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Heat transfer characteristics of high temperature molten salt for storage of thermal energy

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Abstract−The heat transfer characteristics of molten salt for the storage of thermal energy were investigated. The temperature profiles and heat transfer coefficients during the storage and discharge stages were obtained with steam as the heat transfer fluid. Two kinds of inorganic salt were employed as the storage medium and two types of heat exchanger were tested in order to find the effect of heat exchanger configuration on the heat storage. The effects of the steam flow rates, the flow direction of steam in the storage tank, the temperature of the heat transfer fluid and the initial temperature of the discharge tank on the heat transfer were obtained and analyzed.

Key words: Heat Transfer, Molten Salt, Heat Storage, Solar Energy

INTRODUCTION

The electrical output of a solar thermal power generation plant is inherently in a state of change, being influenced by the time and weather. Thermal storage systems have the potential to dispatch electricity to meet the demand peaks and mitigate the changes in the amount of energy produced due to the variation of solar radiation. A thermal storage system can accumulate solar energy in the storage medium when the solar radiation is sufficient, in order to shift its delivery to a later time or to smooth out the plant output during intermittently cloudy weather conditions. Hence, it allows the power output of the plant to be extended or shifted from sunny periods to periods of high or peak demand. Thus, the plant can operate much more flexibly and the periods of mismatch between the energy supply by the sun and energy demand can be reduced [1,2]. Though there are several types of thermal storage systems, the molten salt system has been widely studied due to its higher energy density and reasonable operating temperature without degradation of the thermal properties. Furthermore, molten salt offers a very favorable combination of density, specific heat, chemical reactivity (very low), vapor pressure (very low), and cost (very cheap) [1]. In this study, molten salt was chosen as the heat storage medium and super-

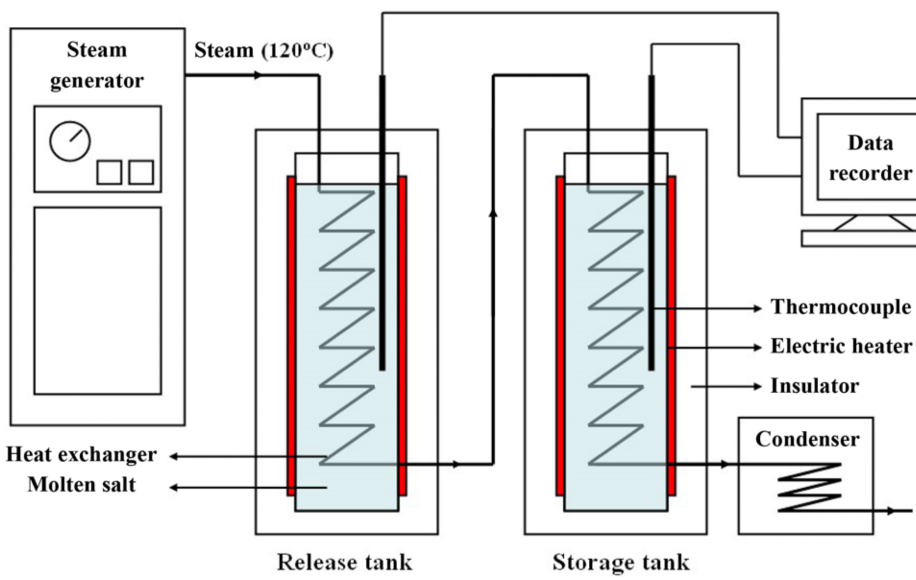

Fig. 1. Schematic diagram of experimental set-up.

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heated steam as the heat transfer fluid. Two thermal tanks were installed in series, one for heat storage (charge) and the other for heat release (discharge) purposes. During the heat storage stage, the superheated steam heats the molten salt in the storage tank and the energy is stored in the salt. As such, in the event that there is a shortfall in the amount of electricity available for use, the heated molten salt releases its heat in the form of steam which is used to produce electricity by means of a steam turbine.

