Comparison of Heat Transfer Fluids for Thermal Energy Storage System Integrated Nuclear Power Plant

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1. Introduction

Traditionally, most nuclear power plants operate for a long-term steady state full power to supply electricity as a base load cheaply in many countries. Small and fast responding power plants such as gas-fired power plants have been supplying electricity to meet the peak demand. However, there is a tendency to reduce fossil fuels and increase renewable energy portion to address global environmental issues such as greenhouse effect and fine dust air pollution. For example, the Korean government announced the 3020 plan in which the share of renewable energy increases to 20% to 2030. More than 95% of new renewable energy generation facilities are solar (63%) and wind (34%). Solar and wind are intermittent energy sources without energy storage system (ESS). Because of the problem of intermittency, it is difficult to match power supply and demand and oversupply problem will be prominent as the proportion of renewable energy generation increases.

Therefore, the expansion of renewable energy should be developed safely and efficiently while keeping nuclear power as a power source to stabilize the grid. This may require load following operation abilities of a nuclear power plant. Thus, thermal energy storage system (TES) integrated nuclear power plant that can follow power supply and demand fluctuations without directly changing the core power was suggested for flexible nuclear power plant operation (Fig. 1) [1]. TES integrated nuclear power plant is a system that stores heat in the TES through heat exchange between a part of mass flow rate at the low-pressure turbine (LPT) inlet and heat transfer fluid (HTF) of TES when oversupply occurs. When additional power is needed, thermal energy is supplied from TES to a dedicated TES power cycle.

As a part of effort to develop TES integrated nuclear power plant, a suitable heat transfer fluid for this system is first searched. Therefore, this study compares possible heat transfer fluids through quantitative evaluation indicators such as storage cost and impact on the secondary side of nuclear power plants to down select TES heat transfer fluid.

2. Heat Transfer Fluids

HTFs that are widely used in industry are synthetic oils and molten salts. In this study, Therminol 66, a type of synthetic oil, and HITEC salt, a type of molten salt, are considered as candidate HTFs.

2.1 Therminol 66

Therminol 66 has good thermal stability and the operating temperature range is -3°C~345°C. The performance of Therminol 66 has been proven through years of industrial experience under a wide range of operating conditions [2]. Therminol 66 is efficient without high pressure and high boiling point helps reduce volatile and fluid leakage problems associated with other fluids. These properties are suitable for TES integrated nuclear power plant.

2.2 HITEC salt

The operating temperature range of HITEC salt is 142°C~538°C. HITEC salt is relatively cheap compared to Therminol 66 and has high heat transfer coefficient, high thermal conductivity and high thermal stability [3]. In addition, HITEC salt is non-flammable, non-explosive and no toxic. It can be used at atmospheric pressure, so

