Research Article

The Impact of Climate Changes on the Thermal Performance of a Proposed Pressurized Water Reactor: Nuclear-Power Plant

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Received 17 February 2014; Accepted 14 March 2014; Published 10 April 2014

Academic Editor: Massimo Zucchetti

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This paper presents a methodology for studying the impact of the cooling water temperature on the thermal performance of a proposed pressurized water reactor nuclear power plant (PWR NPP) through the thermodynamic analysis based on the thermodynamic laws to gain some new aspects into the plant performance. The main findings of this study are that an increase of one degree Celsius in temperature of the coolant extracted from environment is forecasted to decrease by 0.39293 and 0.16% in the power output and the thermal efficiency of the nuclear-power plant considered, respectively.

1. Introduction

The main use of water in a thermoelectric power plant is for the cooling system to condense steam and carries away the waste heat as part of a Rankine steam cycle. The total water requirements of the plant depends on a number of factors, including the generation technology, generating capacity, the surrounding environmental and climatic conditions, and the plant’s cooling system, which is the most important factor governing coolant flow rate.

Thermal power plants are built for prescribed specific design conditions based on the targeted power demand, metallurgical limits of structural elements, statistical values of environmental conditions, and so forth. At design stage, a cooling medium temperature is chosen for each site considering long term average climate conditions. However, the working conditions deviate from the nominal operating conditions in practice. For this reason, efficiency in electricity production is affected by the deviation of the instantaneous operating temperature of seawater cooling water of a nuclear power plant from the design temperature of the cooling medium extracted from environment to transfer waste heat to the atmosphere via a condenser. Present nuclear plants have about 34–40% thermal efficiency, depending on site (especially water temperature).

The cooling process in nuclear power plants requires large quantities of cooling water. The huge amounts of water withdrawal and consumption cause that the electricity has to face the impacts of climate change, that is, in form of increasing sea temperatures or water scarcity. For instance, if seas exhibit too high water temperatures, the continued use of water for cooling purposes may be at risk because the cooling effect decreases and also water quality regulations could be violated.

An increase in the temperature of cooling water may have impact on the capacity utilization of thermal power plants in two concerns: (1) reduced efficiency: increased environmental temperature reduces thermal efficiency of a thermal power plant, (2) reduced load: for high environmental temperatures, thermal power plant’s operation will be limited by a maximum possible condenser pressure. The operation of plants with river or sea cooling will in addition be limited by a regulated maximum allowable temperature for the return water or by reduced access to water.

In the literature, there are few works published to identify these climate change impacts, and few have tried to quantify them. Ganan et al. [1] studied the performance of the pressurized-water reactor- (PWR-) type Almaraz nuclear-power plant and showed that it is strongly affected by the weather conditions having experienced a power limitation.
due to vacuum losses in condenser during summer. Durmazay and Sogut [2] presented a theoretical model to study the influence of the cooling water temperature on the thermal efficiency of a conceptual pressurized-water reactor nuclear power plant. Sanathara et al. [3] gave a parametric analysis of surface condenser for 120 MW thermal power plant and focus on the influence of the cooling water temperature and flow rate on the condenser performance and thus on the specific heat rate of the plant and its thermal efficiency. Daycock et al. [4] measured the actual decrease in efficiencies of gas power plants located in a desert. Linnerud et al. [5] concluded that a rise in temperature may influence the capacity utilization of thermal power plants in two ways. Chuang and Sue [6] studied the performance effects of combined cycle power plant with variable condenser pressure and loading. Costle and Finn [7] reviewed the evaporative cooling technique in application of the energy and mass conservation laws that govern the mass and heat balance of the plant.

In this study, an energy analysis is performed to evaluate the impact of the change in cooling medium temperature on the thermal efficiency of a PWR NPP. The objective is to establish a theoretical methodology to assess the plant performance in different climatic conditions and to emphasize the importance of plant site selection from the environmental temperature point of view. A model for condenser heat balance is developed to determine the functional relationship between the cooling water temperature and the condenser pressure considering that saturation condition exists in the condenser and there is a finite amount of temperature differences between this saturation temperature and the cooling water exit temperature. Employing this condenser heat balance model, a cycle analysis is carried out to determine the heat balance conditions and corresponding power output and thermal efficiency for the prescribed range of cooling water temperatures.

