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The effect of cooling water temperature on the performance of a BWR nuclear power plant

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Abstract

Although PWR reactors make up the large majority of the world's nuclear power plants, BWR reactors also have a share in this industry. It is difficult to find data on the performance of a BWR power plant in off-design and variable load conditions in the literature. Therefore, the paper presents how cooling water temperature affects the efficiency and power output of a BWR unit. The qualitative effect of changes and the trend related to the effect of cooling water temperature on the performance of the power plant are known, but the quantitative effect has to be determined for specific power units. Depending on the location of the nuclear power plant, various temperatures of cooling water for use in condensers and thus various operating conditions of the cooling system can be achieved. To analyze how cooling water temperature affects the performance of the power unit, a model of a BWR power plant was developed using the Ebsilon software. The model was based on data provided in [1] concerning LaSalle County Nuclear Generating Station. Calculations showed that within the examined range of cooling water temperatures at the condenser inlet between 10 and 28°C the gross power output of the unit decreases by 91.405 MW and the gross efficiency drops by 2.773 percentage points.

Keywords: nuclear power plant performance, cooling system, cooling water temperature, boiling water reactor (BWR)

1 Introduction

In a nuclear power plant, heat is delivered to the nuclear reactor system as a result of fission reaction. A steam turbine generates mechanical power which is converted to electrical power in a generator. Therefore, the nuclear power plant can be considered as a heat engine in which heat is produced in the reactor, while work is done in the steam turbine. In the nuclear power plant, part of heat taken from the upper heat source (the nuclear reactor) is delivered, according to the second law of thermodynamics, to the heat source at a lower temperature in the steam condenser. The condenser makes it possible to remove part of heat from the system to the environment, complete the thermal cycle, and meet the second law of thermodynamics. Condensers used in nuclear power plants are shell-and-tube heat exchangers. Cooling water flows inside tubes while steam flowing from the low-pressure (LP) part of the turbine condenses on the outer surface of the tubes [2, 3]. High cooling water mass flow rates are required to make the steam condense, which is why nuclear power plants are usually built near large water reservoirs, such as rivers, lakes or seas. In an open cooling cycle, water drawn from a large water reservoir flows through the condenser, heats up, and returns to the reservoir. If the capacity of the reservoir is not enough to cool down the condenser or if there is no such reservoir near the power plant, the condenser is cooled using a closed cooling cycle which includes a cooling tower [4]. Cooling water temperature at the condenser inlet is lower in the open cycle than in the system comprising the cooling tower. Due to a lower cooling water temperature at the condenser inlet, steam condenses in the condenser at a lower pressure,

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which is why steam in the LP part of the turbine expands to a lower pressure [5-9]. The lower pressure to which steam expands in the LP part of the turbine makes the steam turbine generate more power [6, 9]. For the same energy delivered to the system by the nuclear reactor, the higher power output of the turbine translates into an increase in the efficiency of the whole thermal system [10]. Since sea and ocean water used as cooling water is at a lower temperature than in inland areas (rivers, lakes), nuclear power plants are very often built near seas, as is the case with newly constructed EPR power plants in Olkiluoto in Finland, Flamanville in France, and Taishan in China [11, 12]. Large centres of population and thus high electricity demand are common in inland areas, which is why such facilities have been often built far from the coast. In such power plants water drawn from a lake or a river is used to cool the condenser in an open cooling cycle, or the condenser is cooled down in a closed cycle with a cooling tower. Thus, it can be seen that cooling water temperature affects the performance (power output and efficiency) of a nuclear power plant already at the stage of choosing its location. After the location has been selected and the nuclear power plant has been built, temperature of cooling water used to cool the condenser varies due to daily (day and night) and annual (seasons) temperature cycles.

