Preliminary analysis of thermocline energy storage system coupled with nuclear power system

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1. Introduction

Recently, nuclear systems are considered as one of the most suitable power sources to compensate for intermittent renewable energies [1]. With thermal energy storage (TES) systems, it is possible to increase not only the flexibility of whole systems but also safety by reducing the reactor power variations. For this reason, there are many studies on TES systems coupled with nuclear power systems [1-3].

There are two typical TES types, such as two-tank and single-tank TES systems. The single-tank TES system, called as thermocline TES system, based on the thermal stratification phenomenon has 20-37% economic advantages compared to the two-tank systems by reducing the total tank volumes [4]. However, it is not easy but important to expect the temperature distribution in the thermocline tank for designing and operating the TES system.

In this study, the preliminary analysis of a thermocline TES system is performed to predict the temperature distribution with a one-dimensional (1-D) analytical model. In order to properly analyze the TES system, a molten salt thermocline TES system concept coupled with a pool type sodium-cooled fast reactor is developed as shown in Fig. 1. There are three operation modes; normal operation mode, charging mode, and discharging mode. However, since this study is for preliminary analysis, only the charging mode is analyzed to confirm the feasibility of the TES system. The 1-D analytical model is specified and compared to experimental results of a previous study [5]. Finally, it is used to expect the temperature distribution of the target thermocline TES system in terms of vertical location and time in this study.

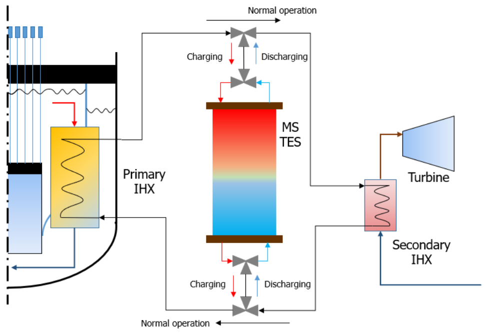

Fig. 1. Schematic of a molten salt thermocline TES system coupled with a sodium-cooled fast reactor.

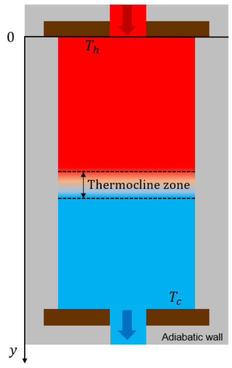

Fig. 2. Schematic of 1-D flow in molten salt thermocline TES system during charging mode.

2. Analysis methodology of thermocline tank

2.1 One-dimensional analytical model

Similar to previous studies [4, 5], the flow of the thermocline TES system is considered as a 1-D flow to simplify the analysis with some assumptions. The assumptions for the 1-D analytical model are as same as the information in the previous study [5]. The schematic for the 1-D analytical model is shown in Fig. 2.

The analytical model could be derived from the 1-D governing energy equation as the following equation:

$$\rho c_p \frac{\partial T(y,t)}{\partial t} + \rho c_p u \frac{\partial T(y,t)}{\partial y} = k \frac{\partial^2 T(y,t)}{\partial y^2} \quad (1)$$

Where, y is the location of the vertical direction; ρ denotes the fluid density; c_p is the specific heat of the working fluid; k denotes the thermal conductivity of the fluid; u is the velocity of the downward for the thermocline. The 1-D governing energy equation could be normalized as follows:

$$\frac{\partial \theta(\zeta,\tau)}{\partial \tau} + Pe \frac{\partial \theta(\zeta,\tau)}{\partial \zeta} = \frac{\partial^2 \theta(\zeta,\tau)}{\partial \zeta^2} \quad (2)$$

Where, $\theta(\zeta,\tau)$ is the normalized temperature; ζ is the normalized vertical location; τ is the dimensionless time as same as the Fourier number; Pe is the Peclet number. The dimensionless parameter are defined as follows:

$$\theta = (T - T_c)/(T_h - T_c) \quad (3)$$

$$\zeta = y/H \quad (4)$$

$$\tau = tk/(\rho c_p H^2) \tag{5}$$

$$Pe = RePr = u\rho c_p H/k \tag{6}$$

Where, T_h is the charging inlet temperature; T_c is the charging outlet temperature; H is the height of the thermocline tank.

There are three boundary conditions for the charging process. The first one is for the initial state. The second one is for the inlet boundary conditions, and the last one is for the outlet boundary conditions [5]. Those are as follows:

$$T(y,0) = T_c\ ,\ \theta(\zeta,0) = 0 \tag{7}$$

$$T(0,t) = T_h\ ,\ \theta(0,\tau) = 1 \tag{8}$$

$$T(\infty,t) = T_c\ ,\ \theta(\infty,\tau) = 0 \tag{9}$$

With the Laplace transform and the boundary conditions, the normalized 1-D governing equation which is the partial differential equation could be the simplified ordinary differential equation as follows:

$$Pe\frac{d\hat{\theta}(\zeta,s)}{d\zeta} + s\hat{\theta}(\zeta,s) = \frac{d^2\hat{\theta}(\zeta,s)}{d\zeta^2} \tag{10}$$

Where, $\hat{\theta}(\zeta,s)$ is the Laplace transform of $\theta(\zeta,\tau)$. By using a Matlab code, it is possible to calculate the temperature distribution according to vertical location and time in the thermocline tank. In this study, this analytical model is adopted to analyze the temperature distribution in the charging process.

2.2 Validation of one-dimensional analytical model

In order to verify the analytical model, experimental data from the previous study [5] are compared with the analytical model used in this study. The experiments based on water as the working fluid were conducted with 1 m of inner diameter tank and 3 m of height tank. The comparison of the analytical model and experimental results is shown in Fig. 3.