In the previous study [3], the preliminary heat transfer characteristics and the thermal properties of molten salts were tested. In this study, the heat transfer characteristics of molten salt systems during the thermal heat storage and discharge stages with steam as the heat transfer fluid were examined. The study's aim is to test the applicability of molten salt as a heat storage medium and choose the proper type of molten salt, according to the heat storage and release performances of the two molten salts, to compare their heat transfer efficiencies and determine the type of heat exchanger to be used. Two types of heat exchanger were used in this study: a coil type and a shell-and-tube type. The heat transfer coefficients during the heat storage and release stages for the two types of heat exchanger were compared and the experimental factors which influenced the heat transfer performances of the two heat exchangers were analyzed based on the experimental results.

EXPERIMENTAL

A schematic diagram of the experimental set-up is shown in Fig. 1. It consisted of a steam generator, release tank, storage tank and data acquisition system. The tanks were made of stainless steel. The dimensions of the tanks were 500 mm in height and 150 mm in diameter. The volume of each tank was about 3.7 liters and the heat transfer area of the heat exchanger was 0.2 m^2. About 3.0 liters of liquid molten salt was added to the tank, in order to take into account its expansion when it was heated to a high temperature. An electric heater was installed on the outside of the tank and could melt the salt in 2 hours. Ceramic wool with 10 cm thickness was used to insulate the walls and roofs of the tanks. Three thermocouples were mounted inside the tank at different axial positions (at the bottom, middle and top of the tank) and the inlet and outlet temperatures of steam were measured with K-type thermocouples.

As the supply of steam at a temperature of 120 °C from the steam generator flowed into the heat release tank, the heat from the molten salt at a temperature of 350-450 °C was transferred to the steam through the heat exchanger and, thus, the thermal energy discharge process was started. During the charge and discharge stages, the transient temperature profiles of the molten salt and steam were recorded via a 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 the so-called SOLAR SALT (binary mixture of $NaNO_3$ (40%): KNO_3 (60%)). The thermo-chemical properties of the molten salts were characterized by DSC and TGA. The melting point and thermal decomposition temperature of HITEC were 143 °C and 580 °C and those of the SOLAR SALT were 220 °C and 560 °C, respectively [3]. From these data, the operating temperatures of the molten salts were determined. The properties of these two salts are shown in Table 1. Two types of heat exchanger were used in this study: coil type and shell-and-tube type.

Table 1. The properties of the employed molten salts

Property/Composition	SOLAR SALT	HITEC
$NaNO_3$	60	7
KNO_3	40	53
$NaNO_2$		40
Freezing point (°C)	220	143
Upper temperature (°C)	560	580
Density ρ, at 300 °C (kg/m^3)	1899	1640
Viscosity μ, at 300 °C (kg/(m·s))	3.26×10^{-3}	3.16×10^{-3}
Heat capacity Cp, at 300 °C (J(kg·K)$^{-1}$)	1495	1560
Thermal conductivity λ (W/(m·K))	0.446	0.483
Coefficient of expansion ξ (K^{-1})	0.34×10^{-3}	0.31×10^{-3}

