

Impact of Local Weather on Thermal Performance of Rooppur Nuclear Powerplant: A Case Study

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ABSTRACT

In current work, the impact of local weather on thermal performance of Rooppur Nuclear Powerplant (RNPP) (2*VVER-1200, Pressurized Water Reactor (PWR)) has been studied. Rooppur is located in north-western region of Bangladesh where the temperature in summer season varies within the range of 35-45°C with relative humidity of 60-90%. For analyzing the effect of temperature and humidity, thermal-hydraulic model of secondary circuit of RNPP has been utilized. Using Rankine cycle and Thermodynamics analytical equations, NPP performance parameters such as condenser back pressure, NPP efficiency and output power are determined with respect to ambient temperature. Current study shows that high ambient temperature incurs a significant loss in nuclear powerplant economy. Hence, a comprehensive condenser design is necessary with forecasted local temperature rise.

Keywords: RNPP, PSMP-2016, VVER-1200, AES-2006, PWR.



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1. Introduction

In order to meet demand for forecasted electricity, the Government of Bangladesh undertook Power Supply Master Plan-2016 (PSMP-2016), where it was planned to generate electricity from different types of fuel sources such as Coal, Liquefied Natural Gas (LNG), Renewables, Combined cycle, Heavy Fuel Oil (HFO), Nuclear and Import of electricity [1]. In PSMP-2016, nuclear power is planned to be used as 'Base load'. For implementing PSMP-2016, Bangladesh government signed a treaty with the Russian Federation to construct the country's 1st ever Nuclear Powerplant, Rooppur NPP (2*VVER-1200, Pressurized Water Reactor). Rooppur is located in the north-western part of Bangladesh, and for the last 2-3 years, this region has been facing an unprecedented severe heat wave during the summer season (April-July) when the ambient temperature rises to a maximum of 45°C. These heat waves eventually increase the local average temperature during those months. The primary function of water in a nuclear power plant is to facilitate the cooling system, which condenses steam and acts as heat sink as part of a Rankine cycle. The overall water requirements of the plant are contingent upon several elements, including the generation technology and capacity, climatic conditions, and condenser type, which are the primary determinant of coolant flow rate. Thermal power plants are constructed according to specified design criteria determined by anticipated power consumption, metallurgical constraints of structural components, statistical environmental data, and other relevant factors. During design, a cooling medium temperature is selected for each location based on long-term average climatic conditions. Nonetheless, the working circumstances diverge from the nominal operating parameters. Consequently, the efficiency of electricity generation is influenced by the variance of the cooling water temperature. Current nuclear

power plants exhibit thermal efficiency ranging from 34% to 40%, depending upon site conditions, particularly water temperature. Like other powerplants, NPP performance is strongly influenced by the atmospheric temperature and humidity. An increase in cooling water temperature may affect the capacity utilization of nuclear power reactors in two respects: (1) Diminished efficiency: elevated environmental temperatures decrease the thermal efficiency of a nuclear power plant. (2) Decreased load: at high environmental temperatures, the operation of a nuclear power plant is constrained by a maximum allowable condenser pressure. In the literature, there are limited publications that identify the implications of climate change, and even fewer have attempted to quantify them. Durmayaz and Sogut 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 [2]. Similar method has been followed in current work.

In this study, thermodynamic analysis of some NPP performance parameters such as Condenser back pressure, efficiency and output power have been evaluated based on the calculated secondary circuit data of RNPP and the ambient condition of Rooppur area [3, 4].

2. Methodology

VVER-1200 is a type of Pressurised water reactor (PWR) which works on 03 circuits namely primary circuit (reactor part), secondary circuit (turbine part), and tertiary circuit (cooling tower part). In this study, we will focus only on secondary circuit. The salient features of RNPP are as given in Table 1. To analyze secondary circuit of RNPP, we will utilize the flow diagram of turbine set (model: K-1200-6.8/50). This flow diagram is supplied by the manufacturer, POWER MACHINES to RNPP authority [3]. Flow diagram

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of K-1200-6.8/50 turbine has been used for comparative analysis of K-1200-6.8/50 turbine with Arabelle type in a previous study [5].