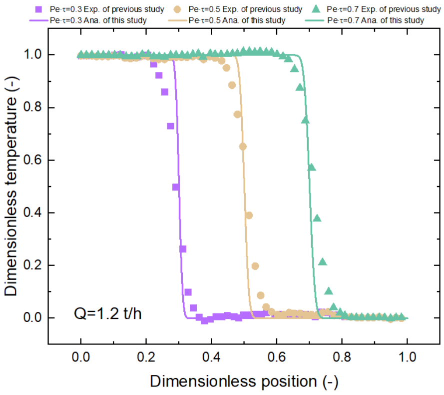

Fig. 3. Validation results of the 1-D analytical model.

From the results, it could be concluded that the 1-D analytical model has enough prediction performance when compared to the experimental data. Since the analytical model is based on dimensionless parameters and water has similar Prandtl number ranges of molten salt in the liquid state [6], it is reasonable that this 1-D analytical model could be applicable to molten salt thermocline tank conditions.

3. Preliminary analysis of thermocline tank

3.1 Specification of molten salt thermocline tank

In this section, the conditions of the thermocline tank shown in Fig. 1 are discussed more in detail. The inlet temperature of the thermocline tank is set as 530℃ by considering the outlet condition of the sodium-cooled fast reactor which is designed as 545℃ in previous studies [7]. The outlet condition of the thermocline tank is calculated by considering the thermodynamic states of a 150 MWe supercritical carbon dioxide (sCO_2) Brayton cycle [8] and 0.88 effectiveness of the secondary intermediate heat exchanger (IHX).

Since the solar salt (60% $NaNO_3$ and 40% KNO_3) has a relatively wide liquid temperature range (almost up to 600℃) and low cost, the working fluid of the thermocline tank is set as the solar salt. The properties of solar salt are summarized in Table I [9].

For the preliminary analysis, the mass flow rate of the molten salt in the initial three-hour charging process is linearly increased from 0 kg/s to 224 kg/s which is almost 15% of the mass flow rate condition in the normal operation mode. After that, the mass flow rate is considered as the constant value. The target value of maximum energy storage capacity is set as 300 MWh. Even though the higher aspect ratio of the thermocline tank is better for thermal stratification, the height of the thermocline tank is limited to 11.89 m for the safety consideration of construction according to previous studies [4, 10]. For this reason, the height of the thermocline tank is set as 11.8 m. With the specifications of the thermocline tank, the preliminary analysis for the charging process is performed.

Table I: Specification of molten salt properties [9]

Solar salt physical properties (270~600℃)	
Density, $\rho\ [kg/m^3]$	$\rho = 2090 - 0.636 \cdot T(℃)$
Specific heat, $c_p\ [J/(kg \cdot K)]$	$c_p = 1443 + 0.172 \cdot T(℃)$
Thermal conductivity, $k\ [W/(m \cdot K)]$	$k = 0.443 + 1.9 \times 10^{-4} \cdot T(℃)$
Viscosity, $\mu\ [Pa/s]$	$\mu = (22.714 - 0.120 \cdot T(℃)$ $+2.281 \cdot 10^{-4} \cdot (T(℃))^2$ $-1.474 \cdot 10^{-7} \cdot (T(℃))^3) \times 10^{-3}$

(a) Initial state

(b) After 2 hr

(c) After 4 hr

(d) After 6 hr

Fig. 4. Normalized temperature distribution in thermocline tank with respect to normalized vertical location and time.

2.4 Preliminary analysis of thermocline tank system

With the specified conditions, the preliminary analysis results of normalized temperature distributions in the thermocline tank are derived as shown in Fig. 4.

The results showed that initially the thermocline tank is filled with the cold fluid condition ($T_c,\ \theta = 0$) as shown in Fig. 4(a). After 2 hr charging process, the hot fluid ($T_h\ ,\ \theta = 1$) is filled over one-fifth of the thermocline tank according to the analytical model (Fig. 4(b)). The thermocline region, the dramatic temperature change zone, is located at almost $\zeta = 0.6$ when the charging time is 4 hr (Fig. 4(c)). Even though the spent charging time is the same as 2 hr each case, the moving distances of the thermocline are different. It might come from the mass flow rate difference at the times. From the results, it can be concluded that variations in mass flow rate conditions have significant impacts on the thermocline location. After 6 hr charging process is performed from the initial state, finally 300 MWh thermocline tank is almost fully charged by the incoming hot fluid (Fig. 4(d)).

The 1-D analytical model has the advantage of fastly confirming the temperature distribution and full charging time. In addition, the parametric study for tank height and mass flow rate conditions could be performed to briefly determine the thermocline tank geometries and operating conditions. However, the effects of diffusers and produced vortex, which affect the growth of the thermocline thickness, were not considered in the current 1-D analytical model. For this reason, additional studies on the thermal stratification phenomenon will be performed with 3-D computational fluid dynamics (CFD) and experiments. With the comprehensive analyses, the thermocline TES system coupled with advanced nuclear systems will be performed to analyze not only charging process but also discharging process more in detail.

3. Conclusions

In this study, a preliminary analysis is performed for the charging process of a thermocline tank coupled with nuclear systems. The 1-D analytical model based on the governing energy equation is used to derive the temperature distribution in the thermocline tank with respect to vertical location and time. The results of the preliminary analysis showed that mass flow rate variations have significant impacts on the thermocline location.

From the results, it can be concluded that the 1-D analytical model has the advantage to expect temperature distribution and full charging time with saved calculation time. In order to consider the complex effects on thermocline thickness and location, further studies with 3-D CFD and experiments will be performed to analyze not only charging process but also discharging process more in detail.

Acknowledgments

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