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Optimization for the Nuclear Heat Storage and Recovery Rankine Cycle

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1. Introduction

Current energy policy established by the Korean government identifies an increase in renewable energy sourced generation with an accompanying reduction in energy generated by nuclear and coal power plants. 'Green' energy supply to the grid is targeted to provide 20% of electricity by the year 2030 [1]. Experience in energy markets in the United States (US) and Germany has demonstrated that non-market based introduction of renewable energy generation can lead to disruption for existing power producers, replacing long-existing dispatch hierarchies with new paradigms. In particular, in several non-regulated US electricity markets, nuclear units with sunk cost but low marginal production rates have become non-competitive [2].

Worldwide, it is common for essentially all nuclear units to be designed for base load operation. This also holds true for Nuclear Power Plants (NPPs) in Korea. Load following by NPPs results in technical issues, aging of large equipment, and increased operational risk [3]. Curtailed generation also results in reduced plant production, challenging economic viability. [4].

One proposed alternative for NPPs faced with load following is to store thermal energy during periods of excess supply (e.g., from renewable energy sources). The energy would then be recovered during increased energy demand or when renewable sources cannot meet supply requirements. Heat storage is cost competitive with other energy storage technologies assuming pumped hydroelectric storage has been fully developed. Alternatives such as battery storage are used mostly as short term grid support options (e.g., frequency and voltage control) and have limited energy storage capacity [2].

Here, the impact of nuclear heat storage and recovery on the Rankine cycle is investigated. The goal is to maximize the 'round trip' efficiency of such a system. The proposed base unit for the heat storage system is the Korean Advanced Power Reactor 1400 (APR1400). The heat storage technology selected for case analysis is the tertiary cycle where the secondary cycle steam is condensed, transferring energy to heat transfer oil through a shell and tube heat exchanger. Hot oil is then circulated through large storage tanks in which crushed rock is the storage medium. Energy is recovered by boiling feedwater with steam returned to the APR1400 steam cycle.

2. Method and Results

This section describes the considerations needed for optimization of the nuclear heat storage and recovery cycle. The procedure proposed here aims to both maximize overall efficiency of the thermodynamic cycle and to simplify the system design. The proposed optimization procedure for APR1400 nuclear heat storage and recovery is based on operational experience and thermodynamic principals (i.e., 1st and 2nd laws). The thermodynamic model of the APR1400 secondary cycle combined with the heat storage and recovery system is currently under detailed evaluation to determine the optimal process paths which balance thermodynamic efficiency and cost.

The APR1400 secondary cycle systems analyzed in this section are as follows: (i) main steam (MS), (ii) steam turbine, (iii) moisture separator reheaters (MSR), (iv) steam extraction, (v) feedwater heaters (FWHs), (vii) feedwater pumps (FWP), and (viii) condensate. The considered systems of the tertiary cycle are: (i) steam extraction, (ii) heat exchange, (iii) condensate return, (iv) feedwater extraction, (v) recovery steam plant, and (vi) steam return.

2.1. Heat storage capacity

Nuclear heat storage capacity is constrained by the capacity of nuclear reactor. The amount of both extracted and recovered energy must be carefully selected in order to minimize impact on NSSS operations and modifications to the secondary cycle. Due to the scale of heat storage at a large nuclear unit, the potential for economic benefit is greater than for other sources of heat [5]. Here, the secondary cycle power output reduction is assumed as 20% of thermal output, and is considered to be a representative maximum amount which does not degrade systems, structures, and components due to low load operation of the steam cycle. The proposal is to extract 20% of Nuclear Steam Supply System (NSSS) thermal power for eight (8) hours with low demand or when an excess of green energy lowers energy prices below the level of economic viability. Cyclical plant power turndown is illustrated in Fig. 1.

