Investigation of thermal stratification in a thermal storage tank with a curve edge obstacle plate

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Abstract

Nowadays, thermal storage tanks have been widely installed because of high demanding for hot water in the production process or daily activities in a household. Numerous energy has been consumed to produce hot water. To reduce the energy consumption and improve the energy efficiency of the hot water system, the design of thermal stratification in a storage tank can play as an important parameter on its thermal efficiency. The basic concept of the thermally stratified tank is attempted to separate a layer of hot and cold water by means of density variation and gravitational effects which cold water is aimed to existing at the bottom and hot water is at the upper part of the tank. The level of temperature stratification significantly impacts on the thermal efficiency. The higher degree of thermal stratification, the better thermal efficiency of the hot water system. However, there are many factors strongly affected the thermal stratification such as height-to-diameter ratio, the inner structure of thermal storage tank, the water flow rate, and etc. Therefore, the purpose of this study is to design a thermally stratified tank by improvement the inner structural design of the tank. Two influenced factors are focused: i) the different configuration of inlet pipes which can impact on the flow pattern and flow velocity of the water and ii) the different design of obstacle plates which can help control a recirculation area of the water in the tank. To obtain a high thermal efficiency of the stratified tank, the computer simulation program Ansys Fluent is applied for the analysis. The results show that uniform distribution of water flow and lower flow velocity due to the appropriate design of inlet pipe and proper buffer plate design can enhance the temperature stratification in the storage tank which increase the thermal efficiency during discharging processes.

Keywords: Obstacle Plate, Thermal Stratification, Thermal Storage Tank

1. Introduction

A key aspect of the thermal stratified tank is designed to encourage the separation regions of the hot water and the cold water by using the fundamental properties of fluid on the different temperatures represented different densities. The interface between hot water and cold-water layers is called the thermocline. Studies over the past two decades have provided important information on the development of the thermal stratification in the storage tank, and many parameters applied such as the height to diameter ratio, the water inlet velocity, the shape of the storage tank and the inlet water pipe [1, 2, 3, 4, 5].
5]. Another way to improve the thermal stratification is the implement of obstacle plates inside the tank to reduce the water recirculation in the whole section.

Some research has been carried out on the obstacle plate utilization where Computational Fluid Dynamics (henceforth CFD) has been adopted on many thermal investigations. Shah and Furbo [6] studied the shape of the obstacle plate where was placed over the inlet pipe during the discharging process. The baffle plate provided the best thermal stratification whereas the metro pipe and the bare pipe were inferior, respectively. Bouhal et al. [7] has studied the variation of the position, the number, and the rotating angle of the flat obstacle plates to investigate their effects on the thermal stratification. The results showed that the change of single flat plate positions could not represent the improvement of temperature stratification distinctively. The best stratification occurred on the obstacle plate with 30-degree rotating angle. Altuntop et al. [8] analysed the effect of the obstacle shape on the thermal stratification where it located at the bottom part of the tank. It was found that the single hole flat plate was the greatest model. Ali et al. [9] has tended to focus on the different types of curved baffles as stratifier in the solar thermal storage tank by varying the radius of curved baffles. The result revealed that a single quarter ellipse curve can minimize the water recirculation over the baffle plate resulted in the enhancement of thermal stratification. It has previously been observed that the flat and curved obstacle plate had different advantages and drawbacks as well as the inlet pipe configurations which affected on the thermal stratification.

The purpose of this paper is to consider the implications of the combination of each dominance. It also attempts to show that the deviation of inlet pipe designs and the different arrangement of obstacle plates has an effect on the thermal stratification during the discharging process.

2. Dimensionless parameters

In this study, the performance of thermal stratification was analyzed via the temperature profile and the velocity profile. Additionally, dimensionless numbers shown in Table 1, including with Richardson Number (Ri), Stratification Number (Str), Dimensionless time (τuse), and Discharging Efficiency (η(τuse)) were also used to characterize the thermal stratification in the storage tank. To comparatively evaluate the different storage tank configurations, dimensionless time is given, and it refers to the mass flow rate multiply with time step divided by the whole replacement of water in the tank. Richardson number is used to identify the stratified temperature which is defined as the ratio of buoyancy forces to mixing force. A larger Richardson Number identifies a better stratification. While Stratification Number is the ratio of the average of the temperature gradient at that time interval at the initial state. Besides, discharging Efficiency which is the comparative value between the amount of useful heat at a specific temperature and the total heat recoverable. The temperature of 45°C was determined as the temperature limit of useful heat in the tank.

| Dimensionless Number | Equations |
|----------------------|-----------|
| Dimensionless time [5] | τ = τ / σ, where σ = 𝑛 / 𝑚 |
| Richardson Number [3] | Ri = ɡ β H(Ttop - Tbottom) / V̇ |
| Stratification Number [7] | Str(t) = (dT/dy) / (dT/dy)max |
| Discharging Efficiency [3] | E(τuse) = E(τ use = 0) |
| and E_st(τuse) = mc p Σj=1(Tj-use(τuse = 0) - T_in) |
3. Numerical investigations

3.1 The geometry model and meshing

The shape of the thermal stratified tank at a 520-liter vertical cylindrical with elliptical end caps was chosen. Figure 1 illustrates the tank dimension had a height of 1,480 mm (H), a diameter of 690 mm (D). The inlet pipes and outlet pipes had the diameter of 30 mm and located in the positions of a = 170 mm, b = 190 mm, c = 130 mm, and d = 700 mm, respectively.