The qualitative effect of cooling water temperature on the performance of a steam power unit and the trend related to this effect are known. On the other hand, the quantitative effects (a decline in power output and efficiency) resulting from a higher cooling water temperature depend on the structure and equipment of the thermal system and should be determined on a case-by-case basis for each power unit, taking into account operating conditions of its cooling system. In addition to cooling water temperature, key factors also include the design of the LP part of the turbine and of the condensers.

Analyses of the effect of cooling water temperature on the performance of power units with various power outputs can be found in the literature. For example, papers [9, 13] analyze the effect that cooling water properties have on the performance of a 200-MW unit. This issue is of particular importance in the case of units with high capacity between 1200 and 1700 MWe with water cooling in an open-cycle system. For PWR nuclear power plants, values of parameters (pressure, temperature, the mass flow rate) of the thermal system and analyses of how cooling water temperatures affect the performance of power plants can be relatively easily found in the literature [14-19]. It is more difficult, however, to find values of these properties of the thermal system in the literature in the case of a BWR nuclear power plant in both nominal and off-design conditions and under variable load.

The authors of this paper found no publication analyzing the influence of cooling water temperature on the performance of a BWR nuclear power plant, which is why this influence is examined in the present paper. Generally, more papers concerning PWR nuclear power plants can be found than ones dealing with BWR plants, which might be caused by the fact that PWR plants are the most commonly used nuclear power plant technologies globally.

2 A mathematical model of a BWR nuclear power plant

Parameters employed in the mathematical model of a BWR nuclear power plant are taken from [1] which provides an exergy analysis of the system. LaSalle County Nuclear Generating Station, a BWR facility located near the city of Ottawa in the U.S., was analyzed in the paper. This power plant has an open cooling cycle and water is drawn from a man-made lake.

To analyze how cooling water temperature affects the efficiency and power output of a BWR unit, a model of the unit was developed in the Ebsilon software [20] (Figure 1). First, a model operating in design conditions was built and validated based on data found in [1] for cooling water temperature at the condenser inlet $t_{2i}=24^{o}C$. After the model for design conditions was validated, a model operating in off-design conditions was developed to analyze the impact of cooling water temperature on the performance of the unit. The cooling water temperature was changed between 10 and 28°C. A typical BWR nuclear power plant comprises a nuclear reactor, a high-pressure (HP) part of the turbine, a low-pressure (LP) part of the turbine, a steam separator/superheater, a condenser, LP and HP regenerative heat exchangers, a deaerator, and pumps of feedwater, condensate, and cooling water. The equipment used in the model is represented by complete components which employ mass and energy balances, a relation for pressure drops, heat transfer equations, and (for groups of stages) the Fugel-Stodola steam flow capacity equation. The Ebsilon software offers no special components dedicated to a nuclear reactor [21], which is why the nuclear reactor was modeled as a heat source. Since no specific efficiency characteristics of the turbine were available, typical characteristics of groups of stages, varying between the HP and LP parts, were taken.