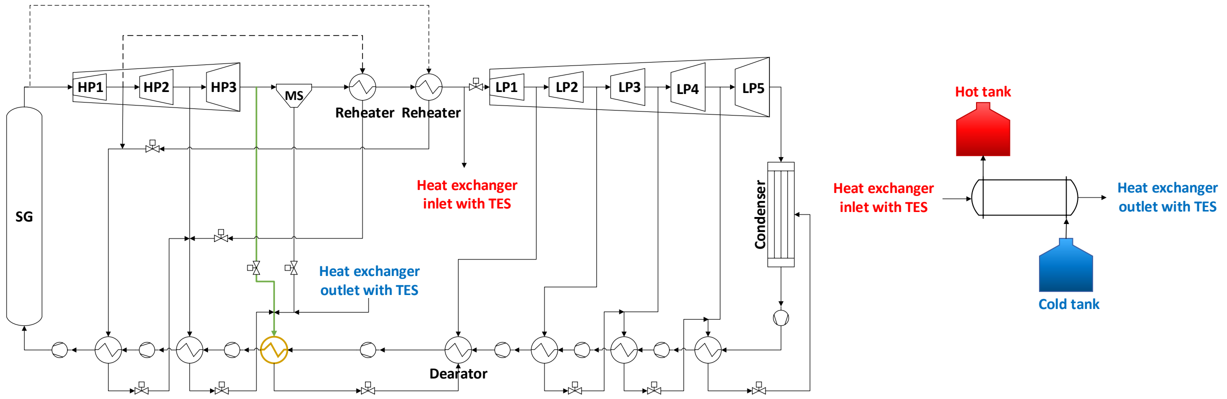

Fig. 1. TES integrated nuclear power plant

Table I: Heat exchange conditions

LPT inlet to TES	Fluid	Steam	
	Mass flow rate [kg/s]	146.78	
	Temperature [°C]	264.34	
	Pressure [kPa]	1443.42	
TES	Fluid	Therminol 66	HITEC salt
	Mass flow rate [kg/s]	250~1750	2000~5000
	Cold tank temperature [°C]	70	150
	Cost [$/kg]	6.72 [4]	0.95 [5]
	Heat exchange pinch temperature [°C]	5	5

no additional pressurizer is required and is less corrosive to common structure materials. HITEC salt with these properties is also suitable for use as HTF in TES integrated nuclear power plant.

3. Impact on Thermal Energy Storage System

As shown in Fig. 1, a part of mass flow rate at the LPT inlet transfers heat to the HTF and the heat exchange conditions are shown in Table 1. Cold tank temperature of Therminol 66 was set to 70°C for a dedicated TES power cycle and the cold tank temperature of HITEC salt was set to 150°C to prevent freezing. The look-up table was used for the physical properties of Therminol 66 [2]. Equation (1) and (2) were used for the physical properties of HTIEC salt.

Therminol 66 has a lower cold tank temperature than that of HITEC salt, so it requires a relatively low mass flow rate to transfer the same amount of heat and can store more heat (Fig. 2).

$$\rho_{HITEC} = 2279.799 - 0.7324 \times T \text{ (1) [6]}$$

$$C_{p,HITEC} = 1582.6104 \text{ (2) [3]}$$

$$C_s \left(\frac{\$}{kWh}\right) = C_m \left(\frac{\$}{kg}\right) \times \frac{\dot{m}\left(\frac{kg}{s}\right) \times 3600\ (s)}{Q\ (kW) \times 1(h)} \quad (3)$$

Storage cost was calculated through equation (3). C_s is the storage cost, C_m is the HTF cost, $\dot{m}$ is HTF mass flow rate, Q is the heat transferred to TES and was based on 1 hour. The results are shown in Fig. 2 and Table 2. V_{hot} is the volume of the hot tank. Therminol 66 is good in terms of heat transferred to TES and TES hot tank volume, but the storage cost of HITEC salt is cheaper than half the storage cost of Therminol 66.

4. Impact on Nuclear Power Plant Secondary Side

The system proposed in this study aims to keep the primary side core power constant during load-following operation, so the steam generator (SG) inlet temperature should be maintained at constant level irrespective to the power plant electricity generation at all times. Therefore, this section analyzes the change in the SG inlet temperature and the change in LPT work due to flow split of the LPT inlet mass flow rate. Table 3 and Table 4 summarize the conditions of the secondary side used in this study.

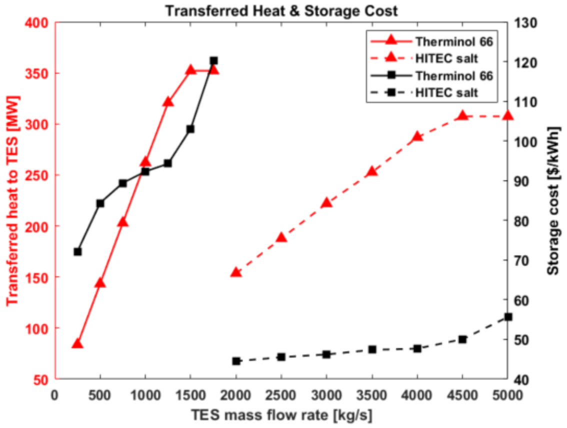

Fig. 2. Transferred heat and storage cost

Table 2: Heat exchange results

1 hour	$\dot{m}$	Q	C_s	V_{hot}
Therminol 66	1500	352.09	103.07	6059.9
HITEC salt	4500	307.36	50.07	8357.9