RESULTS AND DISCUSSION

1. Heat Storage Stage

In this experiment, the temperature of the salt in the release tank

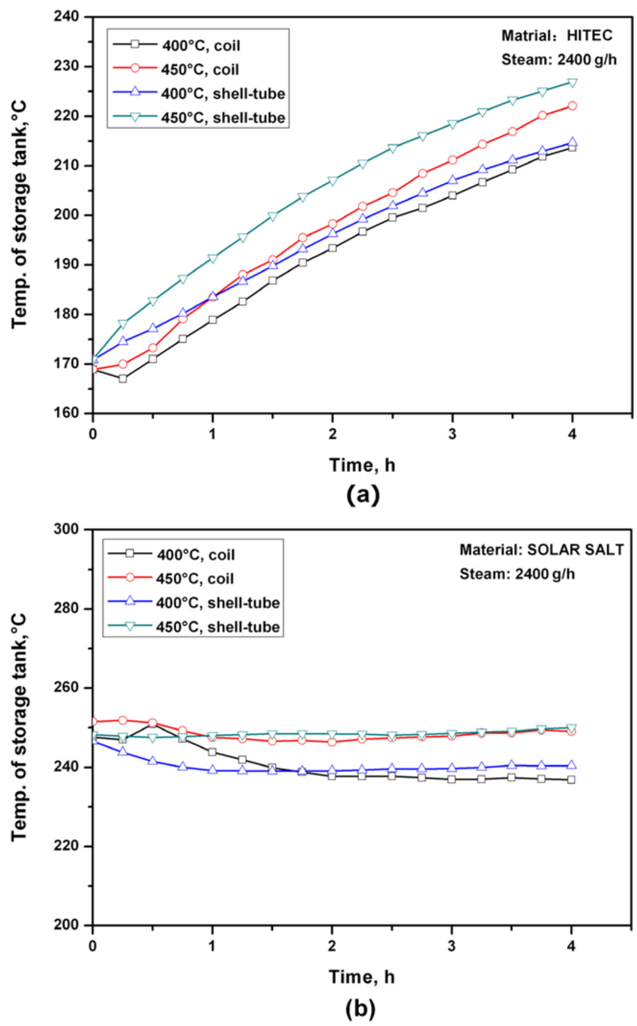

Fig. 2. Heat storage using different inlet temperatures of steam for (a) HITEC, (b) SOLAR SALT.

was set to a constant value of 400 ºC or 450 ºC. Then, the steam of temperature of (120 ºC) flowed through the heat exchanger and was heated by the high temperature molten salt. The superheated steam of temperature of (300-330 ºC) from the release tank flowed into the storage tank to heat the low temperature molten salt. The transient temperature profiles of the HITEC and SOLAR SALT during the heat storage stage are shown in Fig. 2(a), and 2(b), respectively. In these figures, the steam flow rate was 2,400 g/h and two types of heat exchanger were used.

1-1. Effect of the Inlet Temperature of Heat Transfer Fluid

As can be seen in Fig. 2, the heat storage rates are strongly dependent on the inlet temperature of the heat transfer fluid (HTF) and the amount of heat storage increased monotonically with time. Similar phenomena were reported in the case of latent heat storage systems [4]. Increasing the inlet temperature of the steam increased the molten salt temperature. However, in the case of the SOLAR SALT, the molten salt temperature was slightly decreased. The reason for this was that the melting temperature of the SOLAR SALT was higher than that of HITEC and, thus, the heat loss to the ambient was higher than that in the case of HITEC. Although the storage temperature of the SOLAR SALT did not significantly increase during the storage stage, it showed a higher heat storage efficiency of around 75% compared with the value of about 30% for HITEC. Thus, the SOLAR SALT was the better storage medium than the HITEC when superheated steam was used as the HTF.

1-2. Effect of Configuration of Heat Exchanger

The difference in the heat transfer characteristics between the coil type and shell-and-tube type heat exchangers was analyzed. In the case of the HITEC salt, the difference in the storage results between the two heat exchangers was significant. Compared with the coil type heat exchanger, the heat storage performance was more sensitive to the temperature of the HITEC salt in the release tank when the shell-and-tube type heat exchanger was used. In the case of the SOLAR SALT, the temperature of the salt in the release tank did not play as important a role as in the HITEC experiments.