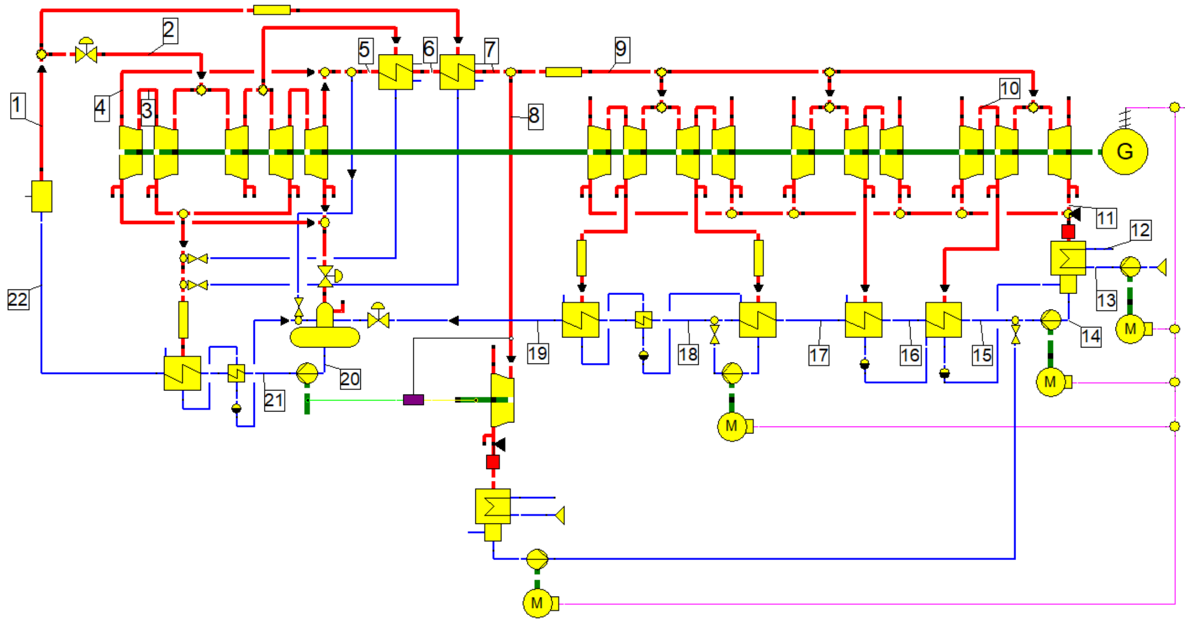

Figure 1. A diagram of the thermal system of the BWR nuclear power plant

The diagram in Figure 1 includes a turbine that drives a feedwater pump. This solution was used due to high power that has to be delivered to the feedwater pump, and the ability to control the rotational speed of the pump. Electric motors coupled with variable-speed drives are increasingly being used in large power generation units to drive feedwater pumps, which enables the control of rotational speed of the pump.

Nearly saturated steam is produced directly in the nuclear reactor. The flow rate of heat delivered to water in the reactor is 3295 MW. At the reactor outlet steam is at 66.53 bar and 282.41°C, and its dryness fraction is 0.997. Since these properties of steam are relatively low, steam can be generated directly in the reactor, which makes it possible to eliminate steam generators from the thermal system of the BWR unit. Steam pressure is 63.29 bar at the inlet and 11.38 bar at the outlet of the HP part. Following expansion, the steam flows to an integrated two-stage steam separator/superheater. After moisture removal and superheating, the steam expands in the LP part of the turbine. Steam pressure at the inlet of the LP part of the turbine is 10.82 bar. From the LP part of the turbine, wet steam flows to the condenser where it condenses. Then, the condensate is pumped by condensate pumps and flows through LP regenerative heat exchangers to a deaerator. From the deaerator, water is pumped by a feedwater pump and flows through an HP regenerative heat exchanger up to the reactor. At the reactor inlet water is at 73.08 bar and 216°C, while its mass flow rate is 1785 kg/s.

Properties (pressure, temperature, specific enthalpy, the mass flow rate, the heat flow rate, dryness fraction, and specific entropy) at selected points numbered in the thermal diagram are listed in Table 1.

Table 1. Pressure, temperature, specific enthalpy, the mass flow rate, the heat flow rate, dryness fraction, and specific entropy at selected points of the thermal system in the BWR power plant

Component	p	t	h	$\dot{m}$	$\dot{Q}$	x	s
	bar	°C	kJ/kg	kg/s	kW	-	kJ/kg/K
1	66.53	282.41	2773.1	1785.00	4950023	0.997	5.833
2	63.29	279.09	2773.1	1716.81	4760932	0.995	5.850
3	23.65	221.02	2614.3	796.82	2083158	0.899	5.899
4	11.38	185.58	2504.0	765.45	1916715	0.861	5.934
5	11.38	185.58	2781.9	1243.22	3458494	1.000	6.540
6	11.17	231.17	2896.0	1243.22	3600319	1.000	6.786
7	10.96	268.29	2980.2	1243.22	3705029	1.000	6.955
8	10.96	268.29	2980.2	23.45	69877.89	1.000	6.955