2. Methodology

The development of a mathematical model depends upon studying, analysis, and evaluation of the thermal performance and thermodynamics of the secondary cycle of nuclear power plant. This model describes how the impacts of climatic variables and conditions of environment affect the temperature marginal limits of condenser cooling water and the extent of its impacts on the efficiency and performance of the nuclear plant. The thermal and thermodynamic properties, parameters, variables, and mathematical relationships will be formulated to determine the thermal efficiency through the application of the energy and mass conservation laws that govern the mass and heat balance.

Figure 1 illustrates a diagram of a proposed PWR nuclear power plant, to address the thermodynamic and heat balance analysis of a PWR NPP. Typical PWR consists of a primary cycle which includes nuclear reactor, steam generator, pressurizer, and reactor coolant pump and the secondary cycle which consists of high-pressure steam turbine (HPST), three low-pressure steam turbines (LPST), moisture separator and reheater (MS/R), deaerator feed water heater, two high-pressure feed water heaters (HPFWH), and three low-pressure feed water heaters (LPFWH), condenser, and necessary pumps (feed water pump and condensate pump).

A computer program based on the mathematical model representing the secondary circuit of the plant and its components was performed using the engineering equation solver computer program (EES) [8]. The algorithm procedures are performed as follows.

(i) Thermodynamic properties (pressure (P), temperature (T), entropy (S), enthalpy (h), and moisture content (X)) at all the inlet and exit of all parts and components of the plant.

(ii) Heat balance for each feed water heater and the steam generator.

(iii) Output useful work of the turbines and pumps.

(iv) Calculation of the amount of heat added to generate steam, as well as the amount of heat rejected from condenser, and calculation of the efficiency of the station.

(v) Hence temperature entropy (T-S) diagram of the plant and its components, as well as numerical tabulation of results, being reported.

(vi) Determination of the cooling water inlet temperature (T_in) and exit temperature (T_out) and the temperature difference.

(vii) Assigning the range of change of cooling water temperature T_cwi during the entire year for the Mediterranean sea as (15–30°C).

(viii) Computing the impact of the changes of cooling water temperature T_cwi on the thermal efficiency η_th and output work W_net of the plant.

(ix) Drawing the relation of T_cwi versus η_th and W_net of the plant.

The energy balance equations for the various processes involving steady-flow equipment such as nuclear reactor, turbines, pumps, steam generators, heaters, coolers, reheaters, and condensers in a PWR NPP are as follows.

2.1. Heat Balance Equations

(i) The total turbine work, W_T, kJ/kg, is as follows:

\[
W_T = W_{HPT} + W_{LPT}
\]

\[
W_{HPT} = \dot{m}_{st}(h_{in} - h_{out})
\]

\[
W_{LPT} = \dot{m}_{st}(h_{in} - h_{out}),
\]

where \(\dot{m}_{st}\) is steam mass flow rate inlet to each turbine, kg/s, \(h_{in}\) is enthalpy of steam inlet to each turbine, kJ/kg, \(h_{out}\) is enthalpy of steam outlet from each turbine, kJ/kg, \(W_{HPT}\) is high pressure turbine work, kJ/kg, and \(W_{LPT}\) is low pressure turbine work, kJ/kg.
Figure 1: Diagram of PWR nuclear power plant.

(ii) The pumping work, $W_p$, kJ/kg, is as follows:

$$W_p = W_{cp} + W_{fwp}$$

where $m_{fwh}$ is steam mass flow rate inlet to each turbine, kg/s, $h_{in}$ is enthalpy of steam inlet to each Turbine, kJ/kg, $h_{out}$ is enthalpy of steam outlet from each turbine, kJ/kg, $W_{fwp}$ is high pressure turbine work, kJ/kg, and $W_{cp}$ is low pressure turbine work, kJ/kg.

(iii) Heat added to steam generator, $Q_{add}$, kJ/kg, is as follows:

$$Q_{add} = m_{st} (h_{out} - h_{in})$$

where $m_{st}$ is steam mass flow rate extracted from turbine to feed water heater, kg/s, $h_{in}$ is enthalpy of feed water inlet to steam generator, kJ/kg, and $h_{out}$ is enthalpy of steam outlet from steam generator, kJ/kg.

(iv) Heat rejected from condenser, $Q_{Rej}$, kJ/kg, is as follows:

$$Q_{Rej} = (m_{mix} * h_{in} - m_{mix} * h_{out})$$

where $m_{mix}$ is mixture mass flow rate through condenser, kg/s, $h_{in}$ is enthalpy of mixture inlet to condenser, kJ/kg, and $h_{out}$ is enthalpy of feed water outlet from condenser, kJ/kg.

