A study on efficiency change of small modular reactor with regional sea temperature in Korea

Jung Hwan Park[a], Jeong Ik Lee[a]*
[a]*Department of Nuclear and Quantum Engineering N7-1 KAIST 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea 305-338,* junghwanpark@kaist.ac.kr
**Corresponding author:* jeongiklee@kaist.ac.kr

1. Introduction

Small Modular Reactor (SMR) is favored by many countries due to its high efficiency, compactness, eco-friendly, and cost-effective power generation technologies [1]. 70 different types of SMR are being developed around the world. Examples are NuScale in U.S.A, KLT-40S in Russia, ACP-100 in China, and SMART in Korea. The SMR market will grow further with expectation of SMRs to supply clean power stably.

Due to the nature of SMRs, SMR is more likely to be used as a distributed power source where the demand of electricity has to be met with SMR mostly [2]. Therefore, site selection of SMR is very important. In S. Korea, there are many places where SMR is likely to be installed, because S. Korea is a peninsula and has many islands. For example, Islands in the East sea, in South sea, and in the west sea can be one of the installation candidates.

The purpose of this study is to evaluate the performance change of steam Rankine cycle for SMR under different conditions encountered in islands around S. Korea. Thermal efficiency of SMR is calculated by reflecting the seawater temperature in each island located at different sea. This study includes modelling of a steam Rankine cycle with basic thermodynamic equations and sensitivity analysis of a heat sink temperature on the thermal efficiency of SMR.

2. Methods

2.1 System description

Fig.1 describes the schematic diagram of SMR steam Rankine cycle.

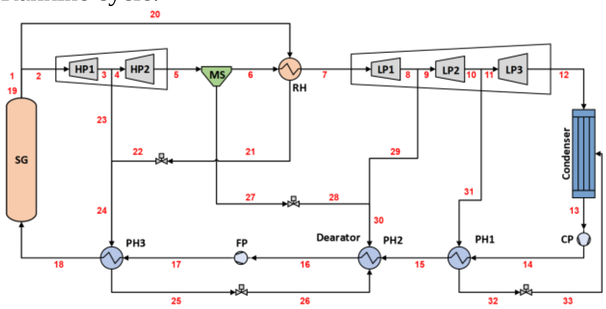

Fig. 1. Schematic diagram of SMR steam Rankine cycle

Small Modular Reactor (SMR) Steam Rankine Cycle includes one steam generator, High Pressure Turbine (HPT), Moisture separator, Reheater, Low Pressure Turbine (LPT), Condenser, Feedwater pump, and Preheater. HPT is divided into two turbine and moisture is extracted in the middle to increase quality of steam. LPT is divided into three turbine and moisture is extracted. In order to increase thermal efficiency, high temperature steam is bypassed from steam generator and goes into reheater which is in between HPT and LPT. After power generation, steam is condensed to heat sink temperature and all water is collected at feedwater line and flows to steam generator.

2.2 Thermodynamic equation

For evaluating performance of proposed system, components are modelled by basic thermodynamic equation.

2.2.1 Turbine and Pump

Turbine and pump are modelled with isentropic efficiency model. The equation is given by:

$$W_P = \dot{m}(h_{out} - h_{in}) = \frac{\dot{m}(h_{out.isen} - h_{in})}{\eta_{Pump}} \quad (1)$$

$$W_T = \dot{m}(h_{in} - h_{out}) = \eta_{TB} * \dot{m}(h_{in} - h_{out.isen}) \quad (2)$$

where W_P and W_T represent the work of feedwater pump and steam turbine, respectively. $\dot{m}$ is mass flow rate, h is specific enthalpy, and η_{isen} is isentropic efficiency of each components.

2.2.2 Heat exchanger

Heat exchanger is modelled with basic heat balance equation. The heat exchanger is assumed as counter-flow heat exchanger and effectiveness model is applied.

$$h_{C_{out}} = h_{C_{in}} + \eta_{HX} * \min(\Delta h_{C_{ideal}}, \Delta h_{H_{ideal}}) \quad (3)$$

$$h_{H_{out}} = h_{H_{in}} - (h_{C_{out}} - h_{C_{in}}) * \frac{\dot{m}_C}{\dot{m}_H} \quad (4)$$

where h_H and h_C are specific enthalpy of hot side and cold side, respectively. Subscript *in* and *out* represent inlet and outlet stream. η_{HX} is effectiveness of heat exchanger and Subscript *ideal* is ideal enthalpy change.

2.3 Design condition

The design conditions are listed below.

