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Performance Analysis of Advanced Nuclear Power Plant with Variation of Sea Water Temperature †

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Abstract: Nuclear power plays a significant role in fulfilling the energy needs of Pakistan and its share in the total energy mix has increased from 4.7% to 8.8% in the past seven years. As per the Pakistan energy outlook report (2021–2030), this share is hypothesized to increase to 10.82% by the year 2030, which will alleviate the energy shortage problem and, at same time, reduce carbon emissions. Like all thermal power plants, it is also necessary for nuclear plants to operate at optimum efficiency. This study is based on the thermodynamic analysis of the conventional side of an advanced HPR-1000 (PWR) nuclear power plant. In this paper, a comparison of indigenously developed model results is made, with vendor-provided sea water temperatures and power curves for year-long sea water temperature variation. Firstly, a computational model is developed using Engineering Equation Solver (EES) software to evaluate the performance of the secondary side of the plant and is validated based on the designer-provided heat balance analysis for full power mode. Then, the condenser heat balance is performed for different cooling medium inlet temperatures and terminal temperature differences to study the relationship of condenser performance, thermal efficiency, and output power. Initial results reveal that sea water temperature varies at the condenser inlet from 5 to 35 °C, the power output of the unit decreases by 54 MW, and the thermodynamic efficiency drops by 1.79%. Thus, this paper highlights the impact of sea water temperature on plant performance and the need to devise more effective techniques to approach the plant's optimum efficiency.

Keywords: energy efficiency; thermodynamic optimization; steam cycle modeling

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1. Introduction

More than 60% of the electricity generation capacity of Pakistan is based on thermal power plants [1]. From a thermodynamic point of view, theoretical and design operational parameters could be compromised due to exacerbating climatic change in two ways, water unavailability and increasing coolant temperature [2]. Although during its design, the cooling medium temperature is chosen based on the average of the available historical data, in practice, these climatic conditions vary, as does the plant performance.

The amount of water consumed, and method of cooling (once through or recirculation), mainly depends on the type, capacity, and fuel used in power plants [3]. The temperature of the cooling water inlet is of particular concern, as it affects the capacity utilization of thermal plants in terms of falling efficiency and shedding load. In the literature, various publications have quantified the abovementioned facts for a variety of plants. Reference [4] highlights that for a 1 °C rise in condenser cooling water temperature, a decrease of the output power and system efficiency by approximately 0.171% and 0.168%, respectively, is observed. Also, the authors of [5] concluded that condenser exergy performance decreases with decreasing sea water temperature, which further influences the condenser duty. Recently, the authors of [6] push concerns related to high cooling water temperatures. The deviation of the heat transfer coefficient is found to be around 27% in the case of a deteriorated condenser vacuum, which eventually degrades the condenser performance. Also, ref. [7] shows the sensitivity of these thermal plants related to the surrounding environment. Yasser and Moftah [8] performed the thermal analysis on the Rankine cycle plant using EES and found that the condenser suffers minimum exergy destruction at lower condenser pressures. Similarly, ref. [9] performed the optimization of a combined cycle power plant utilizing EES software and observed the maximum efficiencies at the lowest condenser pressure.

As the rising rate of the Arabian Sea temperature is far higher than the global average rate [10], the aim of this study is to emphasize the importance of considering environmental effects. For this, a condenser heat balance model is developed using Engineering Equation Solver (EES) software (EES Pro 10.5.6.1) to establish a functional relationship between sea water temperature, condensing steam pressure, turbine power, and thermal efficiency.

2. Methodology

A mathematical model is established to perform thermodynamic analyses on the secondary side of the 1145 MW PWR plant. All computational relationships are formulated by applying energy and mass balance laws on the major secondary side components of the plant. Then, the impact of the sea water inlet temperature on thermal efficiency and power is evaluated for a range of cooling water temperatures (5 to 35 °C). Furthermore, the effect of variation of design parameters, like terminal temperature difference (TTDc) on the condenser performance, are also observed.

2.1. The Selected NPP Description

The typical secondary side consists of a steam generator (SG); one high-pressure turbine (HPT); two low-pressure turbines (LPT); a two-stage moisture separator reheater (MSR); six closed- and one open-feed water heaters; a condenser; and two major pumps, feed water (TFW) and condensate extraction (TFE), as shown in Figure 1.