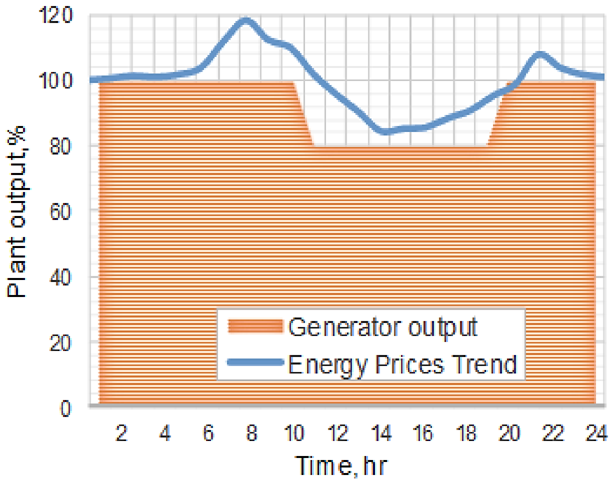

Fig. 1. Nuclear unit output during heat storage mode.

Increased energy demand with higher energy prices justifies increased power output by heat storage recovery. However, the stored energy cannot be recovered at the same rate as which it was extracted. This would require significant turbine and generator modifications. Rather, to minimize plant design modifications the energy would be recovered over double the period for storage, limiting the thermal energy recovery rate to 10% of rated NSSS power. It is expected that this recovery could be accomplished with only minor modifications to the secondary side. Such increased output is similar to that for power uprates which have received licensing approval for more than 160 applications in the US. Fig. 2. illustrates the storage recovery mode. (*Note that the timing of the pricing scenario for Fig. 2. differs from that used for Fig. 1.*)

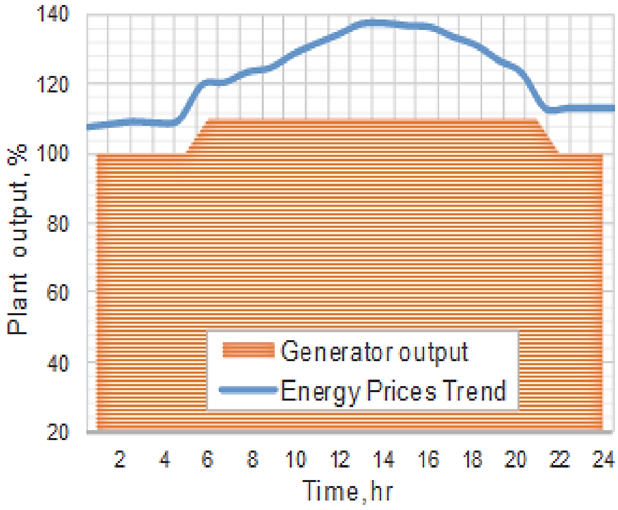

Fig. 2. Nuclear unit output during heat recovery mode.

2.2 Steam extraction

The extraction point for steam export during charging operations was selected considering maximum thermal efficiency and physical aspects of the design. The extracted steam is sent from the turbine hall to the heat exchange building located adjacent to the turbine building where the energy is transferred to the oil transport medium.

The extraction of high energy steam from the Main Steam system maximizes Carnot considerations and reduces the line size due to low specific volume at high pressure. The benefit of this configuration is also simplified design. Extraction of MS does not require any significant turbine modifications. The APR1400 turbine design is favorable for the proposed solution since the High Pressure Turbine (HPT) is designed with partial-arc admission. The partial-arc admission reduces throttling losses during low load operation.

2.3 Steam-oil heat transfer

Since the energy absorbed by the heat storage medium is a function of mass flow rate and differential temperature, design of the tertiary system must achieve a balance of these two parameters. Higher temperature differential reduces the flow rate of the oil and the volume of the storage (i.e., number of storage tanks). Alternatively, lower temperature differentials increase the temperature for the stored heat, increasing the Carnot and Rankine efficiency of the cycle. The balance between transferred and received heat fluxes are expressed by the equation (1) below:

$$\dot{m}_{steam}(h_{MS} - h_{cnd}) = \dot{m}_{oil}\, c_p (T_{hot} - T_{cold}) \qquad (1)$$

where:

$\dot{m}_{steam}$ − steam mass flow rate, kg/s
h_{MS} − main steam enthalpy, kJ/kg
h_{cnd} − condensate enthalpy, kJ/kg
$\dot{m}_{oil}$ − oil mass flow rate, kg/s
c_p − oil heat capacity, kJ/(kg-K)
T_{hot} − higher oil temperature, °C
T_{cold} −lower oil temperature, °C

The second law of thermodynamics determines that heat transfer across a finite temperature difference is irreversible [6]. Condensing of steam on one side of the process and constant heat capacity oil on the other side make the approach to reversible heat transfer difficult. As shown in Fig. 3, the oil temperature increases linearly as energy is transferred. The steam temperature remains constant during condensation and decreases rapidly (due to a low mass flow rate relative to oil) after it becomes subcooled.

The approach to reversibility is improved when the oil temperature difference ΔT (T_{hot}-T_{cold}) is reduced. Fig. 4 shows the heat transfer process with T_{cold}

increased from 36°C to 230°C where T_{hot} is maintained at 274°C.

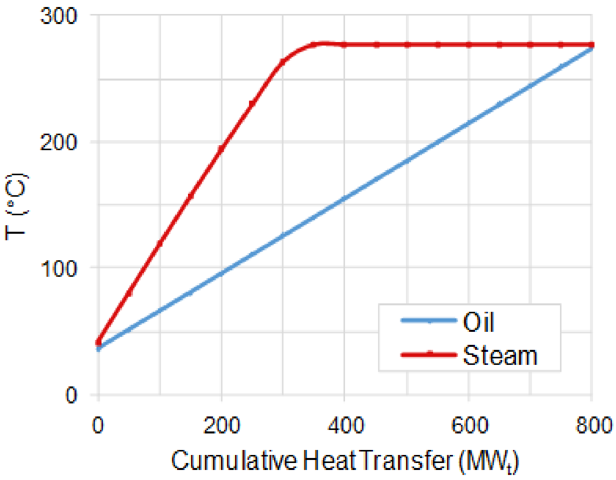

Fig. 3. Heat exchange diagram with large ΔT

The reduction of ΔT results in increased oil mass flow rate. To optimize the oil system, a hydraulic analysis of the oil system was performed using FATHOM® software. Results show that the pumping power increase due to increased oil mass flow is not significant. The required pumping power estimated for the case with large ΔT is estimated at 120 kW. The benefit of lower heat losses is higher than the penalty of higher pumping power for the increased mass flow rate.

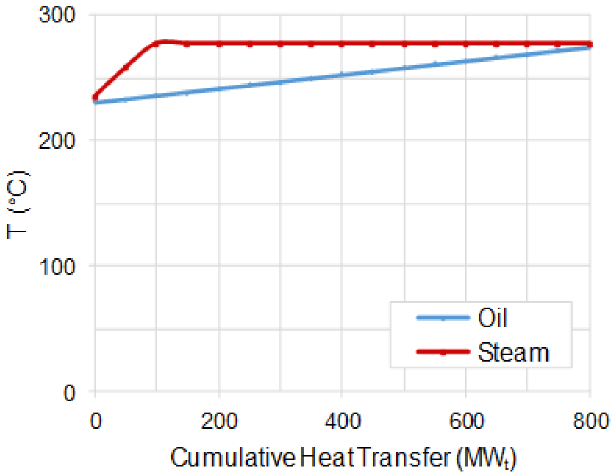

Fig. 4. Heat exchange diagram with reduced ΔT

2.4 Condensate return

Condensate returned to the secondary cycle has high pressure and temperature. Efficiency is maximized when the return is at the point in the cycle where the parameters are close to the condensate parameters. At the same time, the location should be selected in a way that minimizes plant modifications.

The current evaluation assumes that condensate is returned to the deaerator where the energy is transferred to the deaerator drains reducing steam extraction from the low pressure turbine. The design may consider a flash tank to decrease pressure of the condensate before the condensate return point.

2.5 The recovery system

The recovery system has several possible configurations. Two export locations and four return points are considered here.

The extracted water must have sufficient pressure to overcome backpressure in the return location. The proposal is to extract feedwater and to control flow by use throttle valves.