Table 3: Typical nuclear power plant secondary side conditions

Power [MW]	1458.78
Total mass flow rate [kg/s]	2250.61
SG inlet temperature [°C]	232.00
SG outlet temperature [°C]	282.21
SG outlet pressure [kPa]	6632.73
Condenser temperature [°C]	33.16
Condenser pressure [kPa]	5.08

Table 4: LPT inlet on-design conditions

Mass flow rate (on-design value) [kg/s]	1467.83
Flow split to TES at LPT inlet	0~0.5
Temperature [°C]	264.34
Pressure [kPa]	1443.43

4.1 Steam generator inlet temperature

Fig. 3 shows the steam temperature after heat exchange for each HTF. In the heat exchange with Therminol 66, subcooled liquid water exits after the heat transfer, but in the heat exchange with HITEC salt, water is still in two phase at saturation temperature. After heat exchange with TES, water flows to the yellow feedwater heater (shown in Fig. 1) to join with the flow split at high-pressure turbine (HPT) outlet (green line in Fig. 1). Fig. 4 shows how the SG inlet temperature changes after heat exchange with HITEC salt according to flow split at HPT outlet when flow split at the LPT inlet is 0.1. The flow split at the LPT inlet is based on the on-design LPT inlet mass flow rate (equation (4)).

$$flow\ split\ at\ LPT\ inlet = \frac{\dot{m}_{split}}{\dot{m}_{on,LPT\ inlet}} \quad (4)$$

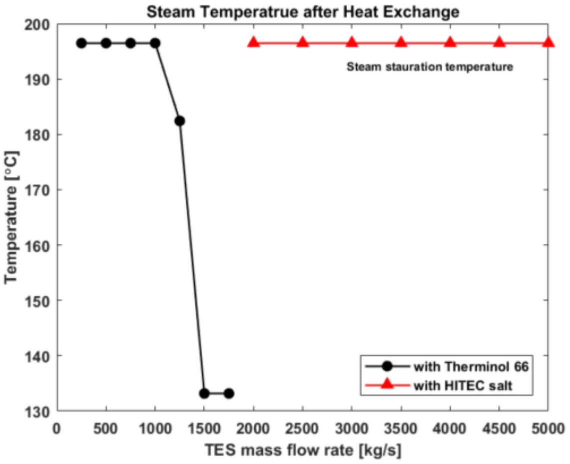

Fig. 3. Steam temperature after heat exchange

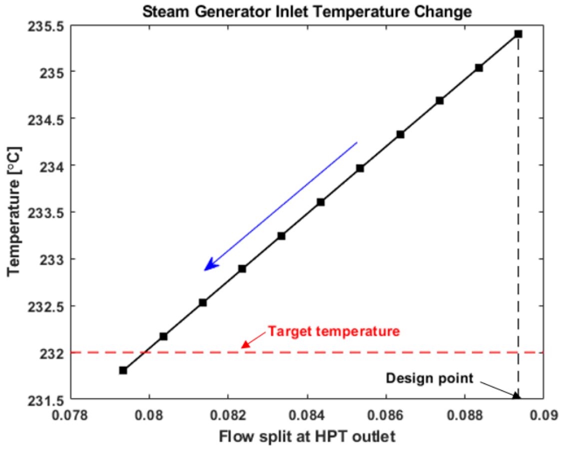

Fig. 4. SG inlet temperature change according to HPT outlet flow split (HITEC salt case, flow split at LPT inlet = 0.1)

