태양열 발전에서 태양열에너지 수송을 위한 고온 축열 물질의 열전달 특성

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Heat Transfer Characteristics of High Temperature molten salt storage for Solar Thermal Power Generation

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Key Words: heat transfer, molten salt, heat storage， solar energy

Abstract: The heat transfer characteristics of molten salt storage system for the solar thermal power generation were investigated. Temperature profiles and the heat transfer coefficients during the storage and discharge stage were obtained with the steam as the heat transfer fluid. Two kinds of inorganic salt were employed as the storage materials and coil type of heat exchanger were installed in both tanks to provide the heat transfer surfaces during the storage and discharge stage. The effects of steam flow rates, flow direction of steam in the storage tank and the initial temperature of storage and discharge tank on the heat transfer were tested.

Nomenclature

Q_{loss} : heat loss of tank, kW/m^2
T_{salt} : temperature of the salt in the tank, ℃

1. Introduction

A thermal storage system can collect solar energy in order to shift its delivery to most demand time or to smooth out the power output during intermittently cloudy weather conditions. Therefore, economic thermal storage system is an important factor in determining the successful operation of solar power plant. There are several types of thermal storage systems and among them, molten salt system is widely studied due to higher energy density and reasonable operating temperature without degradation of thermal properties.
In this study heat transfer characteristics of molten salt systems during energy storage and discharge stage with steam as the heat transfer fluid were examined in order to obtain the basic engineering data such as heat transfer coefficient and transient temperature profiles for the proper determination of size of salt tank and heat transfers area of heat exchangers.

2. Experimental

The schematic of experimental set-up is shown in Fig.1. It is consisted of steam generator, discharge tank, storage tank and data acquisition system. The storage and discharge tank were made of stainless steel. The dimension of tank was 500mm in height and 150 mm in diameter and coil type heat exchanger was installed in the middle of the tank. Three thermocouples were mounted in the tank at different axial position and the inlet and outlet temperature of steam were measured with K-type thermocouples.
As the supply of steam at the temperature of 120 ℃ from steam generator flows into the heat discharge tank where the temperature of 400 – 450 ℃ molten salt transfer the heat to the incoming low temperature steam through the coil type heat exchanger thus the thermal energy discharge process is started. During the storage and discharge stages, the transient temperature profiles of molten salt and steam were recorded via data acquisition device.
In this experiment, two types of molten salt were employed as the storage materials. One was the so called HITEC (tertiary mixture of $NaNO_3$ (7%) : KNO_3 (53%) : $NaNO_2$ (40%) and the other was so called SOLAR SALT (binary mixture of $NaNO_3$ (40%) : KNO_3 (60%)). The thermo-chemical properties of molten salts were characterized by the DSC and TGA. The melting point and thermal decomposition temperature of HITEC were 143 ℃ and 580 ℃ respectively and for SOLAR SALT, the melting and decomposition temperature were 220 ℃ and 560 ℃ respectively [1-2]. From this data, the operating temperature of employed molten salts was determined.

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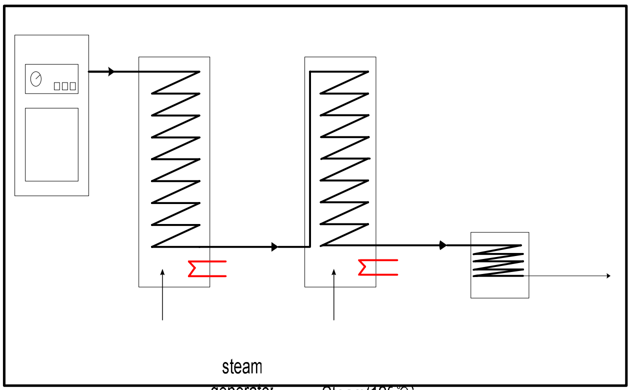