1-3. Effect of Steam Flow Rate

The effects of different steam flow rates on the heat transfer in the molten salt system were tested. As expected, a higher steam flow rate resulted in better heat storage performance since the heat transfer was increased due to increasing turbulence at the higher steam flow rates. The heat storage performance using the different steam flow rates for HITEC and SOLAR SALT is shown in Fig. 3. As

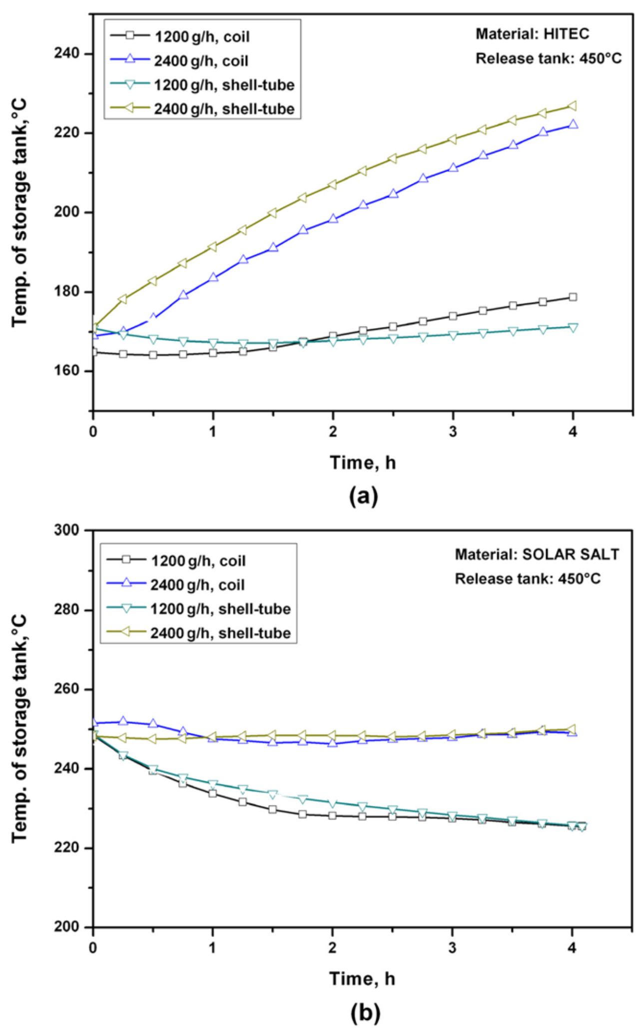

Fig. 3. Heat storage using different steam flow rates for (a) HITEC, (b) SOLAR SALT.