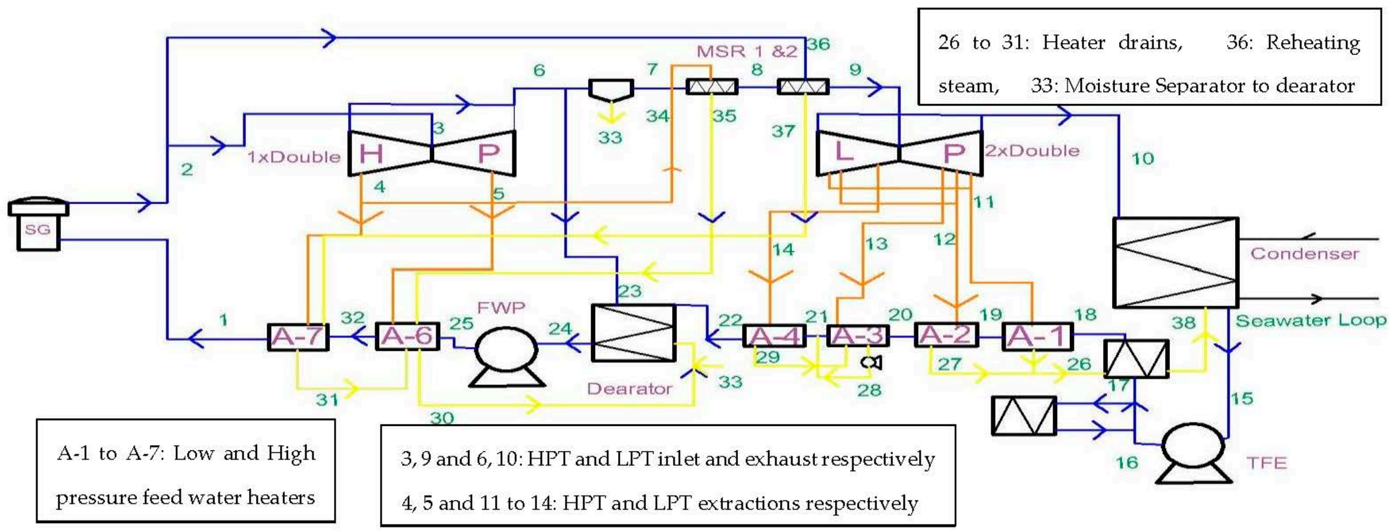


Figure 1. Schematic of the secondary side of the considered NPP. (Blue lines represent the connections, yellow is used for drains, orange represents the steam extractions, and equipment is drawn in black).

2.2. Cycle Efficiency

$$\mu_{th} = \frac{W_T - W_P}{Q_{SG}} \quad (1)$$

where W_T is the work produced by the turbine, W_P is the work consumed by pump, and Q_{SG} is the heat supplied in the steam generator.

2.3. Condenser Heat Balance Equations

$$Q_{cond} = m_{mix} \times h_{in\text{-}cond} - m_{fw} \times h_{out\text{-}cond} \quad (2)$$

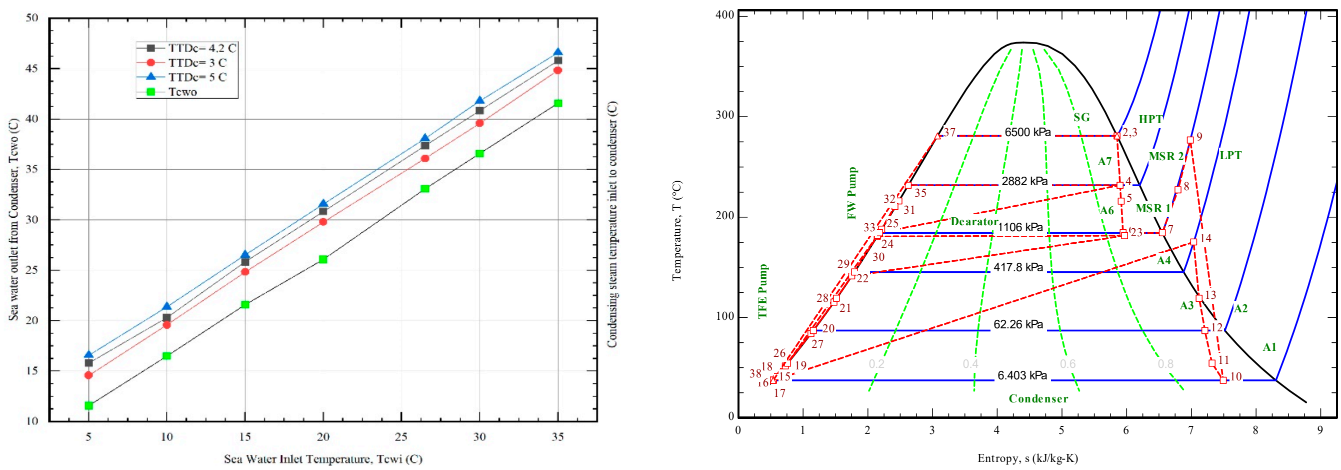
$$Q_{cond} = m_{CW} \times C \times \Delta T \quad (3)$$

where m_{CW} = cooling water mass flow rate through the condenser, kg/s, m_{fw}= feed water mass flow rate outlet from the condenser, kg/s, m_{mix} = mixture mass flow rate inlet to the condenser, kg/s, $h_{in\text{-}cond}$ = enthalpy of the mixture inlet to the condenser, kJ/kg, $h_{out\text{-}cond}$ = the enthalpy of the feed-water outlet from the condenser, and kJ/kg, ΔT = the temperature difference between the cooling water $_4$ exit and inlet temperatures, °C.

