Numerical study on the design parameters of a packed bed thermal energy storage system

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1. Introduction

Renewable energy penetration to the electrical power system has increased. Accordingly, volatility or intermittency of renewable energy became the element endangering the stability of electric grid. Many researchers have focused on research for the power control of various energy sources to solve the related problems [1,2]. In particular, the nuclear power plants (NPPs) can control power through the load follow capabilities, but this has limitations for technical and economic reasons [2]. Thus, thermal energy storage system (TES) can be an option for flexible operation of NPPs.

In the single tank TES system, the hot fluid is injected at the upper part of the tank during the charging process, and the cold fluid injected at the lower part of the tank during discharging process. As the fluid moves, the thermocline moves up and down. During this process, it is crucial to establish a stable thermocline by minimizing the impact of flow non-uniformity and local vortex [1,3–7].

The packed bed TES is one of the thermal energy storage types that can improves the development of thermocline. This can maintain a thin thermocline by reducing contact between the hot and cold fluid through the flier in the tank. In this work, the influence of thermocline in the packed bed TES was analyzed varying the flow velocity and porosity using the commercial CFD code based on ANSYS Fluent. The heat transfer fluid (HTF) is a molten salt and the tank is filled with a quartzite rock as the solid filler. The flow velocity and porosity were varied 5×10^{-4}–3×10^{-3} and 0.12–0.42, respectively.

2. Model description

2.1 Packed bed thermal energy storage

Figure 1 shows the diagram of packed bed TES for charging and discharging processes. In this work, the discharging process was simulated and analyzed. Distributors are installed near the tank's inlet and outlet to ensure uniform flow distribution. As a result, this study focused solely on the simulation of the packed bed region filled with quartzite rocks, with a height and diameter of 5.9 and 3.0 meters, respectively. The HTF is molten salt, and the temperature of initial hot and inlet cold HTF are 663.15 and 563.15 K, respectively. The diameter of the quartzite rocks used as a solid filler is 0.01905 m. In addition, the varying design parameters of this work are flow velocity and porosity. The flow velocity was varied from 5×10^{-4} to 3×10^{-3} and the porosity was varied from 0.12 to 0.42.

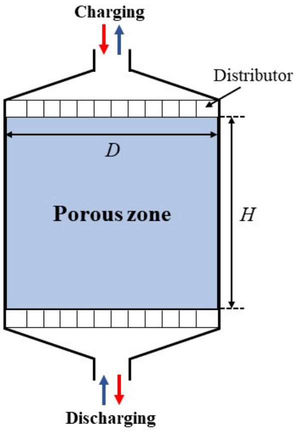

Fig. 1. Schematic diagram of packed bed TES for charging and discharging process.

Table I: Design parameters of study

Parameters	Values
Heat transfer fluid	Molten salt [11]
Solid filler	Quartzite rock [11]
Tank height (m)	5.9
Tank diameter (m)	3.0
Filler diameter (m)	0.01905
Initial hot temperature (K)	663.15
Inlet cold temperature (K)	563.15
Flow velocity (m/s)	5×10^{-4}–3×10^{-3}
Porosity	0.12–0.42

2.2 CFD model

In this work, the simulation was performed by adopting the commercial CFD code based on ANSYS Fluent. The assumptions for this model are as below:

I. Uniform flow of constant velocity is injected into the tank.
II. Flow motion is laminar and three-dimensional
III. packed bed region is insulated (adiabatic condition).
IV. The properties of working fluid and solid filler are independent of temperature.

The pressure-implicit with splitting of operators (PISO) algorithm is used for the pressure-velocity coupling. The second order scheme and first upwind method are applied to the discretization of pressure and momentum/energy equations respectively. The mesh size is 0.1 m and the corresponding the cell number is 89,877. The time step size is 1 s and the residual is 10^{-4}, respectively.

2.3 Thermal performance indicator

Various thermal performance indicators are used to evaluate storage efficiency in TES system [8–11]. Among them, the thermocline thickness is a widely used as the indicator for the thermal stratification efficiency of the TES system. This can be expressed as a dimensionless temperature (θ), and is as follows [11]:

$$\theta = \frac{T_l - T_c}{T_h - T_c} \tag{1}$$

where T_l represents the temperature of HTF at each location in the tank, the T_c and T_h represent the inlet cold temperature and initial hot temperature of HTF during the discharging process.

Figure 2 shows the diagram of the thermocline thickness in TES system. Thus, the thermocline thickness for discharging process is calculated as follows [12]:

$$\delta = \begin{cases} H_{crit,h} - H_{crit,l} & (T_b \le T_{crit,l} \text{ and } T_{top} \le T_{crit,h}) \\ H_{crit,h} - H_b & (T_b > T_{crit,l}) \\ H_{top} - H_{crit,h} & (T_{top} > T_{crit,h}) \end{cases} \tag{2}$$

where the $T_{crit,l}$ and $T_{crit,h}$ mean that the dimensionless temperature (θ) is 0.06, and 0.94, respectively.

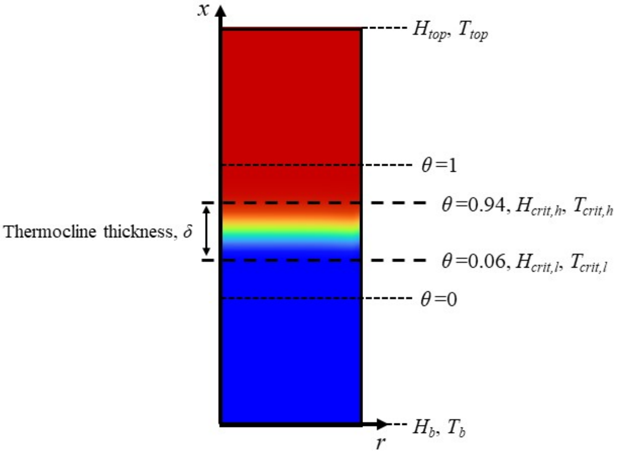

Fig. 2. Schematic diagram of the thermocline in TES system.

