CFD simulations of thermal stratification heat storage water tank with an inside cylinder with openings

Lingkai Konga, Weixing Yua,*, and Ning Zhub

aLaboratory of Ergonomics and Environmental Control, School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, 37 Xueyuan Road, Beijing, 100191, China
bThe company of Beijing Four Seasons Thermal Systems Technology, 19 Tianrong Road, Beijing, 100191, China

Abstract

This paper presents simulation of thermal stratification heat storage water tank with an inside cylinder with openings by three-dimensional Computational Fluid Dynamics (CFD) methods. Specifically, this paper focuses both on investigating the influence of the inner cylinder’s design and operating parameters and on the water flow characteristic, thermal stratification and overall performance of the hot heat storage water tank during heat charging operation process installed in thermal energy systems. Validation of CFD results with experimental data found in the literature has a good consistency. In order to visually compare the efficiency of the energy storage tank with thermal stratification, and the dimensionless fluid temperature, one of existing methods for calculating stratification efficiencies is applied to hypothetical storage process of charging in this paper. Cylinder insides the tank plays a role of uniform diffuser, so that the water in the tank is formed thermal stratification.

1. INTRODUCTION

It is an important research topic that how to improve temperature stratification in a thermal energy storage. Separation of hot and cold fluids contained in a thermal storage tank may be desirable for many applications. In the storage tank, thermal stratification takes place naturally; the cold water remains at the bottom of the tank separated from the hot water, which flows to the top (Lavan and Thompson 1977; Phillips and Dave 1982; Hollands and Lightstone 1989; Cristofari et al. 2003).

The single stratified tank is attractive in low to medium temperature applications, due to its simplicity and low cost. In the solar water heating systems, the improvement of the thermal stratification can improve the charging performance and discharging performance of thermal storage tank. Destratification in thermal storage tank has been
attributed mainly to plume entrainment and mixing produced by inlet flow (Hollands and Lightstone 1989). The structures and parameters of the inlet have great impact on the thermal stratification in thermal storage tank (Zurigat et al. 1991; Eames and Norton 1998). The optimal design of the tank inlet can decelerate the turbulent mixing of the water and enhance the thermal stratification in thermal storage tank, thereby improves the efficiency of the entire system (Al-Najem and El-Reface 1997; Altuntop et al. 2005). The inlet and outlet have a significant influence on the thermal characteristic of the thermal storage tank. The design of inlet and outlet is one key factor of the thermal stratification, the optimized inlet and outlet structures can make the water flow in cylinder toward the direction of stratification, so that the available energy of water in the tank can be utilized in maximum (Berkel 1996; Hahne and Chen 1998). In order to increase the thermal stratification, different plates situate opposite the inlet play good roles. By comparing the different plate sizes, it is found that larger plates make it possible to preserve stratification with larger inlet flow rates than the flow rates of the conventional low flow systems (Zachar et al. 2003). Consequently, thermal stratification in water tank is directly influenced by the inlet configuration. A sintered bronze conical diffuser favours water stratification during thermal charging with both low and high flows. The evolution of the dimensionless height of the midpoint of the thermocline can be used to quantify the mixed volume of water (Eugenio et al. 2013).

Energy storages and the thermodynamic quality or temperature of the energy stored are of primary interest in thermal engineering. Numerous methods have been proposed for the characterization based on temperature of thermal stratification in water storages. As proposed by Panthalookaran et al. (2007), most efficiencies or ratios can be classified as being either based on the first law of thermodynamics or the second law of thermodynamics. To characterize stratification efficiency in a thermal energy storage, the concept of comparing a value derived from an experimentally investigated storage with a value derived from a fully mixed or perfectly stratified theoretical storage has been widely adopted (Abu-Hamdan et al., 1992; Davidson et al. 1994; van Berkel 1997; Shah and Furbo 2003; Andersen et al. 2007; Panthalookaran et al. 2007; Huhn 2007). A fully mixed storage may be obtained assuming complete mixing from the beginning of the experiment (Davidson et al. 1994) or based on a mixing of the experimental storage at the instant of evaluation (Andersen et al. 2007; Panthalookaran et al. 2007).

In the paper, the configuration and operating conditions influence on the stratification performance for thermal energy storage tanks are simulated, using CFD (CFX). A 3D unsteady CFD model has been developed and validated. Three spatial dimensions are used in the mathematical model to calculate the velocity and temperature field.

2. METHODS

The momentum equation of the fluid is based on the two dimensional Navier-Stokes equations and a no-slip boundary condition is specified on the wall. The dependent variables that describe the present flood situation are the temperature, T, the velocity component in the radial direction, U, and the velocity component in the vertical direction, V.

Continuity equation:

$$\frac{\partial U}{\partial r} + \frac{\partial V}{\partial y} + \frac{U}{r} = 0$$

Heat transport equation:

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial r} + V \frac{\partial T}{\partial y} = \frac{\lambda}{\rho c_p} \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial y^2} \right)$$

where $\lambda$ is the laminar thermal conductivity of the fluid and $c_p$ is the specific heat of the water at constant pressure.

This design of a cylinder of openings is mainly aimed at the solar hot water storage tank. Fig. 1 illustrates the geometric model of the solar hot water storage tank. The physical model for charging process in cylindrical tank
consists of inlet and outlet ports. The inlet hot water is from top of the tank and the outlet cold water is from the bottom of the tank as shown in Figure 1. The computational domain is modelled for the whole cylinder.