Fig. 1 Schematic of Experimental Set-up

3. Results and Discussions

3.1 Heat Losses

The heat loss in this experiment was due to the combination of convection and radiation. A test was conducted to quantify the thermal losses of storage tank. The method was to turn off all auxiliary heaters and track the rate of decay of the average tank temperature. By knowing the salt level, an estimate of the heat loss could be made. Actually, the famous SOLAR TWO project (875,000liter) also made an analysis of heat losses of storage and discharge tank [3]. A regression analysis was performed to develop an empirical heat loss equation from the measured values:

$$Q_{loss} = 0.00017\ T_{salt} + 0.012\ (kW/m^2)$$

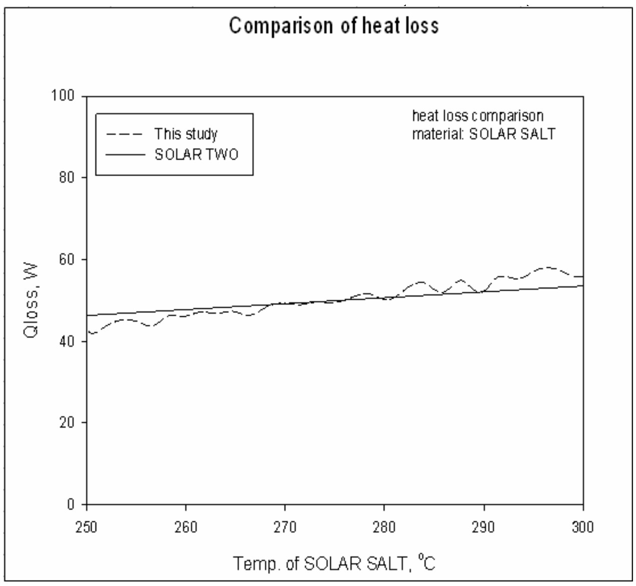

Fig. 2 Comparison of heat loss

According to this semi-empirical heat loss equation, the heat loss per meter square in SOLAR TWO project was similar to the measured thermal loss in this experiment. The Figure 2 showed the comparison of heat loss for this study and SOLAR TWO system. As can be seen in Fig. 2, the heat loss depended strongly on salt temperature in small and large scale on system.

3.2 Heat Storage Stage

In this experiment, the temperature of salt in the release tank was set to a constant temperature of 450℃. Then the steam flowed through the heat exchanger which had been immersing in the high temperature liquid salt, and to be heated. The superheated steam from the release tank with higher temperature than that of molten salt in the storage tank flowed into the storage tank to heat the salt in the storage tank. The transient temperature profiles of HITEC and SOLAR SALT during the heat storage stages were showed in Figure 3 and Figure 4 respectively.

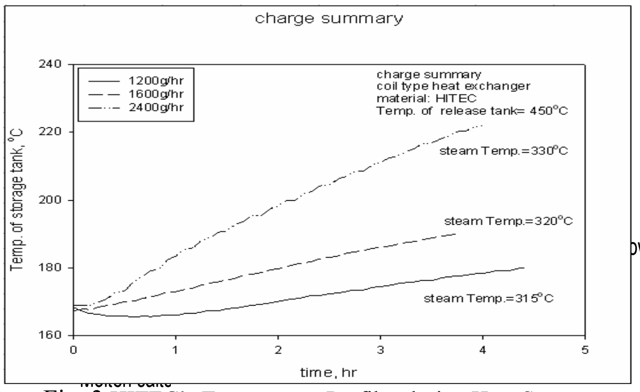

Fig. 3 HITEC's Temperature Profiles during Heat Storage

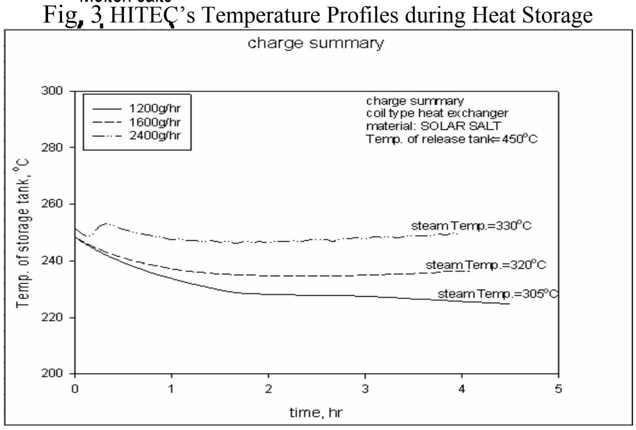

Fig. 4 SOLAR SALT's Temperature Profiles during Heat Storage

As can be seen, the heat storage rates strongly depended on the inlet temperature of heat transfer fluid and the amount of the heat storage increased monotonically with time. Similar results were reported in the latent heat storage systems [4]. The higher inlet temperature of steam increased the molten salt temperature. Furthermore, the thermal storage of molten salts also strongly affected by the steam flow rate. The higher rate steam flow carrying more heat increased the temperature of molten salts in storage tanks. However, for SOLAR SALT the molten salt temperature was slightly decreased. The reason for this was that the melting temperature of SOLAR SALT was higher than that of HITEC and thus the heat loss to ambient was higher than the HITEC.

