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Impact of condenser cooling seawater temperature on energy and exergy efficiencies of a nuclear power plant

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Abstract: *Nuclear power is identified as a reliable solution to generate electricity and desalinate water for the base load without intermittence and non-controlled variations. The recourse to nuclear power in Gulf countries started a few years ago. Few plants have already been constructed in UAE. One of the numerous aspects to be addressed of nuclear power performance is the condenser cooling process which requires large quantities of cooling water resulting in important environmental impacts and energy requirements. This work aims to evaluate the impact of seawater cooling temperature on the first and second-law efficiencies of a typical nuclear power plant. Energy and exergy analyses will be developed to quantify the thermodynamic performance of the nuclear power plant and its components. The methodology consists in developing a mathematical model based on energy and exergy balances on each of the components and the entire plant using updated technical specifications and accurate fluid properties. The study includes three different Saudi locations with different seawater temperature profiles. The variation in the electric production, energy and exergy efficiencies for the three locations will be particularly investigated. The results show that the most important part of the exergy is destroyed in the condenser and the reactor.*

Keywords: Nuclear power, Cooling water, Condenser, Saudi Arabia, thermal efficiency, exergy efficiency.

I. Introduction

The power generation sector is one of the most growing sectors in Saudi Arabia since it is an essential locomotive to the ambitious industrialization and economic development plans of the Kingdom. New plants in single power or cogeneration power and desalination modes are constructed or planned for the next few years. Some of these power generation technologies are no more powered by fossil fuels but are based on non-conventional fuel sources such as solar, wind and nuclear. Therefore, ambitious diversified programs related to the country's energy mix towards the deployment of renewable and nuclear energy sources have been launched and their implementation has already started. The country has already considered heavy investment in solar power for different applications while the kingdom's nuclear plan for electricity and potable water production is in progress. On another side, nuclear desalination has the main advantage of integrating two mature technologies namely nuclear power generation and seawater desalination mainly using multistage flash (MSF), multiple effect distillation (MED) and reverse osmosis (RO) processes. Nuclear desalination is considered a viable and cost effective medium/long term solution to the critical problem of potable water scarcity.

The performance of nuclear power plants strongly relies on the cooling process of the condenser. Huge amounts of cooling water are needed to evacuate the latent heat of steam condensation. In addition, this high amount of water withdrawal back to the natural water body has critical environmental impacts. The variation of the sea water temperature from one season to another and from one region to another makes the design and operation of these power generation plants not well predicted and evaluated. Besides, assessing the impact of climate aspects is essential in the determination of the new nuclear power plants. This topic has attracted several investigations in the open literature aiming to identify these environmental impacts associated with power plants condenser cooling and to implement adequate modifications to enhance the process thermal efficiency by reducing the amount of rejected heat to the natural body and adjusting its temperature.

Attia [1] developed a theoretical model based on heat and mass balances on the condenser of a typical nuclear power plant and concluded that the net power generated, and the plant thermal efficiency are reduced by about 0.44% and 0.15% for each 1 ºC rise in the condenser cooling water temperature. A similar study, using the first law of thermodynamics, conducted earlier by Durmayaz and Sogut [2] on the impact of cooling water temperature on the performance of a pressurized water reactor nuclear power plant concluded that 1°C increase in coolant temperature yields a decrease of 0.12% and 0.45% in the thermal efficiency and the power output of the nuclear plant respectively.

Exergy analysis of power and cogeneration plants is a widely employed methodology. One can find in the literature comprehensive studies on various types of nuclear or fossil fueled power plants in which the exergy efficiency and the exergy destruction in each main component and the entire plants are assessed [3-6]. Marques et al. [6] proposed a theoretical investigation to evaluate the second law efficiency of a nuclear power plant (NPP), Angra 2 in Brazil, with a nominal electric power output of 1300 MW. The plant has a thermal efficiency of 36.18% and an exergy efficiency of 49.24%. It was found also that the reactor core is the least efficient component since it is responsible for the destruction of the highest rate of exergy: about 64% of all exergy destroyed in the Angra 2 plant. Cutillas et al. [7] developed a 3 E (energy, exergy and environmental) investigation to evaluate and compare various heat dissipation methods associated with the condenser of a solar power plant of 50 MWe located in Spain. The wet cooling method using a cooling tower achieved a lower condenser pressure. The exergetic efficiency of the plant was found to be 73.77% for the wet system, 69.21% for the hybrid and 68.46% for the dry system.