Table 1 Salient features of RNPP [6]

Features	Value
Number of Units	02
Basic Design	AES-2006(VVER-1200) Main components [7]:
	• 01 Water-cooled water-moderated thermal neutron reactor (Model: V-392M)
	• 04 Steam generators (Model: PGV-1000 MKP)
	• 01 Turbine set (01xHigh pressure cylinder and 04xLow pressure cylinder) (Model: K-1200-6.8/50)
	• Turbogenerator (Model: T3B-1200-2A)
Reference Plant	Novovoronezh NPP-2
Utilization factor	92%
Thermal output (each unit)	3212 MW
Power unit capacity	Not less than 1150 MW (at water temperature equal to 28°C)
Period between re-fueling	12 months
Coolant pressure at the core outlet	16.2±0.3MPa
Coolant Pressure at the reactor inlet	298.2°C
Coolant Pressure at the reactor outlet	328.6°C

A mathematical model has been developed based on calculated reference data of RNPP. Temperature-entropy diagram has been drawn according to the Thermal-Hydraulic diagram of secondary circuit of RNPP. To determine the variation of thermal power, condenser back pressure and efficiency with respect to ambient temperature, secondary circuit data with 100% power has been used. With the variation of ambient temperature, only the variation of condenser saturation pressure and condenser saturation temperature has been taken into account. So, for the output power calculation, LPT power variation with respect to condenser pressure has been considered. Conservation of energy for control volume is used to evaluate HPT and LPT power.

Some assumptions have been taken into consideration for ease of calculation-

- TR and TTD have been considered as constant.
- Only the variation of dryness factor of condensed steam is being considered.
- Pump powers have been taken as constant.

2.1 Condenser Saturation Temperature and Back Pressure

The saturation temperature, t_s was determined by equation (1) [8]. The saturation pressure corresponding to the saturation temperature, t_s is condenser back pressure, P_{cond} .

The saturation temperature, t_s can be calculated under different inlet cooling water temperature. TTD has a typical value of more than 2°C and is assumed to be constant [9, 10].

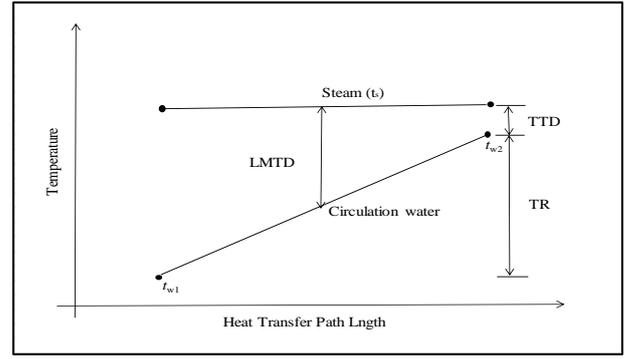


Fig.1 Heat transfer diagram of condenser

From the calculated reference data of RNPP [3], TTD and TR are assumed to be 3°C and 8°C, respectively. Condenser saturation temperature, t_s can be determined by Eq. (1)

$$t_s = t_{w1} + TR + TTD \quad (1)$$

Where, t_s = Condenser saturation temperature (°C)

t_{w1} = Condenser inlet temperature (°C)

TR = Temperature rise of cooling water inside condenser (°C).

TTD = Terminal temperature rise (°C)

Knowing t_s and assuming isentropic expansion of LPT, dryness fraction, x at condenser inlet can be determined by Eq. (2)

$$x = (s^* - s_f) / s_{fg} \quad (2)$$

Where, x = Dryness fraction of steam at condenser inlet.

s^* = entropy of steam at LPT inlet (superheated steam at 555kPa and 270 °C) = 7300 J/kgK.

s_f = Entropy of subcooled liquid at condenser saturation temperature (J/kgK)

s_{fg} = Entropy of saturated steam at condenser saturation temperature (J/kgK)

After knowing dryness factor, enthalpy at LPT outlet, enthalpy of steam at LPT outlet, h_{cond} shall be calculated by Eq. (3)

$$h_{cond} = h_{f@ts,Pcond} + xh_{fg@ts,Pcond} \quad (3)$$

Where, h_{cond} = Enthalpy of steam at LPT outlet (kJ/kg)

