratified water storage tank. In naturally stratified water storage tank, due to the density difference between hot and cold water, the natural stratification occurs. Because of the temperature difference between hot and cold water, the heat conduction process will occur near the interface between cold and hot water. Heat conduction will make the temperature of hot water lower and the temperature of cold water higher, thus forming a temperature transition layer at the interface of hot and cold water called thermocline. The gradient of water temperature in the inclined layer is large, and the temperature rises approximately in a straight line along the vertical direction of the naturally stratified water storage [3].

The thermocline in naturally stratified water storage tank is shown in Figure 1. It is assumed that the water temperature in the thermocline distributes linearly along the vertical direction of the naturally stratified water storage tank. The water temperature at the bottom of the thermocline keeps the initial temperature, while the water temperature at the top of the thermocline approaches the inlet temperature of the naturally stratified water storage tank. The thickness of the thermocline is defined by dimensionless temperature $\theta$:

$$\theta = \frac{T(h) - T_1}{T_2 - T_1}$$

$h$: The height of liquid in the thermocline from the cold side, m.
$\Delta h$: The thickness of thermocline, m.
$T_1$: The temperature of cold water stored at the bottom. (The inlet temperature of cold water), ℃.
$T_2$: The temperature of hot water stored at the top. (The inlet temperature of hot water), ℃.

![Figure 1. Definition of thermocline thickness.](image-url)
The variation range of \( \theta \) in the inclined layer is 0-1, at the top of the thermocline, \( \theta \) is 1, while at the bottom, \( \theta \) is 0. The temperature gradient in the upper and lower parts of the thermocline is very little. Therefore, when calculating the thickness of the thermocline, the upper and lower parts are ignored. Usually the effective range of the thermocline is from \( \theta = 0.15 \) to \( \theta = 0.85 \) [4-7].

Temperature distribution in the thermocline:

\[
T(h) = T_i + \frac{T_2 - T_1}{\Delta h} h
\]  

(2)

Conservatively, it is considered that the heat transferred from the top of the thermocline to the bottom of the thermocline is unavailable which can be calculated as follow:

\[
q = \int_0^{\Delta h} \rho C_p A (T - T_1) dh = \frac{1}{2} \rho C_p A (T_2 - T_1) \Delta h
\]  

(3)

\( A \) : The inner diameter of the thermal storage tank, m.  
\( \rho \) : The average density of the thermocline, which is used to simplify the calculation of the water density, kg/m\(^3\).  
\( C_p \) : The average specific heat capacity of the thermocline, which is used to simplify the calculation of the specific heat capacity, kJ/(kg\(\cdot\)K).  
\( \Delta h \) : The thickness of the thermocline calculated by (2-1), m;  
\( T_1 \) : The temperature of cold water (the inlet temperature of cold water), \( ^\circ \)C;  
\( T_2 \) : The temperature of hot water (the inlet temperature of hot water), \( ^\circ \)C.  

The heat stored in the thermal storage tank is as follow:

\[
Q = \rho C_p A (T_2 - T_1) H
\]  

(4)

\( H \) : Water height in thermal storage tank, m;  
\( Q \) : The heat stored in the thermal storage tank, J.  

The effective heat store rate is defined in this paper as follow:

\[
\epsilon_2 = \frac{Q - q}{Q} = 1 - \frac{\Delta h}{2H}
\]  

(5)

\( \epsilon_2 \) : the effective heat store rate.  

(2-5) indicates that the effective heat store rate of thermal storage tank can be improved by increasing the water height in the storage tank or reducing the thickness of thermocline.

2.2. Design of water distributor

The distributor shown in Figure 2 is designed to decrease the thermocline thickness. At present, many studies have shown that Re number, Fr number, water velocity and the structure of water distributor are the main parameters which have important influence on the performance of water distributor. Among them, Fr number is the most important parameter to determine the performance of water distributor.

Firstly, Re number and Fr number should be considered in the process of designing the water distributor. Secondly, the water distributor should ensure the balance of pressure at any two corresponding points on the outlet of the water distributor under various heat load. The structure of water distributor is designed as follows [5-7]:

[Insert Figure 2 here]
2.2.1. Froude number
Definition of Froude number [5-7]:
\[ Fr = \frac{q_i}{\left[ gh_i^3 \left( \rho_i - \rho_a \right) / \rho_a \right]^{1/2}} \]  
\[ q_i = \frac{Q}{L} \]  
$q_i$: Volume flow rate per effective length of water distributor, $m^3/(m \cdot s)$.
$h_i$: minimum inlet opening height, m.
$\rho_i$: density of the inlet water, kg/m$^3$.
$\rho_a$: density of the ambient water, kg/m$^3$.
$Q$: Total volume flow rate, m$^3$/s.
$L$: effective length of water distributor.

2.2.2. Inlet Reynolds number
Definition of Inlet Reynolds number [5-7]:
\[ Re = \frac{q_i}{\nu} \]  
\[ q_i = \frac{Q}{L} \]  
$\nu$: kinematic viscosity of the inlet water, m$^2$/s.