9	10.82	268.08	2980.2	1219.77	3635151	1.000	6.961
10	0.32	70.59	2450.9	151.68	371751.4	0.924	7.233
11	0.08	41.51	2314.2	203.29	470458.3	0.891	7.395
12	1.5	36.51	153.1	39924.41	6111815	0.000	0.526
13	2	24.01	100.9	39924.41	4027225	0.000	0.353
14	0.08	41.51	173.9	1095.66	190482.1	0.000	0.593
15	12.07	41.62	175.4	1119.11	196250.9	0.000	0.593
16	11.72	67.59	283.8	1119.11	317656.3	0.000	0.925
17	11.38	101.05	424.3	1119.11	474863.5	0.000	1.318
18	11.03	138.33	582.5	1243.22	724192.2	0.000	1.721
19	10.69	157.12	663.4	1243.22	824691.6	0.000	1.913
20	10	179.89	762.7	1785.00	1361389	0.000	2.138
21	75.84	181.23	771.9	1785.00	1377917	0.000	2.143
22	73.08	215.99	926.8	1785.00	1654317	0.000	2.471

Characteristic features of a BWR nuclear power plant include steam properties at the inlet of the HP part of the turbine (steam is nearly saturated), a moisture separator, and a steam superheater located between the HP and LP parts. After expansion, properties of steam in the HP part are below the saturation curve, which is why moisture has to be removed from steam before the latter is fed to the LP part of the turbine to prevent erosion of blades. The curve of expansion in the turbine for parameters at points 1 to 11 of the system is shown in Figure 2.