The present study aims to develop an energy and exergy analyses on the impact of cooling water temperature on the condenser of a nuclear power plant. The specific climate change in Saudi Arabia corresponding to the seawater variation in three typical coastal locations is considered in this investigation.

II. Description of the system

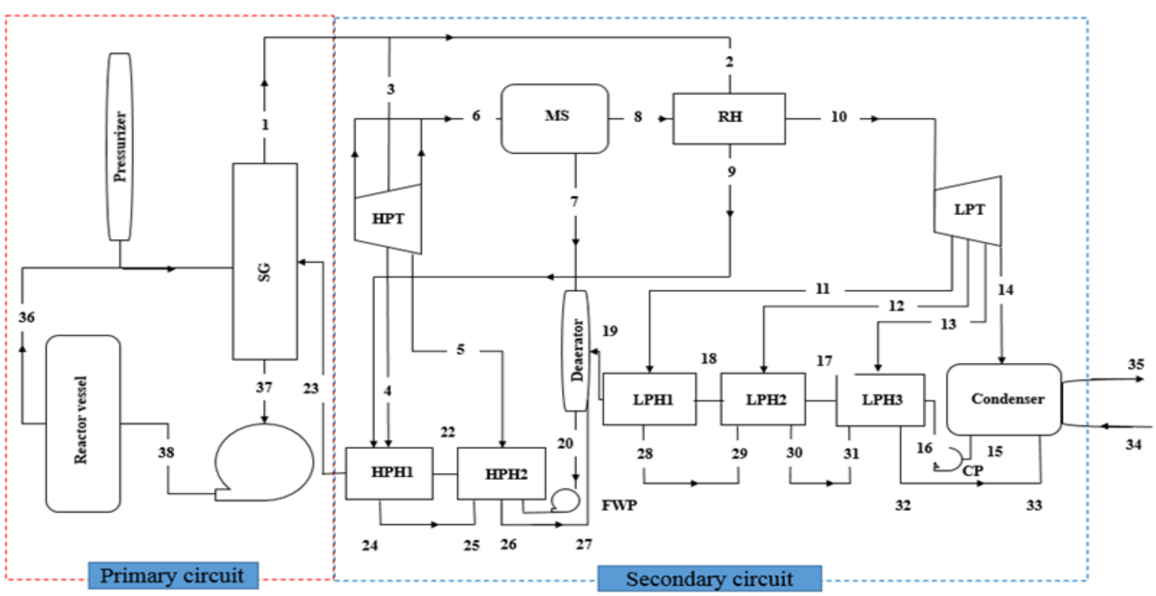

Figure 1: Description of the nuclear power plant considered in this study.

Figure 1 shows a typical NPP, which consists of the primary and secondary circuits. The primary cycle includes a nuclear reactor vessel (RV), steam generator (SG), pressurizer (P) and reactor coolant pump (RP). The secondary circuit of the NPP consists of two high-pressure steam turbines (HPT), three low-pressure steam turbines (LPT), two high-pressure feed water heaters (HPH), three low-pressure feed water heaters (LPH), moisture separator (MS), reheate (RH), deaerator (D), feed water pump (Fp), condenser pump (Cp) and condenser. The high-pressure and temperature steam coming out from the primary circuit steam generator is the primary working fluid in the secondary circuit which is used for the power generator. The heat at the condenser of the secondary circuit is liberated to the cooling water from the sea. The power generation, thermal efficiency, and exergy efficiency of the NPP are evaluated for various condenser sea water cooling temperatures for different locations in KSA.

III. Methodology

Mass, energy, and exergy balance equations derived from the mass and energy conservation and second law principles are developed for the entire plant and its main components. These equations are solved using the computer program Engineering Equation Solver (EES) with updated technical specifications and accurate fluid properties [8]. The model was validated by comparing the obtained results to previous results of Attia [1]. It was used then to conduct several simulations to evaluate the thermal and thermodynamic performance and of the secondary circuit of the NPP for different operating conditions. Sea water temperature corresponding to three different Saudi locations namely Yanbu, Alkhobar and Jeddah are collected and used to evaluate the impact of the condenser cooling water temperature on the thermal efficiency, exergy destruction and efficiency and generated electric power from the nuclear power plant.