2.4 Model validation

Figure 3 shows the validation results compared to the existing studies for packed bed TES [11,12]. The black line represents the results of this work. The temperature distribution of storage tank corresponded well with existing numerical studies and the average relative error with the Xu et al. was about 2.1 %.

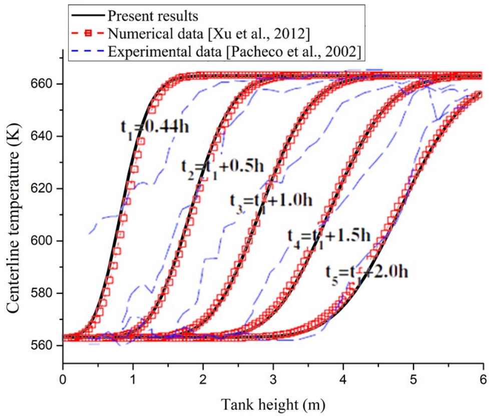

Fig. 3. Comparison of numerical results with existing studies for packed bed TES.

3. Results and discussion

3.1 Influence of flow velocity

Figure 4 presents the variation of outlet temperature according to flow velocity during the discharging process. Each line represents the cases for flow velocity and the porosity was fixed at 0.22. As the flow velocity increased, the discharging time at the total discharging time decreased. The total discharging time was about 3.5 h for $u_{in} = 5\times10^{-4}$ and about 0.6 h for $u_{in} = 3\times10^{-3}$.

Figure 5 shows the variation of thermocline thickness according to flow velocity. As the flow velocity increase, the thermocline thickness in the tank deceases, leading to improved heat storage efficiency. The thickness value was about 1.18 m for $u_{in} = 5\times10^{-4}$ and about 0.83 m for $u_{in} = 3\times10^{-3}$. This is because that the heat transfer between the fluid and the solid filler was improved as the flow velocity increased. Furthermore, this is also due to the reduction in the residence time of the thermocline within the tank. This reduction prevented the diffusion of the thermocline caused by heat conduction between fluids.

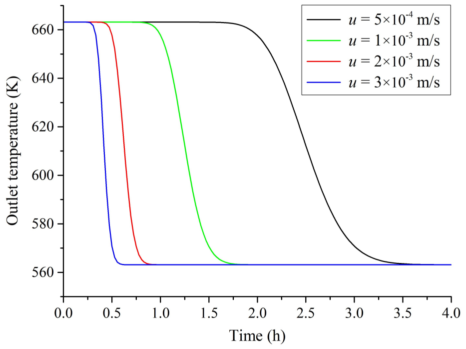

Fig. 4. Outlet temperature variation according to flow velocity during discharging process.

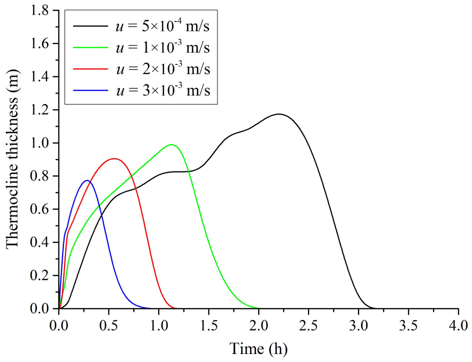

Fig. 5. Thermocline thickness variation according to flow velocity during discharging process.

3.2 Influence of porosity

Figure 6 indicates the variation of thermocline thickness according to porosity during the discharging process. Each line represents the cases for porosity and the flow velocity was fixed at 1×10^{-3}. The thermocline thickness in most cases was similar up to 0.75 h. However, the thickness increased as the porosity increased after 0.75 h, which was 1.3 m for $\varepsilon = 0.42$. It is due to the decrease in the volume of the solid filler as porosity increases. This reduced the heat transfer area of the solid filler and impaired the heat transfer between the fluid and solid filler.

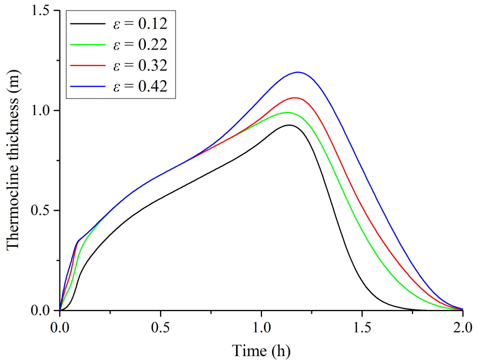

Fig. 6. Thermocline thickness variation according to porosity during discharging process.

4. Conclusions

The influence of design parameters on thermocline in packed bed TES was conducted varying the flow velocity and porosity. The validation test was performed to confirm that the CFD model of this work was well matched to the existing studies.

An increase in flow velocity reduced the thermocline thickness by the enhancement of heat transfer between the fluid and the solid filler. On the other hand, as the porosity increases, the thermocline thickness increased because the heat transfer area of solid filler decreased.

Based on the results obtained in this work, future work will analyze the temperature distribution in packed bed TES by incorporating additional design parameters such as the storage capacity, flier type, etc.

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