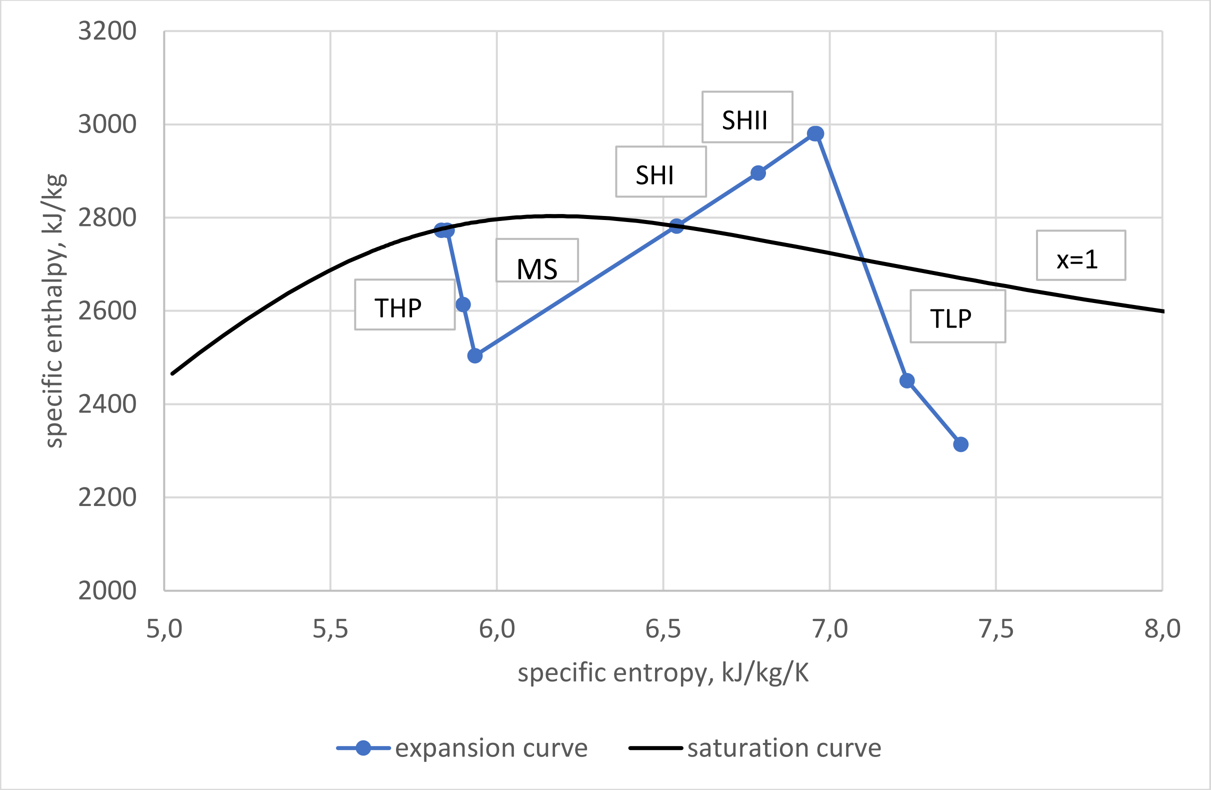

Figure 2. The curve of expansion in the turbine for parameters at points 1 to 11 of the system and the steam saturation curve (MS – moisture separator; THP – steam expansion curve in the HP part of the turbine; SHI, SHII – first and second stages of the steam superheater; TLP – steam expansion curve in the LP part of the turbine)

The effect of cooling water temperature on pressure and temperature of condensing steam and on power output and efficiency of the system was shown using equations provided below. The effect of cooling water temperature on condensing steam temperature and pressure in the condenser can be found using the Péclet equation ($\dot{Q} = UA\Delta T_{log}$), which on rearranging can be given as

$$t_s(p_s) = t_{2i} + \Delta T_w + \delta t_{min} = t_{2i} + \frac{t_{2o} - t_{2i}}{1 - e^{-\frac{UA}{\dot{m}_w c_w}}} \tag{1}$$

where:

A – surface area of heat transfer in the condenser, m^2
c_w – specific heat of cooling water, J/kg/K
$\dot{m}_w$ – mass flow rate of cooling water, kg/s
p_s – pressure of condensing steam in the condenser, kPa
t_{2i} – cooling water temperature at the condenser inlet, ^oC
t_{2o} – cooling water temperature at the condenser outlet, ^oC
t_s – temperature of condensing steam, ^oC
U – overall heat transfer coefficient, W/m^2K
ΔT_w – condenser cooling zone, ^oC
δt_{min} *(TTD)* – terminal temperature difference in the condenser, ^oC.

Pressure of steam in the condenser affects the gross electric power output generated by the turbine which can be calculated from the equation

$$P_b = \{\sum_{i=1}^{i=n} \dot{m}_\iota [h_i(p_i, t_i) - h_{ti}(s_i\,, p_{i+1})]\,\eta_i\}\,\eta_m \eta_G \tag{2}$$

where:

$\dot{m}_\iota$ – steam mass flow rate at the *i*-th group of stages, kg/s
h_i – steam enthalpy at the inlet of the *i*-th group of stages, kJ/kg
s_i – steam entropy at the inlet of the *i*-th group of stages, kJ/kg/K
h_{ti} – steam enthalpy at the outlet of the *i*-th group of stages for isentropic expansion, kJ/kg
η_i – isentropic efficiency of the *i*-th group of stages, -
η_m – mechanical efficiency of the turbine, -
η_G – efficiency of the generator, -

For the gross electric power output, the efficiency of the unit was defined as

$$\eta_b = \frac{P_b}{\dot{m}_R(h_w - h_d)} \tag{3}$$

where:

$\dot{m}_R$ – mass flow rate of water flowing to the reactor, kg/s
h_w – steam enthalpy at the reactor outlet, kJ/kg
h_d – water enthalpy at the reactor inlet, kJ/kg