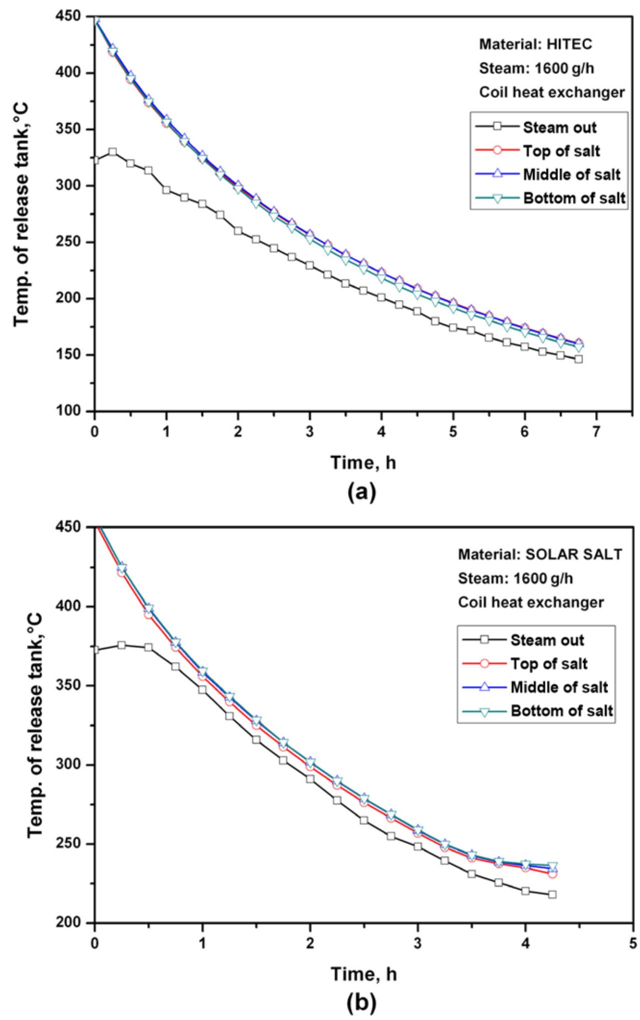

Fig. 4. Temperature profiles of (a) HITEC and (b) SOLAR SALT during heat discharge stage at the coil type heat exchanger.

can be seen, the thermal performance of heat storage and release for the two kinds of molten salt was found to be strongly affected by the steam flow rates. A higher steam flow rate carrying more heat sharply increased the temperature of the molten salt in the storage tanks. In addition, the heat storage results were more sensitive to the steam flow rates in the shell-and-tube type heat exchanger.

Conclusively, the SOLAR SALT was the better heat storage medium in this study, because of its much higher heat storage efficiency than that of HITEC. Compared with the coil type heat exchanger, the performance of the shell-and-tube type heat exchanger was more strongly affected by the temperature of the salt in the release tank and steam flow rate.

2. Heat Discharge Stage

In this experiment, the HITEC and SOLAR SALT were heated to about 450 °C and then steam at a lower temperature was flowed into the molten salt release tank. In this way, the heat from the higher temperature molten salt would be transferred to the steam. The transient temperature profiles of the HITEC and SOLAR SALT during the heat discharge stage at coil type heat exchanger are shown in Fig. 4. As can be seen, the temperatures of the molten salt and steam decreased with time, as expected, and in the case of the SOLAR SALT, a slightly smaller temperature difference between the molten salt and steam was observed compared to that in the case of HITEC and, thus, it could be said that the SOLAR SALT was more effective in discharging its thermal energy than HITEC.

Fig. 5 shows a comparison of the heat discharge experiments for SOLAR SALT with different configuration of heat exchanger. As discussed in the previous section, the steam flow rate influenced the performance of heat storage to a greater extent in the case of the shell-and-tube type heat exchanger. The same phenomenon was also observed in the heat discharge experiments. As can be seen in Fig. 5, a more sharp decrease of release tank temperature was obtained in the shell-and-tube type heat exchanger than the coil type heat exchanger.

3. The Overall Heat Transfer Coefficients

The overall heat transfer coefficient was determined by Eq. (1) as shown.