As mentioned above, the SG inlet temperature should always maintain 232°C, which is nominal value (target temperature in Fig. 4), for constant primary side power. However, at the LPT flow split ratio of 0.1 and maintaining minimal design values of flow split after HPT outlet (design point in Fig. 4), the SG inlet temperature is higher than 232°C. Thus, by adjusting the flow split at HPT outlet to the feedwater heater from the nominal value, SG inlet temperature can be reduced back to 232°C. Thus, the required flow split at HPT outlet to feedwater heater to maintain the SG inlet temperature was calculated for possible flow split values from LPT inlet to TES.

Fig. 5 and Fig. 6 show that the SG inlet temperature is maintained at 232°C by adjusting the flow split at the HPT outlet. Since the temperature is low after heat exchange with Therminol 66, it is necessary to increase the flow split at the HPT outlet to maintain 232°C. After heat exchange with HITEC salt, the temperature is high, so the flow split should be reduced to reduce heating. Therefore, the trend of flow split is opposite in each HTF case.

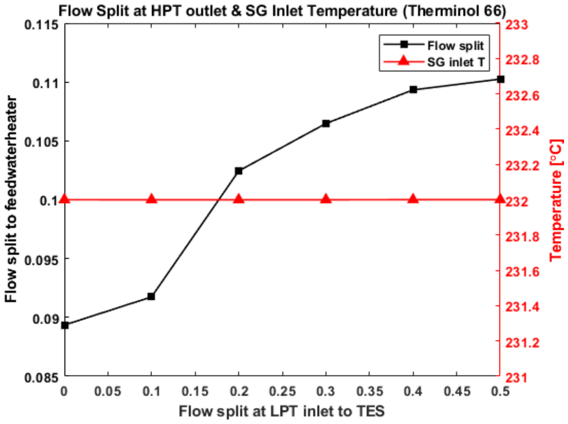

Fig. 5. Flow split at HPT outlet and SG inlet temperature (Therminol 66)

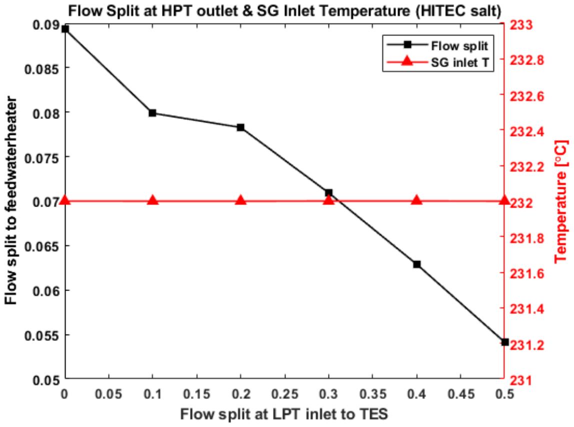

Fig. 6. Flow split at HPT outlet and SG inlet temperature (HITEC salt)

4.2 Low-Pressure Turbine Off-Design Operation

Due to the flow split at LPT inlet, LPT operates at off-design conditions, so a off-design model is needed to correctly evaluate the power reduction due to the flow split. When the steam turbine is operated at part load, the mass flow rate of the steam supplied to the steam turbine is reduced. However, even if the mass flow rate of the steam supplied to the steam turbine is reduced, the volumetric flow rate of the steam must be maintained as in the full load operation at each stage of the steam turbine [7]. Therefore, the throttling process is added at the LPT inlet (Fig. 1) so that the volumetric flow rate is maintained at nominal value after the mass flow rate at the LPT inlet is diverted to the TES.

$$\frac{\dot{m}_{on}}{\rho_{on}} = \frac{\dot{m}_{off}}{\rho_{off}} = const. \, (5)$$

$$Q = c_d A \sqrt{\frac{2\gamma R T_1}{\gamma - 1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]} \quad (6)\ [7]$$

