Preliminary Analysis of Steam Rankine Cycle as Power Conversion System of Thermal Energy Storage using Shell and Tube Steam Generator

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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. However, renewable energy has a problem of intermittency. For instance, solar power cannot produce energy at night, and power generation capacity decreases on cloudy days. As a result, sudden weather changes make renewable energy difficult to match the power supply and demand. This problem is becoming more 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. In order to meet the peak power demand or sudden decrease in power production of the renewable energy, an energy storage system is needed. However, this problem needs to be solved in the nuclear power plant to match the demand and production fluctuation. Thus, a nuclear power plant integrated with a thermal energy storage (TES) system that can follow power supply and demand fluctuations without directly changing the core power was suggested for flexible nuclear power plant operation [1]. In this study, the heat storage medium for TES is selected and the thermodynamic analysis of a steam Rankine cycle, as a power conversion system for TES is performed after developing the steam generator (SG) code.

2. Methods and Results

2.1 HITEC Heat Transfer Salt

Table I shows the advantages of HITEC. Because of these advantages, HITEC is a competitive solution for heat storage and heat transfer medium for PWR TES system [3]. Since HITEC can be used at atmospheric pressure, no additional expensive pressurizer is required. In addition, the high heat transfer and high heat capacity of HITEC make the equipment size and surface area for heat transfer minimized. Maintenances and power costs for circulating the salt are correspondingly low. Thus, these advantages minimize investment and operating costs of TES system. It is less corrosive to common structure materials as well. The main heat transfer fluid used today in central receiver systems (CRSs) in the concentrated solar power plant is HITEC. In this study, HITEC is selected as the heat storage and heat transfer medium for TES.

Table I. Advantages of HITEC [2]

Low- melting point (142℃) / cost
High- heat transfer coefficient / thermal conductivity / thermal stability
Non- fouling / flammable / explosive
No toxic vapor

2.2 Shell and Tube Type Steam Generator (SG)

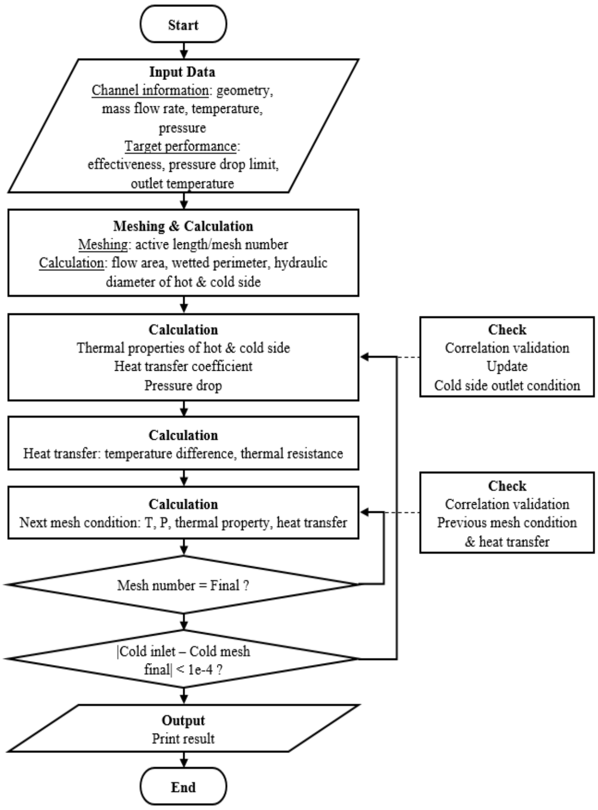

Fig. 1. KAIST_HXD flowchart [4]

The KAIST_HXD is an in-house heat exchanger code based on MATLAB. By providing detail channel geometry and configurations as input information, the code computes heat transfer and pressure drop. Fig. 1 shows the KAIST_HXD flowchart. Based on this code, KAIST research team developed shell and tube type SG code for application to KALIMER-600, which is the 4th generation reactor under development in KAERI. This code uses sodium and water as fluids because KALIMER-600 is sodium-cooled fast reactor (SFR). The physical properties of water are based from REFPROP of NIST, but the physical properties of HITEC cannot be called from REFPROP. Thus, sodium was replaced with HITEC and new correlations for HITEC properties were added to the code in this study.

Table II shows correlations for properties of HITEC. T is the bulk temperature in Kelvin. The friction factor is solved by Colebrook equation. The heat transfer coefficient, Prandtl number, Reynolds number and pressure drop are calculated with well-known equations. Gnielinski suggested Nusselt number equation for high Prandtl number fluids, such as HITEC [5]. Enthalpy was calculated from Fig. 2.

Table II. Correlations of HITEC properties (T is the fluid bulk temperature in Kelvin)

Nusselt Number [5]
$Nu = \dfrac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}} - 1\right)}$ $\left(\begin{matrix} 0.5 \le Pr \le 2000 \\ 3 \times 10^3 \le Re \le 5 \times 10^6 \end{matrix}\right)$
Density [6]
$\rho = -0.733(T - 273.15) + 2080 \left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$
Specific heat capacity at constant pressure [6]
$c_p = 1.560 - \frac{T - 273.15}{1000} \left[\frac{\mathrm{kJ}}{\mathrm{kg}\ ℃}\right]$
Thermal conductivity [6]
$k = 0.78 - 1.25 \times 10^{-3}T + 1.6 \times 10^{-6}T^2 \left[\frac{\mathrm{W}}{\mathrm{m}\ ℃}\right]$
Dynamic [6]
$\mu = \frac{e^b + e^{-b}}{e^b - e^{-b}} - 0.999\ [\mathrm{Pa\ s}]$ $b = 5.9(T - 9.638)/990.362$
Enthalpy [2]
$H = 1.555 \times 10^3 (T - 422.039) + 2.56 \times 10^5 \left[\frac{\mathrm{J}}{\mathrm{kg}}\right]$