3.4 Heat Discharge Stage

In this experiment, the HITEC and SOLAR SALT were heated up to about 450 ℃ and then the lower temperature of steam was flowed into the molten salt in release tank. So the higher temperature molten salt would transfer heat to the steam and the steam was superheated as expected. The transient temperature profiles of HITEC and SOLAR SALT during the heat discharge stages were showed in Figure 5 and Figure 6.

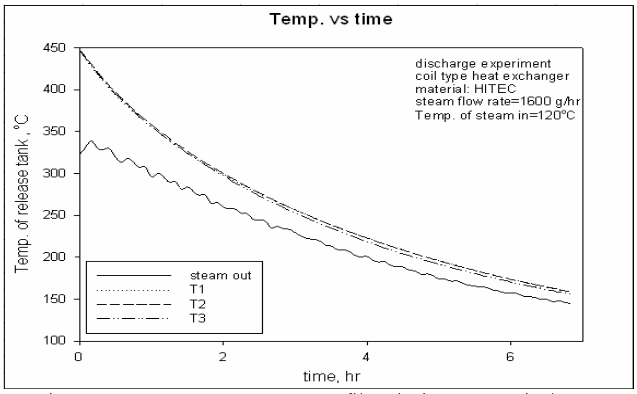

Fig. 5 HITEC's Temperature Profiles during Heat Discharge

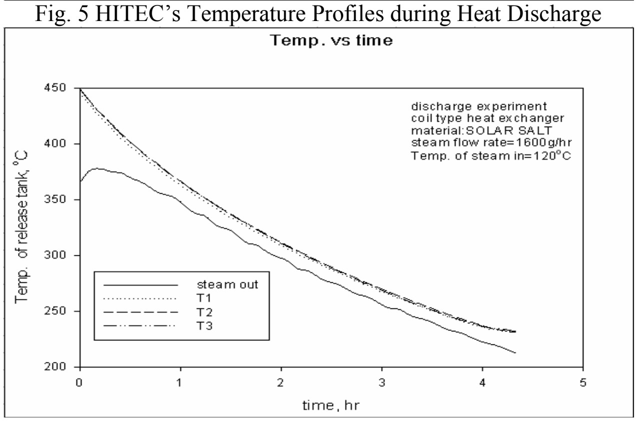

Fig. 6 Solar Salt's Temperature Profiles during Heat Discharge

As can be seen, the temperatures of molten salt and steam decreased with time as expected and for the SOLAR SALT the little smaller temperature difference of molten salt and steam was observed compared to HITEC thus it could be said that SOLAR SALT was more effective in discharging the thermal energy of molten salt than that of HITEC.

3.5. The Overall heat transfer coefficients

The overall heat transfer coefficients of heat storage stages for HITEC and SOLAR SALT with different steam flow rates were given in Figure 7 and Figure 8. As can be seen, the overall heat transfer coefficient of SOLAR SALT showed slightly higher heat transfer coefficient than that of HITEC. As can be seen in figures, the overall heat transfer coefficient was in the ranges of 5 – 30 W/m^2 K and the higher steam flow rates resulted in higher heat transfer coefficient for both molten salts. The relatively lower heat transfer coefficients maybe due to ineffective coil type heat exchanger and need to be changed for better performance.