![Figure 1. Schematic figure of a cylinder of opening thermal stratification storage tank](image)

The working fluid in the storage tank is water. The flow rate inlet boundary condition is applied to the fluid flow, and the outlet of the water storage tank is assigned to be a pressure outlet boundary condition. Adiabatic thermal condition is applied for the storage tank walls by setting a zero heat flux at the wall surface. The hot water enters the tank at the top with velocity \( V_{in} \) through an inlet pipe \( d_{in} \). The inlet is located the top of the cylinder, which is four-fifths of the height. The water exits the tank at the bottom with velocity \( V_{out} \) through an outlet pipe \( d_{out} \). The holes \( d_{hole} \) on the cylinder are evenly distributed. The tank geometrical sizes are specified for the equipment: \( L=2m \), \( d_{T}=1m \), \( d_{in}=0.04m \), \( d_{out}=0.04m \), \( d_{hole}=0.02m \), \( V_{in}=0.05m/s \). The temperature of water flow into the tank is 60°C. The original temperature of water in the tank is 20°C.

The velocity inlet boundary condition is applied to the fluid flow, and the outlet of the water storage tank is assigned to be the opening outlet boundary condition. Adiabatic thermal condition is applied for the storage tank walls by setting a zero heat flux at the wall surface. The relative pressure of the opening outlet boundary condition is zero. No-slip condition is imposed at all solid surface walls, the velocity of the fluid at the wall is zero. That is, the water fluid at the walls is not moving. The condition prescribes:

\[
\begin{align*}
    u &= v = w = 0
\end{align*}
\] (3)

The zero heat flux boundary condition is assigned to every bottom, top and side tank walls, assuming the surface walls are perfectly insulated on outside. The gravity factor is considered in the water tank.

In the dynamic mode the stratified thermal storage system is analyzed for its performance in charge cycle operation. The effects of the operational and geometrical parameters on the thermal stratification are presented in dimensionless temperature and height expressions in order to provide a direct comparison of the results with those found in the literature. Transient temperature profiles are provided as a function of dimensionless height. The dimensionless fluid temperature presented in the figures is defined as follows:

\[
\begin{align*}
    \theta &= \frac{T - T_{ini}}{T_{in} - T_{ini}}
\end{align*}
\] (4)

Where \( T \) is the temperature of water, \( T_{ini} \) is the original temperature of water in the tank and \( T_{in} \) is the temperature of water flow into the tank. The dimensionless fluid temperature can be used to represent the efficiency...
of energy storage tank stratification. For comparison, simulation of tank without an inside cylinder with openings has been finished.

3. RESULTS

Figure 2 shows the results of the CFX after the beginning of the charging process. Dotted lines A indicate the result of tank without an inside cylinder with openings. Solid lines B indicate the result of tank with an inside cylinder with openings. The dimensionless fluid temperature clearly shows the water temperature changes with time, and presents the general trend of the thermocline in the thermal stratification heat storage water tank with an inside cylinder with openings. The hot water flows into the tank and exchanges heat with the cold water. Thus, the thermocline appears. Then as time changes, the thermocline thickness increases, which is caused by heat transfer.

At 1000s, the thermocline is 17% and the stratification efficiency is 83%. At 2000s, the thermocline is 18% and the stratification efficiency is 82%. At 3000s, the thermocline is 18.8% and the stratification efficiency is 81.2%. At 4000s, the thermocline is 19.1% and the stratification efficiency is 80.9%. At 5000s, the thermocline is 20.3% and the stratification efficiency is 79.7%. At 6000s, the thermocline is 21% and the stratification efficiency is 79%. At 7000s, the thermocline is 24.2% and the stratification efficiency is 75.8%. Near the end of the charging process, the thickness of the thermocline increases quickly.

![Figure 2. Cures figure of the dimensionless fluid temperature \( \theta \) in different times after the beginning of the charging process in the tank](image)

4. DISCUSSION

The water in thermal stratification water tank with an inside cylinder can form and maintain the thermal stratification. Compared to tank without an inside cylinder with openings, thermocline is more stable and the upper warm layer is preserved longer in tank with an inside cylinder. The inlet has a little influence at the beginning stage of the charge process. The thermocline temperature changes smooth in thermal stratification water tank with an inside cylinder. Water flows into the cylinder and then to the tank through the holes. Because of the design of the cylinder, the affection by water flow is very small in the tank body area. Even if there is strong turbulence in the cylinder, water flows in tank through the top of the cylinder and these holes, then the water flow rate is small. The low thermal conductivity wall of the cylinder prevents heat conduction between the cylinder and the tank body area.
Inside cylinder with openings plays a role of the uniform diffuser, so that water in tank with an inside cylinder with openings is formed stable thermal stratification. Due to the outlet location and the holes in the bottom of the cylinder, near the end of the charging process, the thermocline thickness increases quickly. When calculating the thickness of the thermocline, the part less than 1°C is ignored. The next work is to explore the impaction of holes spacing.

5. CONCLUSIONS

The 3D transient CFD simulations can be used as an effective tool to optimize thermal storage tank parameters at early design stages. As presented in this paper from numerical result, a cylinder with openings gives better thermal stratification in storage tank when flow rate is slow. An inside cylinder with openings plays a role of uniform diffuser, so that water in the tank is formed steady thermal stratification. The trends for changes of the conditions are well coincident with the results of references.

The thermal stratification efficiency increases in water tank with an inside cylinder with openings. The main factors for stratification efficiency are the parameters of the holes and inside cylinder in water tank with an inside cylinder with openings. The next important task is to find the degree of influence. The cylinder with openings effective parameters can improve stratification efficiency. Thus, the advantages of making simply and installing easily, thermal stratification water tank with an inside cylinder with openings can be widely used.

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References