$h_{f@ts,Pcond}$ = Enthalpy of subcooled liquid at condenser saturation temperature and pressure (kJ/kg)

$h_{fg@ts,Pcond}$ = Enthalpy of wet steam at condenser saturation temperature and pressure (kJ/kg)

2.2 Turbine Work:

The total turbine work, W_T is as follows-

$$W_T = W_{HPT} + W_{LPT} \quad (4)$$

$W_{HPT} = \sum(\dot{m}_{st}h_{st})_{in} - \sum(\dot{m}_{st}h_{st})_{out}$ for HPT Control volume.

$W_{LPT} = \sum(\dot{m}_{st}h_{st})_{in} - \sum(\dot{m}_{st}h_{st})_{out}$ for LPT Control volume
 $= f(h_{cond})$

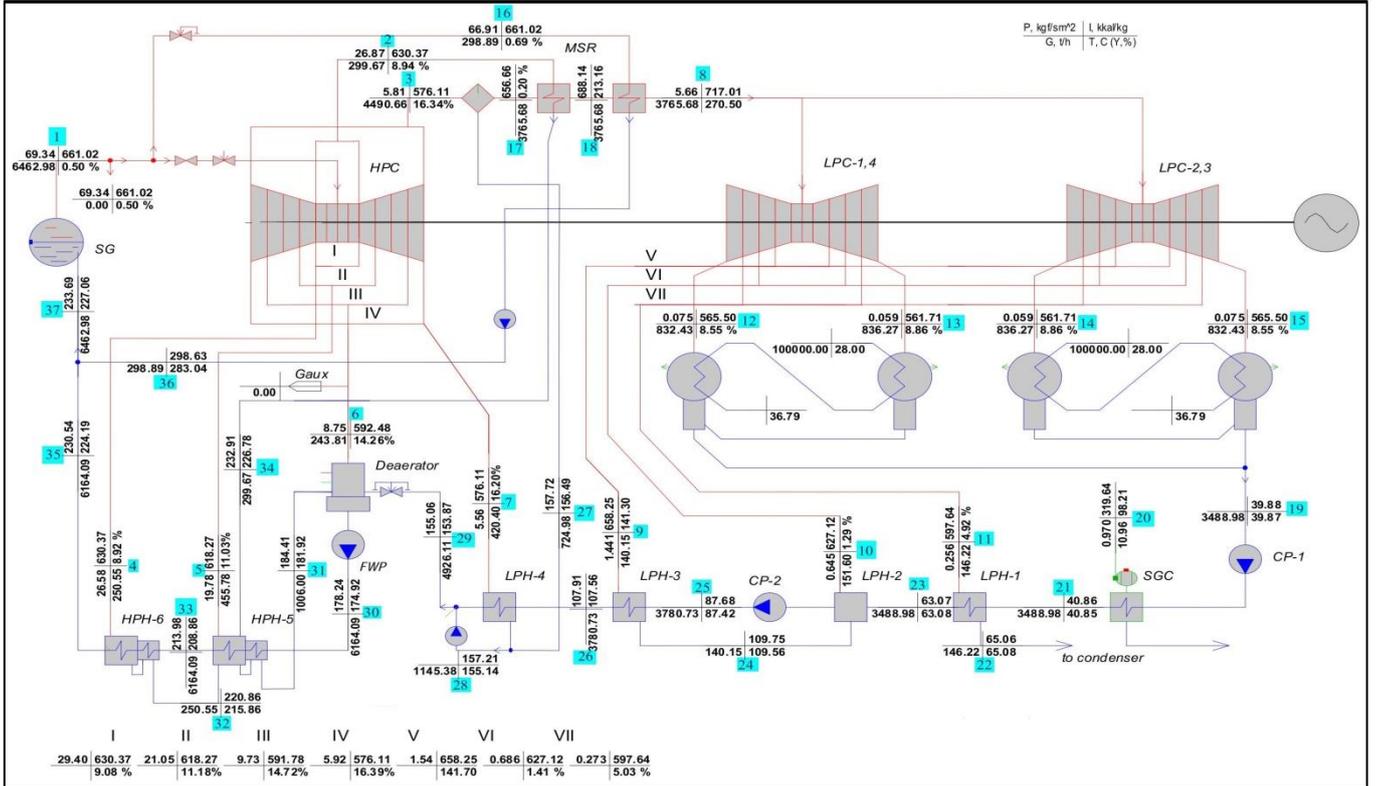


Fig.2 Illustration of RNPP secondary circuit thermodynamic and heat balance analysis (Units are in British unit. For calculation, British units were converted to SI units)

Where, W_{HPT} = High pressure turbine work, kW
 W_{LPT} = Low pressure turbine work, kW
 \dot{m}_{st} = steam mass flow rate at turbine inlet and outlet, kg/s
 h_{st} = enthalpy of steam at turbine inlet and outlet, kJ/kg
 h_{cond} = enthalpy of steam at condenser inlet, kJ/kg

2.3 Pump Work:

For pumping work W_p calculation, electric power of condensate electric pump and feed electric pump are enlisted directly.

Table 2 Electric power of condensate pump and feed water pump

Pump Type (Nos.)	Pump Power (MW)
Condensate Pump-1 (3)	1.25
Condensate Pump-2 (3)	2
Feed Water Pump (5)	4.982

2.4 Heat added to steam generator:

Thermal energy addition to steam generator control volume can be derived from-

$$Q_{IN} = \dot{m}_{st}h_{st} - \dot{m}_{fw}h_{fw} \quad (5)$$

Where, \dot{m}_{st} = steam mass flow rate at steam generator outlet (kg/s)