Table 1 shows the state points of the nuclear power plant schematically presented in Fig. 1 and their corresponding temperature, pressure, quality, mass flow rate and energy and exergy rates. EES software is used to evaluate the thermodynamic properties of points 1 to 38 of the NPP. Point 0 refers to water at the reference state. The values of -100 and 100 corresponding to the water quality, shown in Table 1, refer to sub cooled liquid and superheated steam respectively.

III.A. Mass and Energy balance equations

The basic principle of mass balance for each component of the power plant for steady-state conditions can be expressed as:

$$\sum m_{in} = \sum m_{out} \quad (1)$$

The first law of thermodynamics for a control volume expresses the energy exchange in the power plant and its main components. Under the assumptions of neglecting the kinetic and potential energies and of steady-state conditions, the general energy conservation principle is given as:

$$Q - W = \sum m_{out}\, h_{out} - \sum m_{in}\, h_{in} \quad (2)$$

Where Q and W are the heat and work rates exchanged through the system and its surrounding boundaries while m and h stand for the mass flow rate and the specific enthalpy respectively.

Exergy can be defined as the maximum amount of work that can be produced by a system as it comes into equilibrium with the environment. Exergy analysis is widely employed in fluid and energy systems as a measure of the usefulness or quality of energy. Exergy is conserved during ideal processes while it is destroyed (consumed) during actual processes by irreversibility associated, for example, with friction and heat transfer through a finite temperature difference. The exergy flow in each point can be evaluated, when the chemical energy component is ignored, as:

$$Ex_i = m_i((h_i - h_o) - T_0(s_i - s_o)) \quad (3)$$

Where h_0 and s_0 are the fluid enthalpy and entropy at the reference dead state conditions of T_0 and P_0. The application of the above mass and energy balances on the various components of the NPP allows the full determination of the mass flow rates for all points as shown in Table 1. Table 2 gives the energy flow and exergy destruction entering and leaving each component of the plant.

The exergy destruction in each component of the nuclear power plant is obtained through an exergy balance equation on a control volume corresponding to such a component

Eq. (4) considers the flows of exergy by heat transfer and fluid flow entering and exiting in steady state conditions [6]:

$$\sum\left(1-\frac{T_0}{T}\right)Q+\sum Ex_{in}-\sum Ex_{out}-Ex_{Destroyed}=0 \qquad (4)$$

The concept of exergy as fuel and exergy as product can be introduced and linked to the exergy destruction within the system [6,9]:

$$Ex_{Destroyed}=Ex_{Fuel}-Ex_{Product}=\sum Ex_{in}-\sum Ex_{out} \qquad (5)$$

Table 1: Thermodynamic properties of the various points of the NPP

State point	P(kPa)	T[i]	x[i]	h[i], kJ/kg	s[i], kJ/kg K	m[i], kg/s	E[i], kW	Ex[i], kW
0	100	25		104.8	0.3669	-	-	-
1	7380	289.5	100	2768	5.788	1608	4.45E+06	1.73E+06
2	7380	289.5	100	2768	5.788	171.1	473572	183749
3	7380	289.5	100	2768	5.788	1437	3.98E+06	1.54E+06
4	4168	252.8	0.9284	2678	5.821	153	409736	149123
5	2155	216.2	0.8825	2580	5.862	100.7	259730	87012
6	993.2	179.6	0.8485	2472	5.913	1183	2.92E+06	876849
7	993.2	179.6	0	761.2	2.135	179.2	136411	24762
8	993.2	179.6	1	2777	6.587	1004	2.79E+06	852087
9	7380	289.4	0	1287	3.156	171.1	220150	62381
10	993.2	289.5	100	3029	7.088	1004	3.04E+06	958075
11	393	195.6	100	2852	7.162	69.08	197016	52195
12	126.7	106.4	0.9973	2680	7.264	63.25	169492	34983
13	30.88	69.76	0.9451	2497	7.384	52.21	130393	17535
14	5.078	33.15	0.8928	2302	7.541	819.5	1.89E+06	76991
15	5.078	33.15	0	138.9	0.48	1004	139461	1107
16	993.2	33.17	-100	139.9	0.48	1004	140458	2104
17	993.2	65.47	-100	274.9	0.8989	1004	275975	14325
18	993.2	101.5	-100	426.3	1.324	1004	428025	41297
19	993.2	138	-100	581.1	1.718	1004	583461	80698
20	993.2	179.6	0	761.2	2.135	1183	900685	163495
21	7380	180.5	-100	768.4	2.135	1608	1.24E+06	233746
22	7380	211.6	-100	906.9	2.43	1608	1.46E+06	317282
23	7380	248.2	-100	1077	2.769	1608	1.73E+06	431437
24	4168	252.8	0	1099	2.819	324.1	356278	89406
25	2155	216.2	0.09255	1099	2.837	324.1	356278	87735
26	2155	216.2	0	925.9	2.482	424.8	393304	85460
27	993.2	179.6	0.08173	925.9	2.499	132.3	122531	25969
28	393	143	0	601.9	1.77	69.08	41579	5939
29	126.7	106.4	0.06962	601.9	1.789	69.08	41579	5546
30	126.7	106.4	0	446	1.378	132.3	59022	5930
31	30.88	69.76	0.06597	446	1.401	132.3	59022	5050
32	30.88	69.76	0	292.1	0.9522	184.5	53898	2920