3 Results

The impact of cooling water temperature at the condenser inlet on the performance (power output and efficiency) of the unit was analyzed for the constant water mass flow rate at the nuclear reactor inlet $\dot{m}_R$ = 1785 kg/s = const. and the constant thermal power delivered to the system $\dot{Q}_R$ = 3295 MW. It was assumed that t_{2i} varies between 10 and 28^oC, which is a typical range of temperatures in Europe. Figures 3 to 6 show the effect of cooling water temperature at the condenser inlet on: pressure and temperature of condensing steam, cooling water temperature at the condenser outlet, the mass flow rate of steam flowing to the turbine-driven pump, the power of the turbine-driven pump, and gross power output and efficiency of the system.

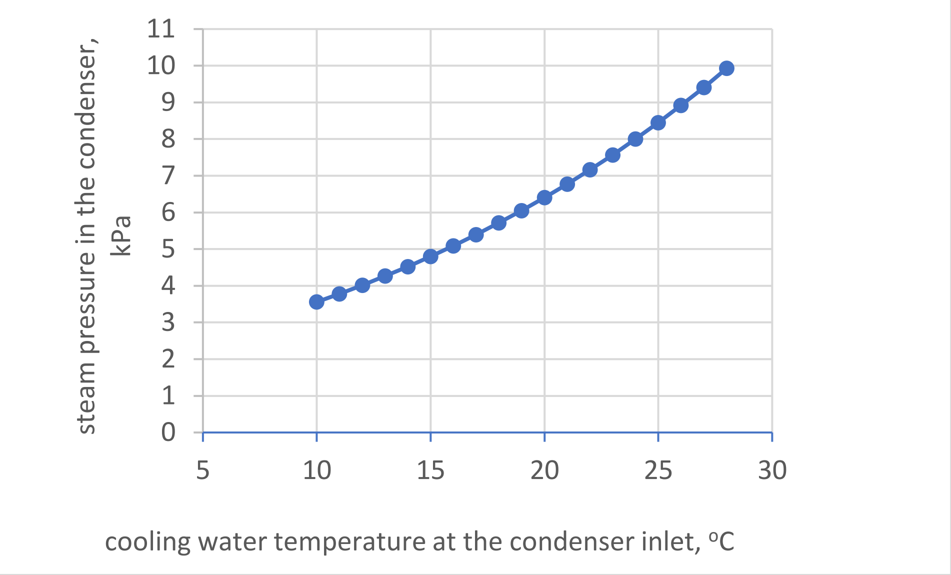

Figure 3. The effect of cooling water temperature on condensing steam pressure in the condenser

The higher the temperature of cooling water is, the higher the pressure of condensing steam becomes. This relation is non-linear. Within the examined range of cooling water temperatures at the condenser inlet between 10 and 28ºC, the condensing steam pressure rises by 6.37 kPa. On average, following an increase of 1ºC in cooling water temperature, steam pressure rises by 0.353 kPa.