3. Results and Discussion

Thermodynamic computations are performed using EES to determine the thermodynamic parameters at the inlet and outlet of each component in Figure 1. This helps to determine the main thermodynamic parameters like enthalpy, quality, entropy, temperature, and mass flow rates. Achieving the same results by keeping the vendor-provided initial conditions validates the EES computational model. After the validation of the model with the main thermodynamic parameters, condenser heat balance is performed to obtain the condenser pressure, Pc; sea water outlet temperature, Tcwo; and the condenser terminal temperature difference, TTDc (Tc−Tcwo).

The condenser behavior is of particular concern, which is described in Figure 2a; both vary directly in response to the sea water inlet temperature. Figure 2b explains the thermodynamic relationship between temperature and entropy for the secondary side of the typical PWR nuclear power plant, based on the calculations performed with the EES model.



(**a**) (**b**)

Figure 2. (**a**) Relation of condensing steam inlet temperature, Tc, and sea water outlet temperature, T_{cwo}, with sea water entering temperature. (**b**) TS diagram of the considered NPP at design condition (blue represents the constant pressure lines, red represents connecting points, green represents constant quality fractions, while the black dome represents saturation points).

Figure 3a highlights the adverse effects of the sea water inlet temperature on the thermal efficiency of the plant, which follows the same trend as is observed in [11]; a decline from 37.89% to 36.1% is obtained while varying T_{cwi} from 5 to 35 °C. Figure 3b compares the vendor-provided power curve with the developed EES model-determined output power corresponding to the inlet temperature. With the theoretical model, a linear declining relationship is observed, but designer estimation depicts that it will almost remain constant for initial values (5 to 15 °C) and then be followed by a sharp decrease in final interval (30 to 35 °C). The differences in the designer's model's results and our model results is due to the fact that the condenser vacuum is not only disturbed by sea water temperature, but also by salinity and fouling. Moreover, the designer used different correlations to accommodate various losses in major components. Our scope is restricted to temperature because it holds the most significant impact on the performance of the plant.

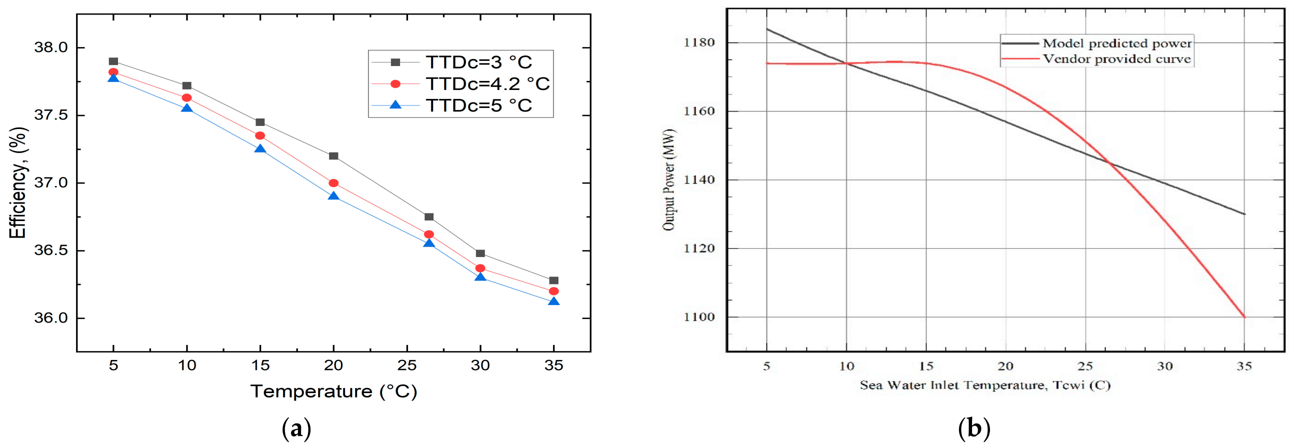


Figure 3. (**a**) Relation of cycle efficiency of the plant with the sea water inlet temperature for three different TTD_c comparisons of output power obtained using the EES-developed model for a range of sea water inlet temperatures to the condenser, with designer-provided output power curves for the same *x*-axis range.

4. Conclusions

This paper presents the thermodynamic computations for the secondary side of a HPR1000 pressurized water reactor nuclear power plant. Based on the analysis, it can be concluded that for a 1 °C rise in cooling medium temperature, the output power and thermal efficiency of the plant decrease by 1.8 MW and 0.158%, respectively. Thus, it emphasizes the significance of nuclear power plant site selection and the need to devise more reliable approaches to compensate for the loss in performance of the plant and system capacity.

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