Two modification concepts were adopted to evaluate the thermal stratification in the storage tank: modified inlet pipes and using obstacle plates. Figure 2 provides the three different models of the inlet pipe, i.e., direct downward, annular downward, and annular upward, while the original design was non-insertion of the inlet pipe into the tank. The annular inlet pipe had the radius of 172.5 mm included the six water outlets equivalent. Regarding the obstacle plate, four models of plate feature and various in its position (y) were used as the obstacle plate. Model 1, model 2, and model 3 were normal plate, whereas, model 4 was a perforated plate with 30 mm in diameter. The mesh quality is very good where the skewness and orthogonal quality were about 0.23 and 0.77. The minimum volume of meshing is 6.677×10⁻¹⁰ m³. The number of mesh elements was approximately 1,300,000 elements.

3.2 Governing equations

The simulation model was currently chosen on the flowing fluid and the energy transfer between fluid. Therefore, Computational Fluid Dynamics (CFD) Ansys Fluent was applied to solve the temperature and velocity distributions in each cell through 3 conservative models (see Table 3).

| Contents                       | Equations                                                                 |
|--------------------------------|---------------------------------------------------------------------------|
| Conservation of mass           | \( \frac{D\rho_f}{Dt} + \rho_f \vec{V} \cdot \vec{V} = 0 \)               |
| Conservation of momentum       | \( \rho_f \frac{D\vec{V}}{Dt} = -\nabla p + \mu_f \vec{V}^2 \cdot \vec{V} + (\mu_f + \lambda) \nabla (\nabla \cdot \vec{V}) + \vec{F} \) |
| Conservation of energy         | \( \rho_f c_{p,f} \frac{DT_f}{Dt} = \rho_f c_{p,f} \left[ \frac{\partial T_f}{\partial t} + (\nabla \cdot \vec{V}) T_f \right] = \nabla (k_f \nabla T_f) + \beta T_f \frac{Dp}{Dt} + \mu_f \Phi \) |
3.3 Boundary conditions
In Ansys Fluent model, the water was adopted as a single fluid domain with the application of the turbulent model of laminar flow. The gravitational effect was also included. Three-dimensional flow with transient calculation was set. The mass flow rate of inlet water was fixed at 0.259 kg/s and its density was changed depending on its temperature. The PISO and body force weight formulations were used as calculation algorithm.

4. Experimental design
The dimension and configuration of the storage tank were used to model the actual storage tank, and it was then carried out using the performance test of the heat pump at KMUTT, Thailand. It was made by 2 mm thickness of stainless steel and insulated with 45 mm thickness of polyurethane. The simulation was started from the full existence of 55°C hot water in the tank. The inlet pipe connected to the 25°C water supply tank. During the discharging process, the hot water was discharged from the storage tank while the cold water of 25°C simultaneously flowed into the tank with the same flow rate. Five probes of type K thermocouples were installed at the real tank to acquire the transient water temperature which was used to validate the accuracy of the simulation model.

5. Results
5.1 Model validation
The accuracy of the simulation model was validated with the experimental data during the discharging period. The numerical results were used to identify the relative errors of temperature at the thermocouple probe which located at the top, middle and bottom of the storage tank were 2.17%, 2.91%, and 1.55%, respectively.

5.2 Richardson Number analysis
The Richardson Number of three different inlet pipe configurations were plotted respect to Dimensionless time as shown in Figure 3. The results found that all pipe modifications can achieve to provide higher Richardson Number than the original model. It also can observe the tendency of Richardson Number of all models were similar by promptly increased at the beginning, then gradually increased or constant depended on the pipe models and decreased rapidly at the end of the process. It can be noticed that the annular downward pipe can offer the best Richardson Number while the annular upward has been inferior, and the worst model was the direct downward. Higher Richardson Number represents a larger temperature difference between the upper part and the lower part of the storage tank.