(v) Network done, $W_{net}$, kJ/kg, is as follows:

$$W_{net} = W_T - W_p.$$
where $m_{RCW}$ is reactor coolant water mass flow rate of primary circuit, kg/s, $m_{fw}$ is feed water mass flow rate inlet to steam generator, kg/s, $m_{st}$ is steam mass flow rate outlet from steam generator, kg/s, $h_{in}$ is enthalpy of feed water inlet to steam generator, kJ/kg, $h_{out}$ is enthalpy of steam outlet from steam generator, kJ/kg, $T_{H1}$ is temperature of reactor coolant g water at hot leg, °C, $T_{CL}$ is temperature of reactor coolant g water at cold leg, °C, and $C_{RCW}$ is specific heat of reactor coolant water of primary circuit, kJ/kg K.

2.4. Heat Balance of Moisture Separator and Reheater. Consider

$$m_{st} \cdot h_{in} = (m_{st} \cdot h_{i}) + (m_{fw} + m_{st}) \cdot h_{out}$$

where $m_{st}$ is steam mass flow rate inlet to moisture separator and reheater, kg/s, $m_{st}$ is water mass flow rate exit from moisture separator and reheater to feed heater, kg/s $h_{in}$ is enthalpy of feed water inlet to moisture separator and reheater, kJ/kg, $h_{out}$ is enthalpy of steam outlet from moisture separator and reheater, kJ/kg, and $h_{i}$ is enthalpy of steam outlet from moisture separator and reheater, kJ/kg.

2.5. Heat Balance of Cooling Water System (Condenser). The condenser is a large shell and tube type heat exchanger. The steam in the condenser goes under a phase change from vapor to liquid water. External cooling water is pumped through thousands of tubes in the condenser to transport the heat of the condensation of the steam away from the plant. Upon leaving the condenser, the condensate is at a low temperature and pressure. The phase change in turn depends on the transfer of heat to the external cooling water. The rejection of heat to the surrounding by the cooling water is essential to maintain the low pressure in the condenser. The heat is absorbed by the cooling water passing through the condenser tubes. The rise in cooling water temperature and mass flow rate is related to the rejected heat as

$$Q_{Rej} = (m_{mix} \cdot h_{in}) - (m_{fw} \cdot h_{out})$$

$$Q_{Rej} = m_{CW} \cdot C \cdot \Delta T$$

where $m_{CW}$ is cooling water mass flow rate of condenser, kg/s, $m_{fw}$ is feed water mass flow rate outlet from condenser, kg/s, $m_{mix}$ is mixture mass flow rate of inlet to condenser, kg/s, $h_{in}$ is enthalpy of mixture inlet to condenser, kJ/kg, $h_{out}$ is enthalpy of feed water outlet from condenser, kJ/kg, $T_{cwe}$ is condenser saturation temperature, °C, $T_{cwe}$ is temperature of cooling water outlet from condenser, °C, $T_{cwi}$ is temperature of cooling water inlet to condenser, °C, $\Delta T$ is temperature difference between the cooling water exit and inlet temperature, °C, and $\Delta T_{sat}$ is temperature difference between the saturation temperature and the cooling water exit temperature, °C.

Modeling assumptions for the secondary cycle are as follows.

(i) The thermodynamic conditions of steam at exit of the SG are fixed.

(ii) Thermal power of the PWR changes slowly to provide constant thermodynamic properties of steam at exit of the SG since the variation in cooling water temperature occurs seasonally and very slowly.

(iii) The condenser vacuum varies with the temperature of cooling water extracted from environment at fixed mass flow rate into the condenser.

(iv) There are constant mass flow rates of condensate and cooling water.

(v) There is no pressure drop across the condenser.

(vi) The potential and kinetic energies of the flow and heat losses from all equipment and pipes are negligible.

3. Results and Discussions

Thermodynamic analysis of the proposed PWR NPP is conducted to investigate the key parameters such as heat added to steam generator, heat rejection, net turbine work, and overall thermal efficiency. Figure 2 illustrates the calculation of the thermodynamic and heat balance analysis of the proposed PWR NPP.

Figure 3 showed the thermodynamic and heat balance analysis of the proposed PWR NPP, on the T-S diagram of steam Rankine cycle as obtained from the heat balance of the plant.