It can be seen from equation (6) that the pressure ratio is constant when the volumetric flow rate is constant. c_d is discharge coefficient, A is orifice area, γ is ratio of specific heats, R is gas constant. Subscript 1 is inlet and 2 is outlet. When the pressure ratio is kept constant, each stage of the steam turbine exhibits design efficiency regardless of load fluctuations. Also, even if the mass flow rate and pressure of the steam entering the steam turbine are different, the condenser pressure is always maintained. [7]. Therefore, the pressure ratio of the last stage of the LPT varies depending on the load fluctuation. In this case, the last stage efficiency was calculated using ray`s semi-empirical equation (7). N is rotational speed, Δh_s is isentropic enthalpy difference, α is 2 in this study.

$$\eta_{off} = \eta_{on} - \alpha\left[\frac{\dfrac{N_{off}}{\sqrt{\Delta h_{s,off}}}}{\dfrac{N_{on}}{\sqrt{\Delta h_{s,on}}}} - 1\right]^2 \quad (7)\ [8]$$

4.3 Low-Pressure Turbine Work Change

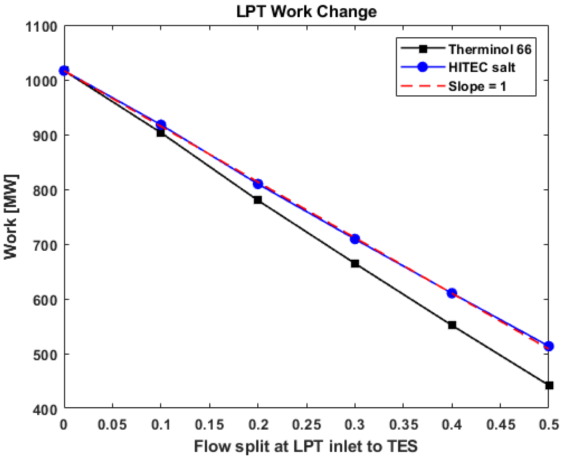

Fig. 7. LPT work change according to flow split at LPT inlet

The calculated results based on the information in section 4.2 are shown in Fig. 7, which shows the LPT work change when each HTF was used. In the case of HITEC salt, it can be seen that the LPT work decreases at the same rate as the flow split. However, in the case of Therminol 66, the LPT work is significantly lower than that of HITEC salt. This is because in the case of HITEC salt, since the flow split at the HPT outlet is reduced (Fig. 6), more mass flow rate is sent to the LPT, whereas the Therminol 66 increases the flow split at the HPT outlet (Fig. 5), so the mass flow rate to the LPT is reduced.

In this system, the round-trip efficiency can be defined as in equation (8). W_{LPT_loss} is the power loss by branching the flow at the LPT inlet to the TES and $W_{TES\,power\,cycle}$ is the power that can be produced from a dedicated TES power cycle. Therefore, the use of Therminol 66 as an HTF may cause lower round-trip efficiency.

$$\eta_{round-trip} = \frac{W_{TES\,power\,cycle}}{W_{LPT\,loss}} \quad (8)$$

3. Conclusions

In this study, Therminol 66 and HITEC salt were compared and analyzed to select a suitable HTF for the TES integrated nuclear power plant. Therminol 66 has an advantage in terms of heat transfer and hot tank volume because the lowest operating temperature is lower than that of the HITEC salt. However, due to the relatively expensive fluid cost, the storage cost is twice of HITEC salt.

This study showed that the SG inlet temperature can be controlled by adjusting flow split at the HPT outlet to the feedwater heater. This control has the advantage of maintaining the performance of HPT. Since the temperature after heat exchange with each HTF is different, the tendency of flow split at the HPT outlet is opposite, which affects the LPT work change. As a result, LPT work change affects round-trip efficiency, so the use of HITEC salt is more recommended in this study due to the steam cycle characteristics.

Acknowledgement

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