APR1400 has three Main Feedwater Pumps (MFWP) and two strings of High Pressure Feedwater Heaters (HP FWHs). To simplify feedwater export line design the considered locations are at the header after the MFWPs and at the header after the HP FWHs. The benefit of the second location is preheated water, minimizing the temperature difference between feedwater and hot oil.

The design includes three stages of heat recovery. The process is divided into stages to minimize the temperature difference between feedwater and oil, reducing irreversibility. The feedwater pressure for each of the stages determines the saturation temperature of the produced steam. Thus the selection of the pressure levels is an important step in optimization process. Initially estimated parameters for APR1400 heat recovery are summarized in Table 1.

Table 1: Initially estimated parameters for heat recovery from APR1400 heat storage

	Stage 1	Stage 2	Stage 3
FW temperature (°C)	145	234	234
FW pressure (bar)	25.5	33.48	39.78
Sat. steam. temperature (°C)	225	240	250

Each of the heat transfer stages provides steam supply to a different location in the steam cycle. Considered return locations from the steam plant are first stage reheating steam, FWH No. 7, FWH No. 6, and FWH No. 5. The turbine extraction to FWH No. 7 and to the first stage of reheat has the same parameters. The heat transfer diagram of the recovery process is presented at Fig. 5.

Determination of the optimal steam flow parameters require evaluation by analysis of the thermodynamic model of the cycle.

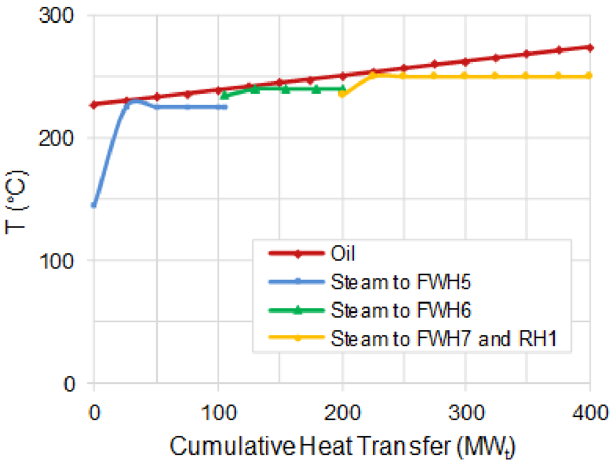

Fig. 5. Recovery heat exchange diagram

4. Conclusions

Global trends and changes to energy policy are changing energy markets. The ability of NPPs to provide variable power output may improve the economic competitiveness of nuclear energy in future energy markets with a higher share of renewable sources. Effective heat storage systems represent an opportunity for NPPs to adapt to future energy market conditions.

The proposed optimization procedure for an APR1400 nuclear heat storage system is aimed to maximize thermodynamic efficiency and simplify design. The optimization is initiated by estimation of heat storage capacity and energy extraction and recovery rates.

Following these steps, optimal steam extraction locations are selected, the range of operating temperatures to minimize energy losses is established, the condensate return location is chosen. Subsequently, feedwater extraction points are selected and pressures of feedwater streams entering the steam plant stages need to be optimized. The final stage is to choose steam return locations.

The proposed solution for APR1400 heat storage and recovery is to charge storage with 20% of NSSS thermal power for eight (8) hours and discharge to the secondary cycle at a rate of 10% of thermal output for sixteen (16) hours. Steam export is localized at the Main Steam Line.

The temperature difference is minimized and the hot condensate is returned to deaerator. During energy recovery, feedwater is extracted from two locations (header after MFWPs and header after HP FWHs). The feedwater pressure is throttled before entering the steam boilers. Heat transfer is divided into three (3) stages. Steam coming from first stage goes to FWH No. 5, the second stage supplies FWH No. 6 and the last stage provides steam to FWH No. 7 and the first stage reheater.

4.1 Future work

The system design proposed in this paper requires detailed evaluation by simulation of the thermodynamic model in appropriate software. The heat balance of APR1400 combined with heat storage and recovery system is currently under study. The model is being developed in PEPSE® software.

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