$$Q=U_oA_o(\Delta T)_{lm} \quad (1)$$

Where Q is the rate of heat transfer, U_o is the overall heat transfer co-

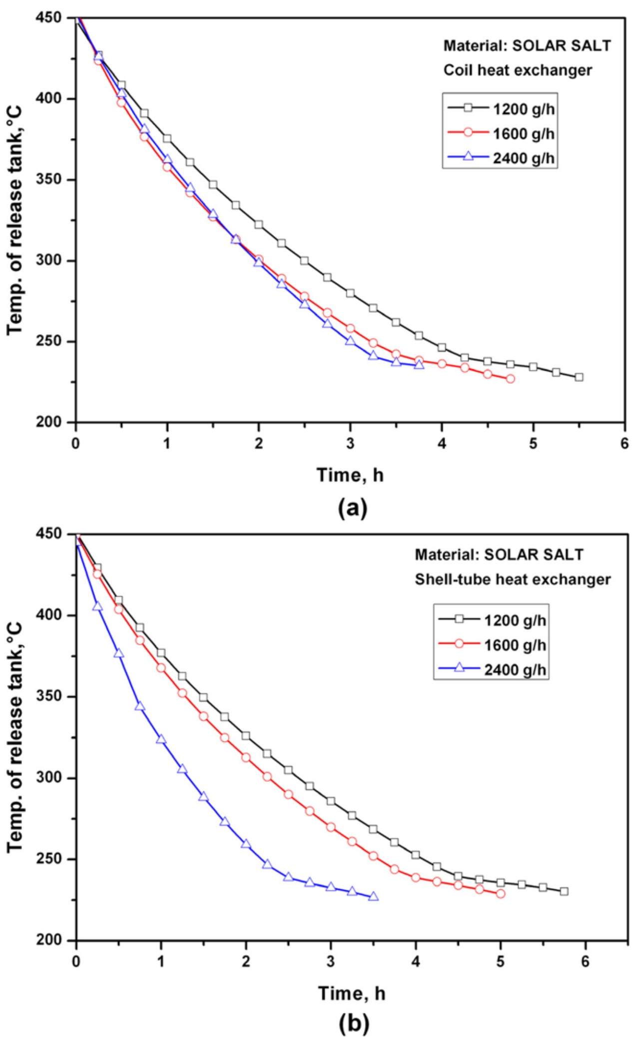

Fig. 5. Temperature comparison of SOLAR SALT during discharge stages at (a) coil type heat exchanger and (b) shell-and-tube type heat exchanger.

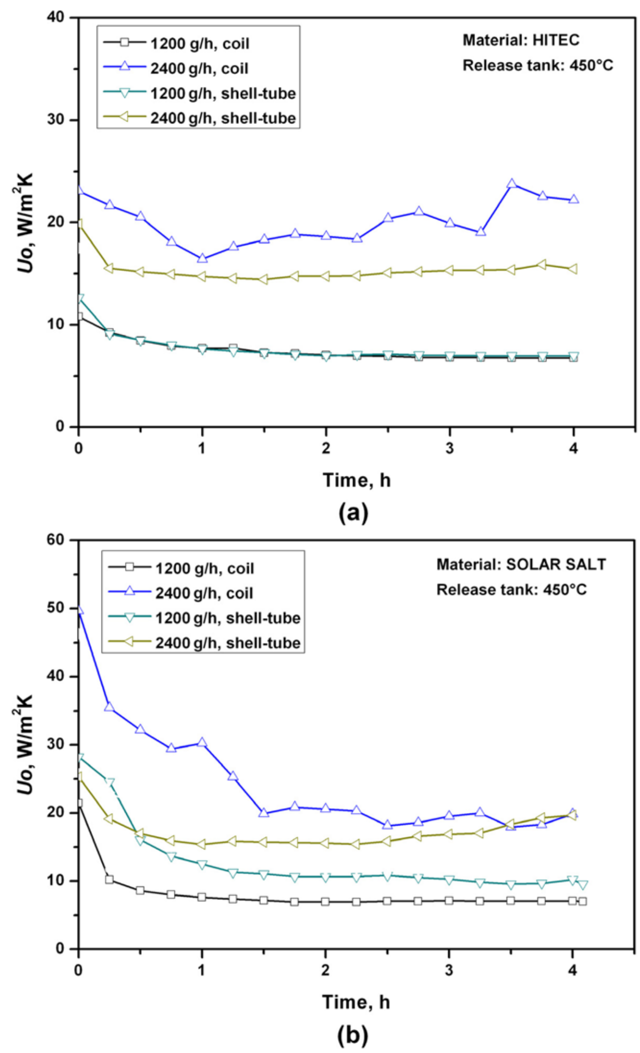

Fig. 6. Heat transfer coefficients of (a) HITEC and (b) SOLAR SALT during charge stages.

efficient, A_o is the area across which the heat is being transferred, and $(\Delta T)_{lm}$ is the logarithmic mean temperature difference between the inlet and outlet temperatures of two fluids. In this work, Q is the accumulated thermal energy in the storage tank of the superheated steam passed through the heat exchanger; A_o is the surface area of heat exchanger; and $(\Delta T)_{lm}$ is logarithmic temperature difference of the molten salt and steam. Thus, the U_o is determined from the measured temperatures of steam and molten salt and flow rates of steam. The experimentally determined overall heat transfer coefficients of the heat charge stages for HITEC and SOLAR SALT with different steam flow rates are given in Fig. 6. As can be seen, the overall heat transfer coefficient of SOLAR SALT was slightly higher than that of HITEC.