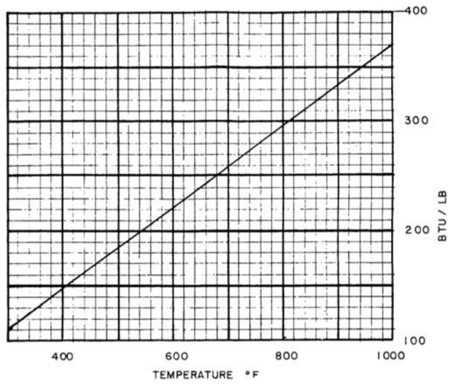

Fig. 2. Temperature-Enthalpy graph of HITEC [2]

Since TES receives heat from the secondary side of the nuclear power plant, the temperature of HITEC cannot exceed 275℃ which is the outlet temperature of typical PWR SG. In this study, the HITEC (hot side) inlet temperature was set 275℃ to of shell and tube type SG assuming that the TES was fully charged. Other shell and tube shape SG design conditions are listed in Table III.

As a result, HITEC and water outlet temperature are 248.958℃ and 244.326℃, respectively. The amount of heat transferred is 202.489 MW. Using these results, a thermodynamic analysis of superheated steam Rankine cycle, which is the most popular cycle in this operating temperature, was performed.

Table III. Shell and tube SG conditions

Input		
Hot side	Fluid	HITEC
	Inlet temperature	275℃
	Inlet pressure	400 kPa
	Mass flow rate	15000 kg/s
	Channel number	200000
Cold side	Fluid	Water
	Inlet temperature	200℃
	Inlet pressure	2.5 MPa
	Mass flow rate	80 kg/s
	Channel number	205000
Tube	Length	1.39 m
	Diameter	6 mm
	Thickness	3.5 mm
	Pitch	16 mm
Output		
Hot side	Outlet temperature	267.9414℃
	Pressure drop	2.2049 kPa
Cold side	Outlet temperature	255.2674℃
	Pressure drop	0.59402 kPa
Heat load		163.423 MW

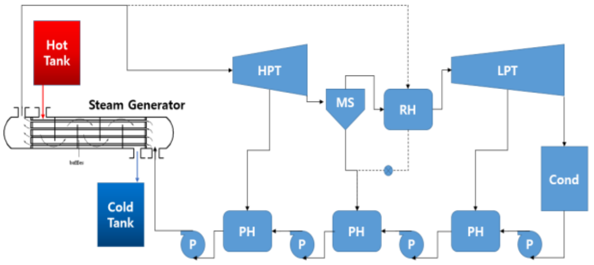

Fig. 3. Schematic diagram of TES-steam Rankine cycle

Table IV. Steam Rankine cycle conditions

Working fluid	Water
Thermal input	163.423 MW
Maximum pressure	2.5 MPa
Minimum pressure	5 kPa
Maximum temperature	255.2674℃
Turbine efficiency	90%
Pump efficiency	80%
Re-heater effectiveness	90%
Pressure losses	Neglected

For thermodynamic analyses, KAIST-CCD developed by KAIST research team was used. This code has been verified from previous studies [7, 8]. Fig. 3 shows the schematic diagram of steam Rankine cycle with TES. This cycle analysis first neglected any pressure losses associated with the fluid flow in the piping. The cycle design conditions are show in Table IV and the condenser outlet was assumed at saturation condition with zero quality. In addition, the split ratio of mass flow was controlled to prevent two-phase at the preheater outlet (pump inlet).

Fig. 4 shows the T-S diagram of this cycle. Dotted lines indicates the preheat process. The results are shown in Table V.

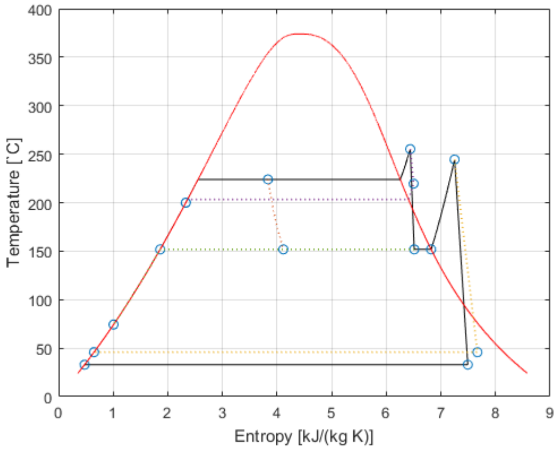

Fig. 4. T-S diagram of superheated steam Rankine cycle

Table V. Steam Rankine cycle results

HPT work	16.263 MW
LPT work	33.722 MW
Pump work	0.226 MW
Net work	49.762 MW
Cycle efficiency	30.722 %

3. Conclusions

In this study, HITEC was first selected as a heat storage and transfer medium for TES because of several advantages. For HITEC physical properties, new correlations were added to the previously developed shell and tube SG design code and a preliminary analysis was conducted. As a result, water temperature of SG outlet which is used in thermodynamic analysis of a steam Rankine cycle reached 255.2674℃ at given conditions. Based on shell and tube SG code results, the efficiency of superheated steam Rankine cycle approaches 30.722%.

This study is a preliminary study to gain an insight on approximate behavior of TES-steam Rankine cycle. Therefore, future studies will optimize each input variables of both codes after determining TES size, storage capacity and work produced from the TES.

Acknowledgements

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