33	5.078	33.15	0.06323	292.1	0.98	184.5	53898	1417
34	100	20	-100	84.01	0.2965	45419	3.82E+06	0
35	100	29.48	-100	123.7	0.4296	45419	5.62E+06	28499
36	15700	324.9	-100	1483	3.474	19644	2.91E+07	9.19E+06
37	15700	291.1	-100	1290	3.141	19644	2.53E+07	7.31E+06
38	16350	291.4	-100	1291	3.142	19644	2.54E+07	7.33E+06

Table 2. Energy and Exergy flow for each component of NPP

Component	**Energy in**	**Energy out**	**Ex_in**	Ex_{36}
Reactor	$m_{38}h_{38}$	$m_{36}h_{36}$	$\left(1-\frac{T_0}{T_{Reactor}}\right) X\,\dot{P} + \dot{Ex}_{38}$	$Ex_1 + Ex_{37}$
Steam Generator (SG)	$m_{23}h_{23}$	$m_1h_1 + m_{37}h_{37}$	Ex_{23}+Ex_{36}	$Ex_7 + Ex_8$
Moisture Separator (MS)	m_6h_6	$m_7h_7 + m_8h_8$	Ex_6	$Ex_9 + Ex_{10}$
Reheater (RH)	$m_2h_2 + m_8h_8$	$m_9h_9 + m_{10}h_{10}$	$Ex_2 + Ex_8$	$Ex_{15} + Ex_{35}$
Condenser	$m_{14}h_{14} + m_{33}h_{33} + m_{34}h_{34}$	$m_{15}h_{15} + m_{35}h_{35}$	$Ex_{14} + Ex_{33} + Ex_{34}$	$Ex_4 + Ex_5 + Ex_6 + W_{HPT}$
High Pressure Turbine (HPT)	m_3h_3	$m_4h_4 + m_5h_5 + m_6h_6$	Ex_3	$Ex_{11} + Ex_{12} + Ex_{13} + Ex_{14} + W_{LPT}$
Low Pressure Turbine (LPT)	$m_{10}h_{10}$	$m_{11}h_{11} + m_{12}h_{12} + m_{13}h_{13} + m_{14}h_{14}$	Ex_{10}	$Ex_{23} + Ex_{24}$
High Pressure Heater 1 (HPH1)	$m_9h_9 + m_4h_4 + m_{22}h_{22}$	$m_{23}h_{23} + m_{24}h_{24}$	$Ex_4 + Ex_9 + Ex_{22}$	$Ex_{22} + Ex_{26}$
High Pressure Heater 2 (HPH2)	$m_5h_5 + m_{21}h_{21} + m_{25}h_{25}$	$m_{22}h_{22} + m_{26}h_{26}$	$Ex_5 + Ex_{21} + Ex_{25}$	$Ex_{19} + Ex_{28}$
Low Pressure Heater 1 (LPH1)	$m_{11}h_{11} + m_{18}h_{18}$	$m_{19}h_{19} + m_{28}h_{28}$	$Ex_{11} + Ex_{18}$	$Ex_{18} + Ex_{30}$
Low Pressure Heater 2 (LPH2)	$m_{12}h_{12} + m_{17}h_{17} + m_{29}h_{29}$	$m_{18}h_{18} + m_{30}h_{30}$	$Ex_{12} + Ex_{17} + Ex_{29}$	$Ex_{17} + Ex_{32}$
Low Pressure Heater 3 (LPH3)	$m_{13}h_{13} + m_{16}h_{16} + m_{31}h_{31}$	$m_{17}h_{17} + m_{32}h_{32}$	$Ex_{13} + Ex_{16} + Ex_{31}$	Ex_{16}
Cooling Water Pump 1	$m_{15}h_{15}$	$m_{16}h_{16}$	W_{p1}+Ex_{15}	Ex_{21}
Feed Water Pump 2	$m_{20}h_{20}$	$m_{21}h_{21}$	W_{p2}+Ex_{20}	Ex_{38}
Coolant Pump 3	$m_{37}h_{37}$	$m_{38}h_{38}$	W_{p3}+Ex_{37}	Ex_{36}