3. CFD analysis of naturally stratified water storage tank

3.1. Modeling and meshing
A 10000m$^3$ naturally stratified water storage tank model is established. 2D-space axisymmetric model is used the CFD analysis of water distributor. The water distributors are positioned in the x-axis direction. The Pressure-Based solver and transient time solver are used. Acceleration of gravity is 9.81m/s$^2$. Quadrilateral and triangular unstructured grids are used in the thermal storage tank. The unit length of the grids is 0.1m except for the water distributor, which the unit length of along it is 0.02-0.03m. In order to improve the calculation accuracy and convergence, the flow boundary layer is set on all the inner walls of the distributor. The number of boundary layers is 5 layers, the thickness of the first layer is 0.0005 m, and the growth rate is 1.2 per layer. The total number of grids is about 52085. The mesh is shown in Figure 3 and Figure 4.
3.2. Solution settings

2D axisymmetric transient solution solver is set up. Because the CFD process involves heat exchange between cold and hot fluids, the energy equation is opened. RNG k-ε turbulence model is selected. Because the natural stratification in tank is mainly driven by gravity flow, the Full Bouyancy Effect is turned on, so that the Energy equation includes buoyancy effect.

The pressure-velocity coupling method is PISO, the pressure difference method is Body Force Weighted method.

3.3. CFD analysis results

The following figures show the temperature distribution in the naturally stratified water storage tank which changes with time during the exothermic stage. Initially, the thermal storage tank is filled with hot water, and the cold water flows from the outlet of the water distributor. After 7 hours, the tank is filled with cold water. The temperature distribution is shown in Figure 5-8.

![Figure 3. Mesh in the thermal storage tank model.](image)

![Figure 4. Mesh along the water distributor.](image)

![Figure 5. t=0.5h.](image)

![Figure 6. t=2.5h.](image)

![Figure 7. t=4.5h.](image)

![Figure 8. t=6.5h.](image)
The thickness of the thermocline is shown in Figure 9:

![Figure 9](image-url)  
**Figure 9.** The thickness of the thermocline changes with time.

Figure 9 shows that the thickness of the thermocline in the tank rises from 0.43 m to 0.65 m, with an average thickness increase of 0.06m per hour, which has good stability.

4. **Performance test of naturally stratified water storage tank and water distributor**  
A 10,000m³ naturally stratified water storage tank and its internal water distributor were designed for a power plant. The parameters of them are shown in Table 1.

| No. | Name                          | Unit | Value   |
|-----|-------------------------------|------|---------|
| 1   | Design pressure              | Pa   | 2000    |
| 2   | Design vacuum degree         | Pa   | 500     |
| 3   | diameter                      | m    | 21      |
| 4   | height                        | m    | 30      |
| 5   | Discharging Flow              | m³/h | 1428.6  |
| 6   | Charging Flow                 | m³/h | 1428.6  |
| 7   | Hot water temperature         | °C   | 95      |
| 8   | Final temperature             | °C   | 45      |
| 9   | Mixing layer thickness        | mm   | 1000    |
| 8   | Tank material                 |       | Q235B、Q345R |
| 9   | Water distributor material    |       | Stainless steel |

The power plant uses six electrode boilers to heat the water stored in the naturally stratified water storage tank.  
The effective volume of the naturally stratified water storage tank in the power plant is 10,000 m³, which has a 560MWh/7 hours heating capacity. The upper and lower temperatures of the hot water storage tank are 95 °C and 45 °C. During peak load regulation period, six 40MW electrode boilers are operated, water in the tank is heated. During non-peak load regulating period, the hot water in naturally stratified water storage tank is sent to the heating network of the urban area.  
Photos of the naturally stratified water storage tank and the water distributor shown in Figure 10-11.
In this paper, the data is selected from 15:21 to 19:40 in an afternoon, which shows the thickness of the thermocline in the heating release period. Comparison of CFD analysis results and experimental results are shown in Figure 12.

Figure 12 shows that the thermocline thickness in the tank increases from 0.43 m to 0.66 m, with an average hourly thickness of 0.06m, which has as well agreement with the CFD analysis results. The effective height of the tank is 29.836, from which we can calculate that its thermal storage efficiency is as high as 96.7%.

5. Conclusions
Thermal storage is one of the key technology in the transformation of thermal power flexibility. The use of naturally stratified water storage technology for the flexible transformation of thermal power units can greatly reduce the load rate of the unit while ensuring heating.

This paper first introduces the definition of thermocline thickness, and then discusses the design method of the water distributor. Next, a naturally stratified water storage tank with a water distributor in it was designed. A model of naturally stratified water storage tank is established, and CFD analysis of heat release process is made. As can be seen from experimental results, the thermocline thickness in the tank increased from 0.43 m to 0.66 m, with an average hourly thickness of 0.06m, which has well agreement with the CFD analysis results. The effective height of the tank is 29.836, from which we can calculate that its thermal storage efficiency is as high as 96.7%.
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