 h_{st} = enthalpy of steam at steam generator outlet (kJ/kg)
 \dot{m}_{fw} = feedwater mass flow rate (kg/s)
 h_{fw} = enthalpy of feedwater at steam generator inlet (kJ/kg)

2.5 Rankine Cycle efficiency:

Rankine Cycle efficiency, η_{th} can be calculated by-

$$\eta_{th} = \frac{W_{NET}}{Q_{IN}} .100\% = \frac{W_T - W_P}{Q_{IN}} .100\% \quad (6)$$

3. Results and Discussions:

A thermodynamic analysis of the secondary circuit of RNPP is performed to examine critical parameters such as heat input to the steam generator, condenser back pressure, net turbine work, and rankine cycle efficiency. Fig. 2 illustrates the calculation of the thermodynamic and heat balance analysis of RNPP. Fig. 3 shows the simplified T-s diagram of rankine cycle as obtained from the heat balance of the plant. Fig. 2 summarizes the thermodynamic properties (temperature, pressure, mass flow rate, dryness factor and enthalpy) at design conditions satisfying the heat balance of RNPP. Fig. 2 is the basis of the parametric study and analysis of the present work.

Major equipment of secondary circuits are as follows-

- a. Steam Generator (SG)
- b. High Pressure Cylinder (HPC)
- c. Low Pressure Cylinder (LPC)
- d. Moisture Separator Reheater (MSR)
- e. Condensate Pump (CP)
- f. Feed Water Pump (FWP)
- g. Low Pressure Heater (LPH)
- h. High Pressure Heater (HPH)
- i. Deaerator
- j. Steam-gas condensate (SGC)

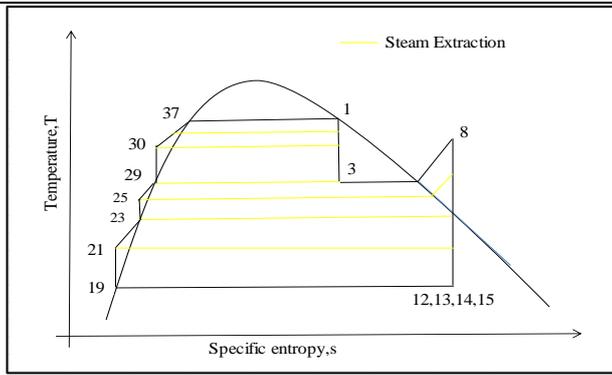


Fig.3 Simplified T-s diagram of RNPP secondary circuit

The T-s diagram has been drawn based on the following processes:

- Isentropic expansion of both HPT and LPT. (1-3: HPT and 8-12,13,14,15:LPT)
- Regenerative heating at Moisture separator-reheater. (3-8)
- Isothermal heat rejection at Condenser. (12,13,14,15-19)
- Isentropic compression. (19-21: Condensate pump-1)
- Regenerative heating at LPH-1 and LPH-2. (21-23)
- Isentropic compression. (23-25: Condensate pump-2)
- Regenerative heating at LPH-3 and LPH-4. (25-29)
- Isentropic compression. (29-30: Feed water pump)
- Regenerative heating at HPH-5 and HPH-6. (30-37)
- Isothermal heat addition at steam generator. (37-1)

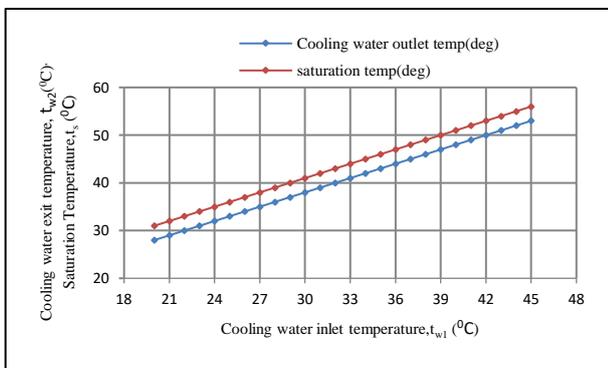


Fig.4 Variations of cooling water exit temperature and Saturation temperature with cooling water inlet temperature

A parametric study is performed to determine the saturation temperature t_s , corresponding condensate pressure P_{cond} , and also the cooling water exit temperature, t_{w2} for the cooling water inlet temperature, t_{w1} and condenser terminal temperature difference, $(t_s - t_{w2})$ by using the condenser heat balance model. The results are given in Fig. 4. Fig. 4 shows that the relation between t_{w1} and t_{w2} exhibits a proportional linear variation with no effect of the condenser terminal temperature difference $(t_s - t_{w2})$. The variation of t_s with t_{w1} also shows a linear dependency. Several studies confirm the linear variation between t_s and t_{w1} [8, 9] [11].

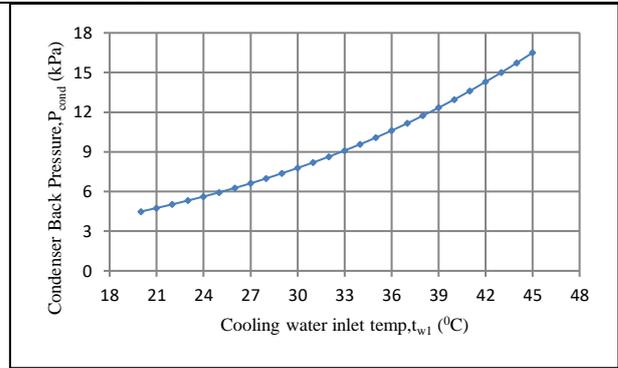


Fig.5 Variation of Condenser back pressure with respect to cooling water inlet temp

Fig. 5 illustrates variation of the saturation pressure P_{cond} , corresponding to the saturation temperature t_s , with cooling water inlet temperature t_{w1} . It is seen that an increase in t_{w1} of 1°C, 5°C, 10°C, and 25°C results in an increase in P_{cond} of 0.263, 1.45, 3.29, and 12.01 kPa, respectively. Fig. 6 presents the variation of rankine cycle efficiency, η_{th} with cooling water inlet temperature t_{w1} . When t_{w1} increases by 1°C, 5°C, 10°C, and 25°C, the rankine cycle efficiency, η_{th} decreases by 0.2, 1.0, 1.92, and 4.38%, respectively.