IV. Results and discussions

Figure 2 illustrates the variation of the condenser saturation pressure with the cooling water temperature. One can observe that when cold water is used to cool the condenser, the saturation pressure is low while warm cooling water results in higher condenser pressure. This increase becomes important at higher cooling water temperatures. A higher terminal temperature difference of the condenser rises slightly the required condenser pressure.

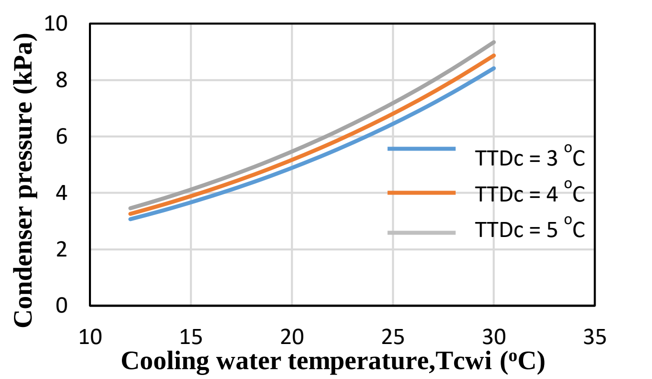

Figure 2: Variation of the condenser saturation pressure, Pc, with the cooling water inlet temperature Tcwi.

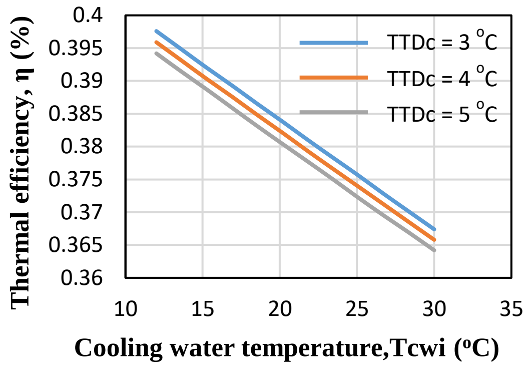

Figure 3: Variation of the NPP thermal efficiency with the cooling water inlet temperature Tcwi.

Figure 3 depicts the decline of the thermal efficiency of the nuclear power plant as the cooling water temperature rises from 12 °C to 30 °C. A decrease of the thermal efficiency of about 3% is obtained with an increase in the cooling water temperature of 17 °C resulting in a power loss of 80 MW (Figure 4). Figures 3 and 4 show that a smaller condenser TTD is preferable since it has a positive impact on the thermal efficiency and the power output of the plant. It is worth mentioning that the results presented in Figures 2, 3 and 4 generated using the developed model in the work compare fairly with the equivalent results developed by [1].

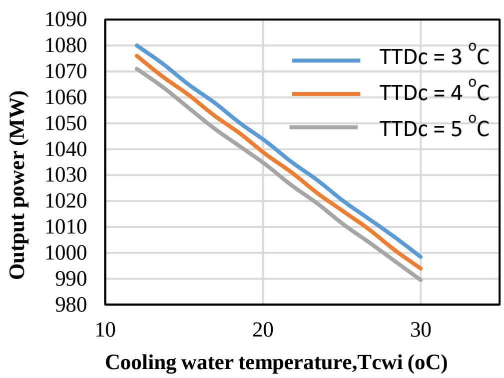

Figure 4: Variation of the NPP output power with the cooling water inlet temperature Tcwi.

The developed numerical model was used to evaluate the thermal performance and thermodynamics of the secondary circuit of the NPP for different condenser conditions in KSA. Three locations namely Alkhobar, Yanbu, and Jeddah are selected in this work.