In the coil type heat exchanger experiments, when the steam flow rate was 2,400 g/hr, the overall heat transfer coefficients were not as stable as those in shell-and-tube type ones. Thus, the shell-and-tube type heat exchanger exhibited better heat storage performance during the heat storage experiments. The overall heat transfer coefficients of the heat discharge experiments for HITEC and SOLAR SALT with different steam flow rates are given in Fig. 7. As can be seen, the overall heat transfer coefficient was in the range of 0-20 W/m^2 K and was lower than that in the heat storage processes. These relatively lower heat transfer coefficients may be due to increase of thermal resistance of solidified salt and the decrease of temperature difference between the steam and molten salt.

4. Effect of Natural Convection

Since the density of the molten salt employed in this study varied significantly with temperature [5-11], the effect of natural convection was examined. During the heat storage stage, the two different directions 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, the molten salt exhibited a temperature difference in the axial direction. However, when the steam flowed from the bottom of the storage tank to the top, due to the difference in density of the molten salt during the heat storage, as shown in Fig. 8(b), there was no axial temperature difference. Therefore, it was assumed that natural convection occurred. The same phenomena were not observed for the shell-and-tube type heat exchanger.

CONCLUSIONS

The use of molten salt as a heat storage medium for solar ther-

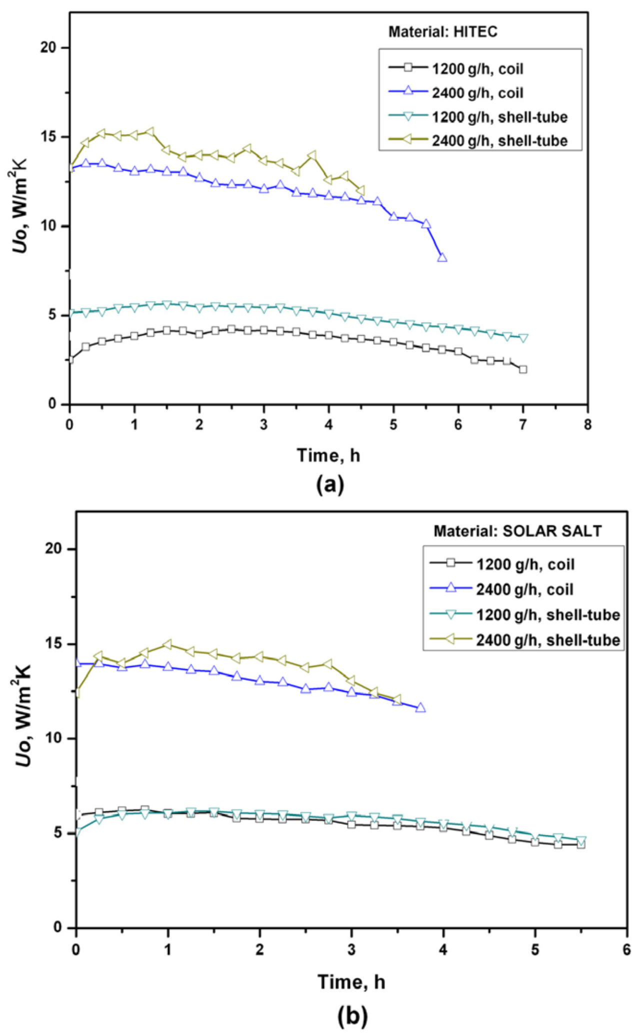

Fig. 7. Heat transfer coefficients of (a) HITEC and (b) SOLAR SALT during discharge stages.