Figure 4 illustrates the Richardson Number of each obstacle plate model. The result cannot notice the deviation of the Richardson Number in each model. Nevertheless, the use of obstacle plates can provide larger Richardson Number than the original one. It is possible, therefore, that the Richardson Number can only indicate the temperature difference between the upper part and the lower part of the tank, but it is not applicable to evaluate the temperature distributions at the middle part of the storage tank. Thus, other parameters (i.e., Stratification Number) are required to specify the performance of the stratification in the storage tank.
Figure 3. $Ri$ of the modified pipes models

Figure 4. $Ri$ of the obstacle plate models

5.3 Stratification Number analysis

Figure 5 provides the Stratification Number of each modify pipe model gives explicitly difference. The annular downward pipe can approach the highest Stratification Number ($Str = 1$) and faster than other models even direct downward pipe model. It also provides higher Stratification Number at low dimensionless time. The current study found that the use of an annular downward pipe can be effectively applied to improve the thermal stratification in the storage tank compared to the other models.

As can be seen in Figure 6, the use of the obstacle plate in the tank did not evidently show the difference from the Stratification Number. However, the increasing length of the obstacle plate (see model 2) can notice small improvement of the Stratification Number rather than adding the number of obstacle plates (see model 3). Figure 7 compares the highest Stratification Number of each modification. This study confirms that the modified inlet pipe is associated with the improvement of thermal stratification rather than the obstacle plate.
5.4. Discharging Efficiency

A high value of the Discharging Efficiency represents a larger volume of useful energy which reveals a better thermal stratification of the storage tank. Figure 8 summarizes the Discharging Efficiency for all models when the useful temperature of hot water is limited at 45°C. The results indicate that the implementation of either the water inlet pipes or the obstacle plates can achieve toward the enhancement of the discharging efficiency, and it was higher than the conventional storage tank. However, all tank models cannot reach the unity of Discharging Efficiency as much as the location of the hot water outlet pipe is not being at the top of the tank. Therefore, some hot water cannot be drawn off, especially the hot water in the area of an elliptical end cap.

5.5. Temperature profiles and Velocity profiles

Temperature profiles are the best visualization method to explain stratified behaviour in the tank. The original tank was used as a base case to compare the performance of stratification with the other modifications.

Figure 9 (a) illustrates the temperature distribution of water in the storage tank at $\tau_{use} = 0.3$ for all models. The model of annular downward pipe can perform outstandingly on the excellent thermal stratification with clearly thermocline expression rather than other models. These were the results from a lower inlet water velocity by increasing the cross-section area of water inlet and the downward flow direction of inlet water which effectively reduces the water recirculation in the tank as represented the velocity profile in figure 10.

The implementation of the obstacle plate can be noticeable as a smaller control flow area of the water recirculation which is limited only in the bottom part of the storage tank. It was also found that the thermocline was in a broad region. The use of the obstacle plate can achieve towards the control of the recirculation area whereas it is unable to reduce the velocity of the water recirculation resulting in the dispersal of the temperature profiles.

Figure 9 (b) shows the end of the discharging process at $\tau_{use} = 0.9$. The water temperature of the obstacle plate models is still able to distinguish a broad temperature gradient which represents a poor performance of thermal stratification. However, all modification models can improve the performance of the thermal stratification as compared to the original model.
6. Conclusions

This study has identified the modification of inlet water pipes efficiently performs the improvement of the thermal stratification in the storage tank as compared to the installation of the obstacle plate. It also set out to identify the significant decrease of inlet water velocity and the controlling flow direction of inlet water. The findings from this study make several contributions to the current literature. First, the design of obstacle plate models can be done by enlarging the plate length, increasing in the obstacle plate numbers, or using perforated plate design. It seems that it is able to control the recirculation area of the water. Second, the results of this investigation show that this approach cannot achieve to reduce the inlet water velocity which is a key parameter that has an effect on the stratification. These findings suggest that in general Richardson Number, the Stratification Number, and Discharging Efficiency can have a pivotal role in the significant indicators of the thermal stratification performance. Finally, the use of well-design thermal stratified storage tank can have a benefit in obtaining greater withdrawal high quality and quantity of useful heat. These findings have significant implications for the understanding of how to improve the efficiency of the heat production systems such as a heat pump and a solar collector which can result in high energy efficiency.

Nomenclature

\( \tau_\text{u} \quad \) Dimensionless time [-] \\
\( \tau \quad \) Discharge time [s] \\
\( \sigma \quad \) The unit replacement time [s] \\
\( V_r \quad \) Volume of water tank [m³] \\
\( M \quad \) Total mass of water in tank [kg] \\
\( c_r \quad \) Specific heat capacity [kJ/kg·K] \\
\( k \quad \) The number of data acquired \\
\( T_\text{o u} \quad \) Outlet water temperature [K]
The temperature on each water layer [K]
Mass of each water layer [kg]
Density of fluid [kg/m³]
The velocity vector [m/s]
The local pressure [Pa]
The viscous dissipation term [-]
The body force vector per unit volume [N]
Specific heat capacity of fluid [kJ/kg·K]
The temperature of fluid [K]
Fluid thermal conductivity [W/m·K]
Water temperature [K]
Total energy discharge [kJ]
Total energy stored in tank [kJ]

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