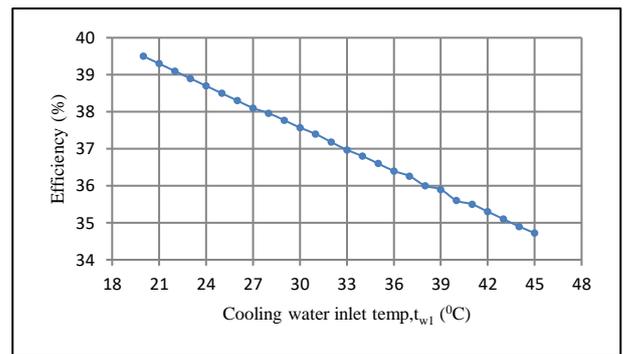


Fig.6 Variation of rankine cycle efficiency with cooling water inlet temperature

Fig. 7 gives the variation of net power output, W_{net} with cooling water inlet temperature, t_{w1} . An increase in t_{w1} of 1°C, 5°C, 10°C, and 25°C corresponds to decrease in W_{net} by 6.42, 31.92, 61.42, and 153.02 MW, respectively.

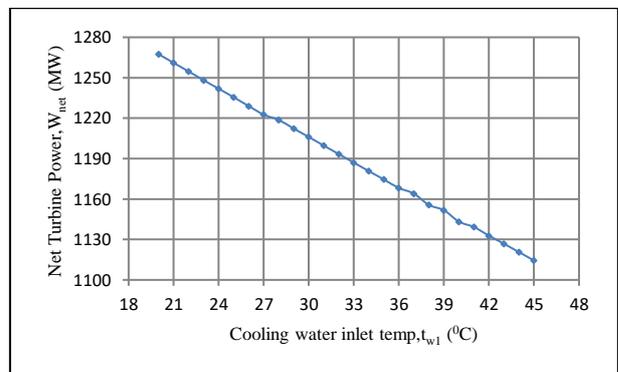


Fig.7 Variation of Net Turbine Power with cooling water inlet temperature

The change of condenser conditions, that is, t_s and P_{cond} , with t_{w1} results in a decrease of 153.02 MW in output power of the plant, W_{net} for the t_{w1} range of 20–45°C as shown in Fig. 7. It is observed from Fig. 6 that an increase from 20 to 45°C in the temperature of the coolant extracted from environment results in a decrease from 39.1 to 34.72% in the rankine cycle efficiency of the NPP.

4. Conclusions:

Condenser heat balance model and related thermodynamic equations have been utilized to evaluate the plant output parameters with respect to cooling water temperature. This work is based on manufacturer's simulated data which of course might have some deviation from real plant data. Additionally, all the thermodynamic processes have been assumed as isentropic and isothermal. But, for real nuclear plant processes, there must be some irreversibility for all isentropic and isothermal processes, which can be evaluated utilizing adiabatic efficiency of all equipment of primary, secondary, and tertiary circuit. The probable solution to the power reduction due to ambient temperature might be as follows:

- Quick rental powerplant to compensate the power reduction.
- More effective design of condenser to balance the increased temperature.
- Design modification in tertiary circuit and cooling tower.
- Improvement of water chemistry to inhibit the formation of scale and corrosion products on condenser tube.

Analysis done in current work might facilitate the policy maker for economic evaluation of RNPP and selecting plant location for future nuclear powerplant.

5. Acknowledgements:

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NOMENCLATURE

s :	Entropy (kJ/kg.K)
h :	Enthalpy (kJ/kg)
m :	Mass flow rate(kg/s)
W :	Work done by Turbine/Pump (kW)
P :	Pressure (kPa)
Q :	Thermal energy (kW)
t :	Temperature ($^{\circ}$ C)
TTD :	Terminal Temperature Difference ($^{\circ}$ C)
η :	Efficiency (%)
$Cond$:	Condenser
TR :	Temperature rise ($^{\circ}$ C)
CP :	Condensate Pump
FWP :	Feed water pump
HPT :	High Pressure Turbine
LPT :	Low Pressure Turbine
in :	inlet
out :	outlet
P :	Pump
T :	Turbine
t_s :	Saturation temperature ($^{\circ}$ C)
st :	steam
f :	sub-cooled liquid property
fg :	wet steam property
fw :	Feed water