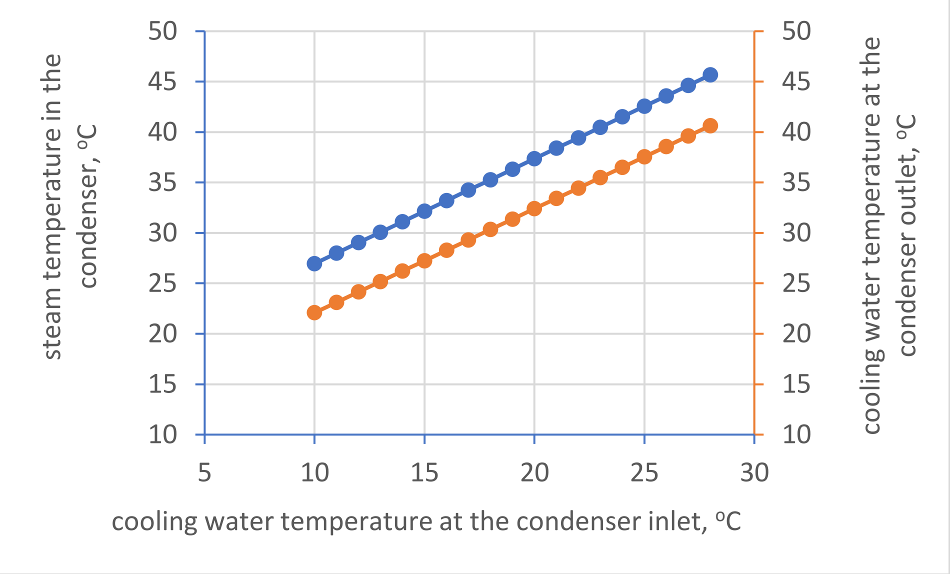

Figure 4. The effect of cooling water temperature at the condenser inlet on temperature of condensing steam in the condenser and temperature of cooling water at the condenser outlet

As temperature of cooling water at the condenser inlet increases, temperature of condensing steam and temperature of cooling water at the condenser outlet increase. These relations are approximately linear. Within the examined range of cooling water temperatures between 10 and 28ºC, the condensing steam temperature rises by 18.71ºC, while the cooling water temperature at the condenser outlet rises by 18.54ºC. The increase of condensing steam temperature is slightly bigger than that of cooling water temperature at the condenser outlet.

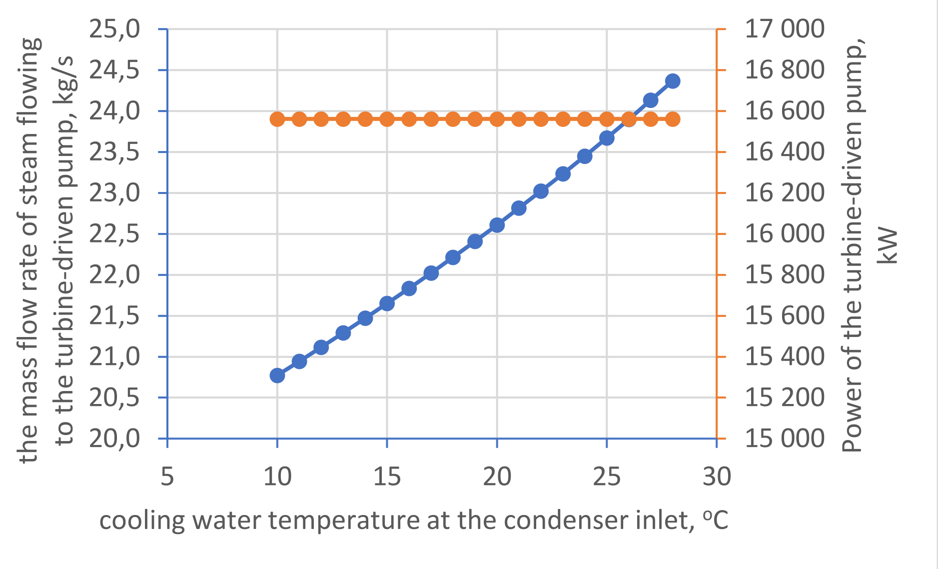

Figure 5. The effect of cooling water temperature on the mass flow rate of steam flowing to the turbine-driven pump and power of this pump

Since the mass flow rate of water flowing through the reactor and the reactor power output are both constant, power generated by an auxiliary turbine driving the feed water pump is also constant. The mass flow rate of steam fed to the auxiliary turbine increases with an increase in cooling water temperature. As the cooling water temperature rises, pressure of condensing steam in the condenser becomes higher (Figure 3). Steam in the auxiliary turbine expands to a higher pressure which leads to a smaller drop in enthalpy. For the smaller drop in enthalpy, the mass flow rate of steam drawn has to increase so that the constant power of the auxiliary turbine is maintained (Figure 5).