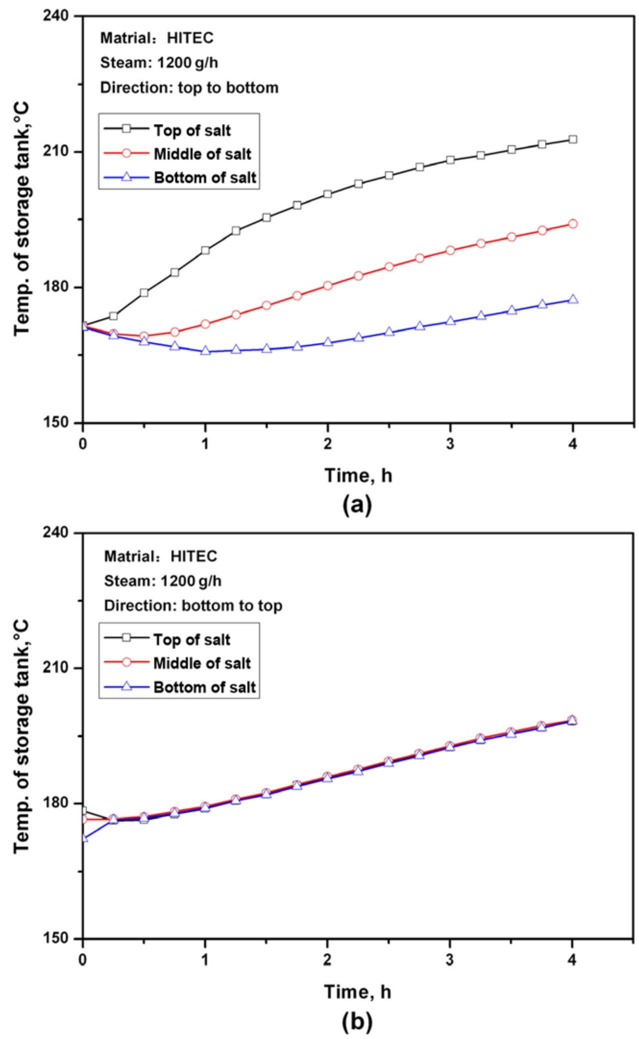

Fig. 8. Temperature profile with different direction of steam flow at coil type heat exchanger: (a) top to bottom, (b) bottom to top.

mal power generation offers the potential of increased performance and much lower costs. In the present study, the heat transfer characteristics of molten salt storage systems were investigated, and some ideas about the engineering aspects of this storage system were obtained. The heat storage performance strongly depended on the heat transfer fluid inlet temperature and flow rate, especially when the shell-and-tube type heat exchanger was used for the heat transfer. Compared with HITEC, the SOLAR SALT was the better heat storage medium because of its higher heat transfer efficiency during the heat storage and discharge stages. The shell-and-tube type heat exchanger provided a slightly higher and more stable heat transfer coefficient than the coil type heat exchanger. The natural convection of molten salts (liquid phase) was observed in the case of the coil type heat exchanger during the heat storage stages. No natural convection of liquid salt was observed in the case of the shell-and-tube type heat exchanger. While several issues concerning the use of molten salt as a heat storage medium have been addressed in this study, further studies of its engineering characteristics under different conditions and using different heat transfer fluids are required.

NOMENCLATURE

ρ : density [kg/m^3]
μ : fluid viscosity at the bulk fluid temperature [kg/(m·s)]
C_p : heat capacity [J/kg-K]
λ : thermal conductivity [W/(m·K)]
ξ : coefficient of expansion [K^{-1}]
Q : accumulated thermal energy in the storage tank [W]
U_o : overall heat transfer coefficient [W/m^{2}K]
A_o : area across which the heat is being transferred [m^2]
$(\Delta T)_{lm}$: logarithmic mean temperature difference [K]

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