Table 1 summarizes the calculation of the thermodynamic properties at design conditions satisfying the heat balance for the proposed PWR NPP. Figure 2 and Table 1 are the basis of the parametric study and analysis of the present work.

A parametric study is performed to determine the saturation temperature $T_{C}$, corresponding condensate pressure $P_{C}$, and also the cooling water exit temperature $T_{cwe}$ for the cooling water inlet temperature $T_{cwi}$ and condenser terminal temperature difference $(T_{C} - T_{cwe})$ by using the condenser heat balance model. The results are given in Figures 4 and 5. Figure 4 shows that the relation between $T_{cwi}$ and $T_{cwe}$ exhibits a proportional linear variation with no effect of the condenser terminal temperature difference $(T_{C} - T_{cwe})$. The variation of $T_{C}$ with $T_{cwe}$ also shows a linear dependency having approximately $1^\circ$C difference in $T_{C}$ for subsequent condenser terminal temperature difference $(T_{C} - T_{cwe})$ values at any constant value of $T_{cwi}$.

Figure 4 depicts the variation between cooling water exit temperature $T_{cwe}$ and saturation temperature $T_{C}$ in condenser with cooling water inlet temperature $T_{cwi}$. $T_{cwi}$ increases, the saturation temperature $T_{C}$ increases, and this affect the output work and consequently the efficiency.

Figure 5 illustrates variation of the saturation pressure $P_{C}$, corresponding to the saturation temperature $T_{C}$ with cooling water inlet temperature $T_{cwi}$. It is seen that an increase in $T_{cwi}$ of $1^\circ$C, $5^\circ$C, $10^\circ$C, and $15–30^\circ$C results is an increase in $P_{C}$ of 0.00238, 0.01215, 0.02989, and 0.031 bar, respectively.

Figure 6 presents the variation of thermal efficiency $\eta_{th}$ with cooling water inlet temperature $T_{cwi}$. When $T_{cwi}$ increases by $1^\circ$C, $5^\circ$C, $10^\circ$C, and $15–30^\circ$C, the thermal efficiency $\eta_{th}$ decreases by 0.16, 0.76, 1.52, and 2.27%, respectively.
A condenser heat balance model is developed to determine the functional relationship between the cooling water temperature and the condenser pressure. Thus, a cycle analysis...
for the proposed NPP is carried out to determine the heat balance conditions originating from temperature change of cooling medium. It can be concluded that the output power and the thermal efficiency of the plant decrease by approximately 0.3929 and 0.16%, respectively, for 1 °C increase in temperature of the condenser cooling water extracted from the environment.

The impact of climate changes in condenser cooling water is an important design consideration when constructing PWR NPP. A reduction in production capacity due to an increase in environment temperature would represent a drop of production that might need to be replaced somewhere. The effect of climatic changes shows to be important in the design of more effective cooling technique and to device methods to compensate for the loss in plant output and system capacity. Climate considerations will also become even more important when deciding where to build new thermal power plants.
Figure 6: Variation of thermal efficiency $\eta_{th}$ with cooling water inlet temperature $T_{cwi}$.

Figure 7: Variation of net power output $W_{net}$ with cooling water inlet temperature $T_{cwi}$.

Nomenclature

- $C$: Specific heat (kJ/kg·K)
- $h$: Enthalpy (kJ/kg)
- $\dot{m}$: Mass flow rate (kg/s)
- $p$: Pressure (bar)
- $Q$: Net rate of heat transferred (kW)
- $T$: Temperature (K)
- TTD: Terminal temperature difference
- $W_{net}$: Net rate of work (kW)
- $\eta$: Efficiency (%)
- add: Added
- $c$: Condenser
- CP: Condensate pump
- CW: Cooling water
- cwi: Cooling water inlet
- CL: Cold leg
- cwo: Cooling water outlet
- fw: Feed water
- fwp: Feed water pump
- HL: Hot leg
- HPT: High pressure turbine
- LPT: Low pressure turbine
- in: Inlet
- mix: Mixture
- out: Outlet
- p: Pump
- RCW: Reactor cooling water
- Rej: Rejection
- T: Turbine
- : Per unit time
- HP: High pressure
- LP: Low pressure
- NPP: Nuclear power plant
- PWR: Pressurized water reactor
- RC: Reactor coolant
- SG: Steam generator

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

References