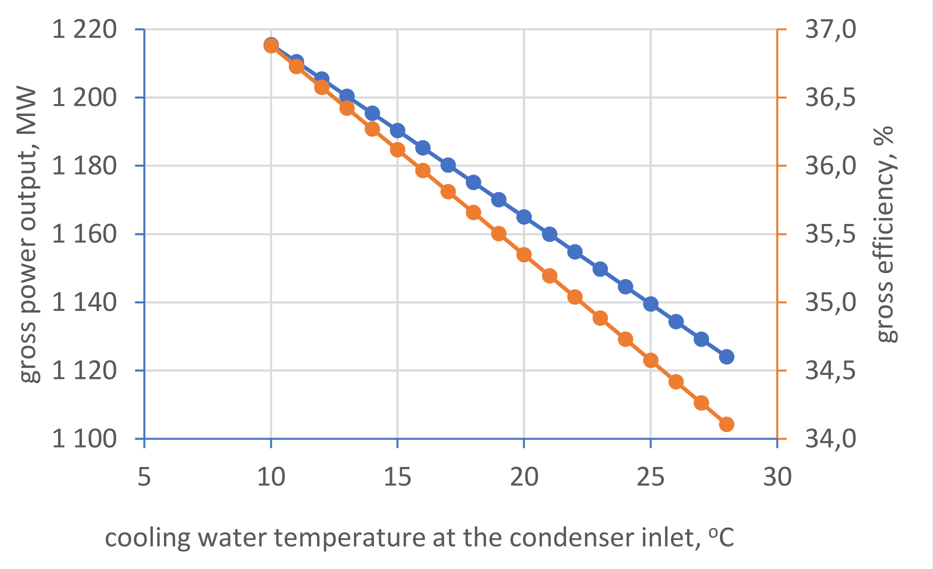

Figure 6. The effect of cooling water temperature on the gross power output and gross efficiency of the power unit

As the temperature of cooling water at the condenser inlet increases, the power output of the unit declines, which results from a higher condensing steam pressure (Figure 3). Within the examined range of cooling water temperatures at the condenser inlet between 10 and 28°C, the power output drops by 91.405 MW. For the increase of 1°C in cooling water temperature at the condenser inlet, the power output drops by 5.08 MW. Assuming the constant thermal power of the nuclear reactor, a decrease in the power output of the system is accompanied by a reduction in the system efficiency. Within the examined range of cooling water temperatures, the gross efficiency decreases by 2.773 percentage points. The characteristics of gross power output and gross efficiency as functions of cooling water temperature are approximately linear.

4 Conclusions

The paper presents the effect of cooling water temperature on the performance (power output and efficiency) of a BWR nuclear power plant. A model of the nuclear power plant was developed using the Ebsilon software and validated based on data available in the literature [1].

Within the examined range of cooling water temperatures between 10 and 28°C, the gross power output drops by 91.405 MW while the gross efficiency of the system declines by 2.773 percentage points. The characteristics of gross power output and gross efficiency as functions of cooling water temperature are approximately linear (Figure 6).

Based on the analysis concerning the BWR nuclear power plant, it can be demonstrated that when cooling water temperature rises by 1°C, the power output drops by about 5.08 MW. Such a decrease is significantly larger than in the case of conventional power units. This is due to the smaller enthalpy drop available in the turbine of the BWR nuclear power unit compared to turbines of conventional units. Assuming that a nuclear power plant operates on average 8000 hours per year and the average electricity price in Poland is in the range of EUR 60/MWh, a rise of 1°C in cooling water temperature at the condenser inlet will result in losses amounting to EUR 2.4 million per year.

As the share of unstable power sources (renewable energy sources) is increasing, nuclear power plants will have to be able to operate under both design and lower load conditions. The results presented in the paper indicate that in the case of a nuclear power plant with BWR reactors, as with conventional high-capacity power units and PWR units, under lower load conditions the cooling water flow rate should be optimized.

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