The distribution of the ambient seawater temperature for each region is given in Table 3. It is shown that Yanbu and Jeddah have almost the same seawater temperature over the year while Alkhobar shows lower temperatures in the cold months and slightly higher temperatures in the summer period.

Table 3. Sea water temperature distribution along a year for the selected cities [10]

Location	Yanbu	Alkhobar	Jeddah
JAN	25.51	18.18	26.1
FEB	24.79	17.85	25.5
MAR	25	20.34	25.7
APRIL	25.99	23.81	26.75
MAY	27.68	27.91	28.15
JUNE	28.56	30.39	29.15
JULY	29.79	32.5	30.5
AUGUST	30.61	33.66	31.45
SEP	30.39	32.84	30.95
OCT	30.42	30.22	30.7
NOV	28.92	26.28	29.05
DEC	27.1	21.09	27.7

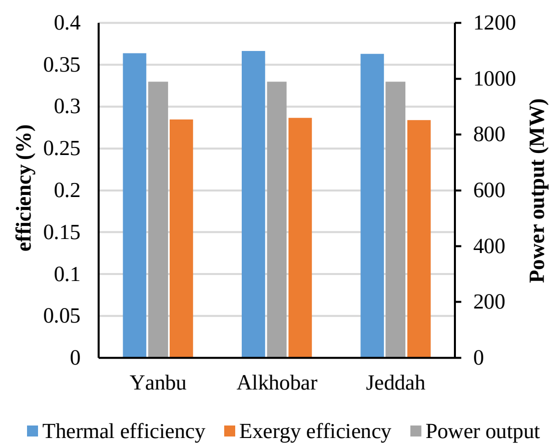

Figure 5: Distribution of the average values of the plant thermal efficiency, exergy efficiency, and power output corresponding to a condenser TTD of 3 °C

Figure 5 presents the average values of the thermal efficiency, exergy efficiency and power output of the nuclear power plant for the three selected cities. The thermal and exergy efficiencies are almost not affected by the location of the plant. However, the electric power generated changes from one region to another. Its average value is highest at Alkhobar while it is the lowest in Jeddah.

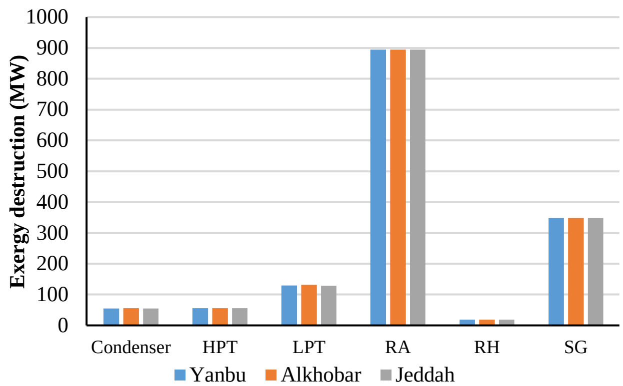

Figure 6: Exergy destruction of the main components of the power plant (Condenser TTD = 3 °C)

The evaluation of the exergy destruction of each component of the plant and the entire plant is an essential step in the exergy analysis. It identifies which component has the highest irreversibility rates which helps in proposing recommendations to improve the performance of such a component. Figure 6 depicts the exergy destruction of the main sub-systems of the plant corresponding to the main cities based on their average annual seawater temperatures. For the three cities, the condenser and the reactor have the highest exergy destruction rates. These high rates of exergy destruction are related to the high heat transfer rates involved in both plant components. For the condenser, the discharge of a high amount of heated seawater back to the sea generates high rates of exergy destruction. This is attributed to the fact that more than 60% of the added heat to the power plant is wasted in the atmosphere as condenser rejected heat.

V. Conclusion

The present work proposed a theoretical study on the impact of seawater cooling temperature on the first and second law efficiencies of a typical nuclear power plant. Energy and exergy equations were first developed and then solved using EES software. Various simulations have been performed to investigate first the impact of changing the seawater cooling temperature on the first and second law efficiencies of the plant and its main components. The power output, energy and exergy efficiencies and exergy destruction were evaluated for the cases of three selected Saudi coastal regions.

It was found that despite the non-negligible variation of the seawater temperature during a year in each of these locations, the average values of the plant energy and exergy efficiencies are just slightly affected. On another side, the steam generator and the reactor core are found to be the least efficient components of the nuclear plant given their high exergy destruction as compared with the other main sub-systems.

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