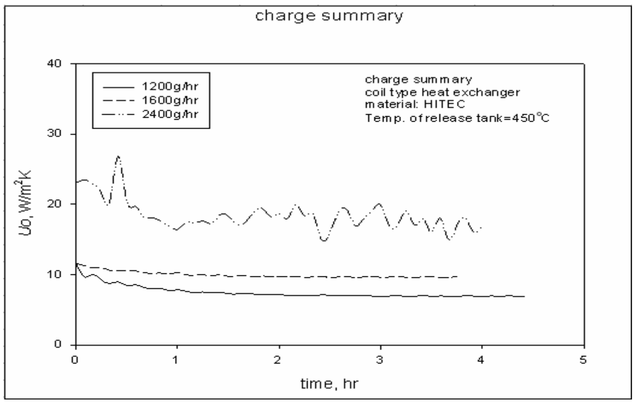

Fig. 7 HITEC's Overall Heat Transfer Coefficients

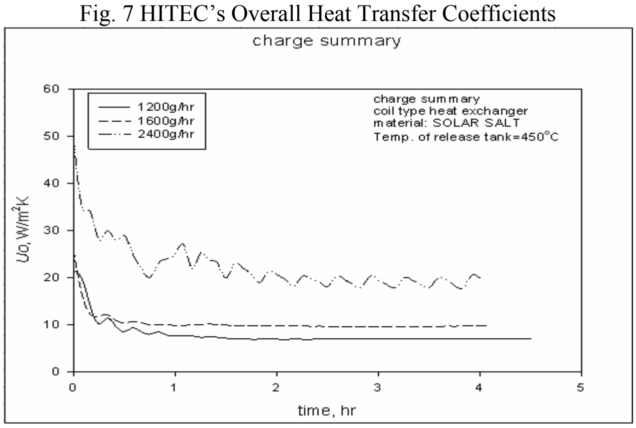

Fig. 8 SOLAR SALT's Overall Heat Transfer Coefficients

3.6. Effect of Natural Convection

Since the density of employed molten salt significantly changed with temperature, the effect of natural convection was examined. During the heat storage stage, two different direction of steam flow were tested for the coil type heat exchanger. When the steam flowed from the top of the storage tank to the bottom of the tank, there was the temperature difference of molten salt with axial direction. However, when the steam flowed from the bottom of the storage tank to the top of the tank, due to density difference of the molten salt during the heat storage, natural convection occurred and there was no axial temperature difference of the molten salt. The Figure 9 below showed the temperature distribution in the storage tank.

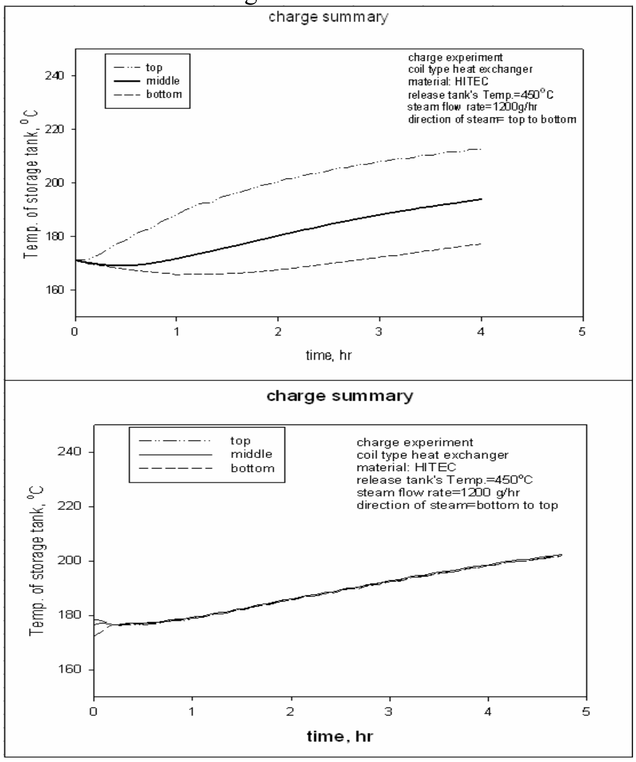

Fig. 9 The effect of natural convection

Several studies have sought to develop natural convection heat transfer correlations for such heat exchangers during the transient discharge and charge processes. Farrington and Bingham [5-6] and Feiereisen et al., [7] conducted experiments with coiled tubes immersed in a vertical storage tank. There were many reports [8-10] studying the thermal conductivity of the molten salt. Thus the effect of natural convection can be evaluated.

4. Conclusion

The use of molten salt heat storage medium for the solar thermal power generation offers the potential of increased performance and attractively lower costs. In the present study, the heat transfer characteristics of molten salt storage system were investigated, and some ideas about engineering aspects of this storage system were obtained. The heat loss per square meter was comparably similar to the value measured in famous SOLAR TWO project. The performance of heat storage was strongly depended on the heat transfer fluid inlet temperature and flow rate. The natural convection of molten salts (liquid phase) was observed with the coil type heat exchanger during the heat storage stages and the heat transfer enhancement due to natural convection was observed. While several issues have been addressed in the previous parts, as discussed here, the next step is to go into further study of its engineering characteristics in different conditions and using different heat transfer fluid.

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