Table. 1. Cycle parameters

Cycle parameters	Value
SG thermal power	540MWth
SG pressure out	5.2MPa

SG temperature out	310℃
Turbine efficiency	85%
Pump efficiency	80%
HX pressure drop	10%
HX effectiveness	92%
Turbine exit quality	>88%
HPT pressure ratio	9
LPT pressure ratio	175.5
Reheater bypass	11% of total mass flow rate
Generator efficiency	95%

Total three sea are selected for the potential SMR site. Monthly seawater temperature data is collected from Korea Meteorological Administration (KMA) [3]. Based on this data, maximum, minimum, and average efficiencies are calculated and compared.

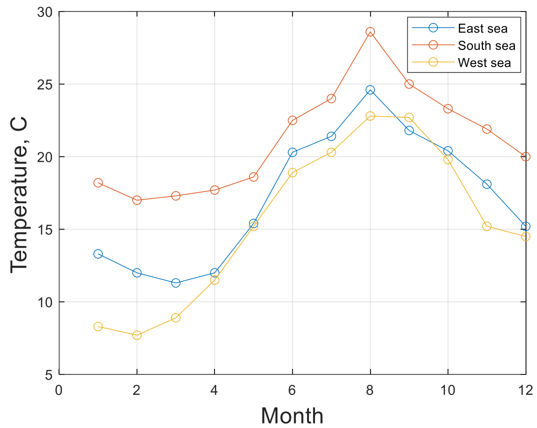

Fig. 2. Monthly seawater temperature in each region

3. Results

Fig. 3 presents T-s diagram of designed steam Rankine cycle.

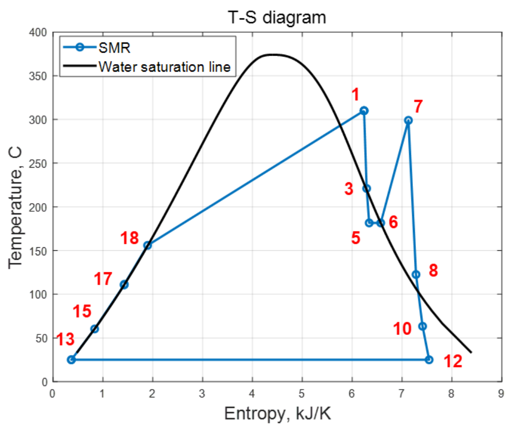

Fig. 3. T-s diagram of SMR steam Rankine cycle

Table 2. Calculated cycle performance at 25℃

Cycle Parameters	Value
Total Q in	2.32MWth/kg/s
Turbine work	840kW/kg/s
Net electricity	790kWe/kg/s
SG inlet T	147℃
Pump work	8.2kW/kg/s
Net efficiency	33.9%

The performance of designed SMR is calculated and listed at Table 2. Total turbine work is 840kW per unit steam mass flow rate and 8.2kW per unit steam mass flow rate consumed as a feedwater pump work. Steam mass flow rate is calculated as 232.3kg/s to remove heat from primary side. Net efficiency is calculated as 33.9%.

Sensitivity analysis of seawater temperature on the thermal efficiency is also investigated. Final heat sink temperature is defined as 10℃ higher than the seawater temperature in consideration of pinch of heat exchanger.

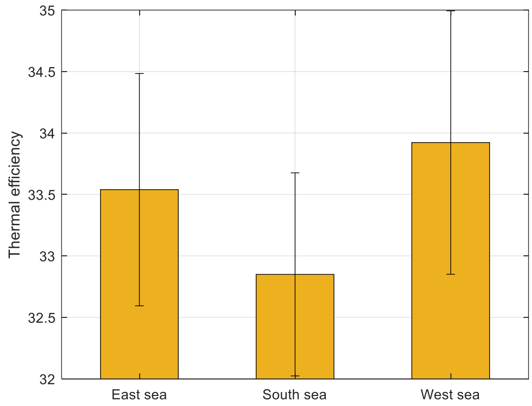

Fig. 4. Thermal efficiency of steam Rankine cycle in each region in Korea

From the calculation, the west sea shows high thermal efficiency with the lowest seawater temperature on average. South sea shows low thermal efficiency due to the high seawater temperature. Overall, there is not much significant difference in efficiency, but the west sea is most suitable place.

4. Conclusions

With an increase of demand for efficient, stable, eco-friendly power source, research and development works on SMR are being actively conducted. Currently, SMR is likely to be utilized as a distributed power source, such as in island. For various islands located on three sides of S. Korea, the suitable sea is evaluated in terms of thermodynamic evaluation. Steam Rankine cycle of SMR is modelled with MATLAB code. Sensitivity analysis of seawater temperature is conducted on thermal efficiency of SMR. As a result, west sea shows the highest thermal efficiency because of its low seawater temperature. Indeed, the site cannot be determined with the seawater temperature alone, further modelling and evaluation will be conducted in the future.

5. Acknowledgment

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