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Performance comparison of PWR/EPR and steam generator with and without economizer

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Abstract

The article presents a model of a steam generator based on mass and energy balance equations, heat transfer coefficients, criterion relations and Peclet's law. The presented model was applied to a steam generator without and with an economizer for a PWR/EPR nuclear power plant. Based on the calculations, the steam pressure at the outlet of the steam generator without the economizer is 74.17 bar, and for the model with the economizer it is 77.2 bar. The pressure difference for these two variants, based on the calculations, was therefore 3 bar. Higher steam pressure at the outlet of the steam generator translates into a greater enthalpy drop in the turbine and greater power generated by the steam turbine and the efficiency of the entire nuclear power plant. Based on the economic calculations carried out for 60 years of operation of a nuclear power plant with four steam generators, the profit from the use of the economizer amounted to about PLN 0.6 billion.

Keywords: steam generator, economizer, steam pressure, PWR, EPR

1 Introduction

One of the main components of a nuclear power plant, in addition to a nuclear reactor, is a steam generator. The pressure and mass flow rate of steam at the outlet of the steam generator and the vapor condensation pressure in the steam condenser determine the power and efficiency of the entire nuclear power plant [1, 2]. Over the years, there has been a visible increase in the power and efficiency of nuclear units, mainly related to the increase in steam pressure and mass flow rate of steam at the outlet from the steam generator. For example, for a Konvoi power plant [3] with a net electrical capacity of 1287 MW, the net electrical efficiency is 34% and the steam pressure at the outlet of the steam generator is 63.5 bar. For a nuclear power plant with units of type N4 [3] with a net electrical capacity of 1450 MW and3%, the steam pressure at the outlet of the steam generator is 72.3 bar. For an EPR unit with a net electrical capacity of 1600 MW [4], the net electrical efficiency is 37. 2% and the outlet pressure from the steam generator is about 77 bar. The issue of optimization of vapour pressure as well as optimization of the entire secondary circuit are presented, among others, in articles [56677.

The increase in steam pressure at the outlet of the steam generator was achieved, among others, by: reducing flow pressure drop for water and steam on the side of the secondary circuit, improving the efficiency of separators and steam dryers and, above all, by using an economizer, i.e. a water heater constituting an integral part of the steam generator, in which the feed water on the side of the secondary circuit is heated from the water temperature at the inlet to the steam generator to the saturation temperature. An increase in steam pressure at the outlet from the steam generator can also be achieved by increasing the temperature of the water in the primary circuit. At the same time, the temperature of the water in the primary circuit is limited by the occurrence of boiling water in the primary circuit.

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For safety reasons, an adequate temperature reserve (margin) must be provided so that there is no evaporation of water in the primary circuit.

The article compares the unit performance and steam pressure at the outlet from the steam generator for the steam generator for a PWR nuclear unit without an economizer and with an economizer. The increase in power of a nuclear unit with a steam generator with an economizer used in an EPR unit in relation to a nuclear unit with a steam generator without an economizer and the financial profit for 60 years of operation of the power plant were also estimated.

2 Description of steam generator for EPR nuclear power plant

The steam generator in PWR nuclear power plants combines the primary and secondary circuits. In the steam generator, heat is transferred from the primary circuit, produced in a nuclear reactor, to the secondary circuit and the steam is produced [22 4]. The steam generator for a nuclear power plant type PWR/EPR is a vertical shell-tube heat exchanger [8, 9]. Water from the primary circuit is fed into the inlet chamber of the steam generator and then flows inside the tubes, turns around and flows down to the outlet chamber. During the flow of primary water in the tubes, heat transfer occurs. From the side of the secondary circuit, feed water is supplied to the steam generator, which flows down (in cold leg), returns and flows into the tube bundle, washing the tubes on the outer surface, absorbs heat leading to a partial phase change and production of wet steam. The wet steam then flows through separators and steam dryers, in which the moisture contained in the wet vapour is separated. At the outlet from the steam generator we obtain vapour with a degree of dryness of 0.997. A diagram of the steam generator is shown in Figure 1 [4]. In the lower part you can see the inlet and outlet chamber on the water side of the primary circuit and a bundle of inverted U-tubes. In the central (conical) part of the steam generator, the water inlet of the secondary circuit is visible, separators and steam dryers are visible inside the steam generator, and the steam outlet is located at the very top of the steam generator.

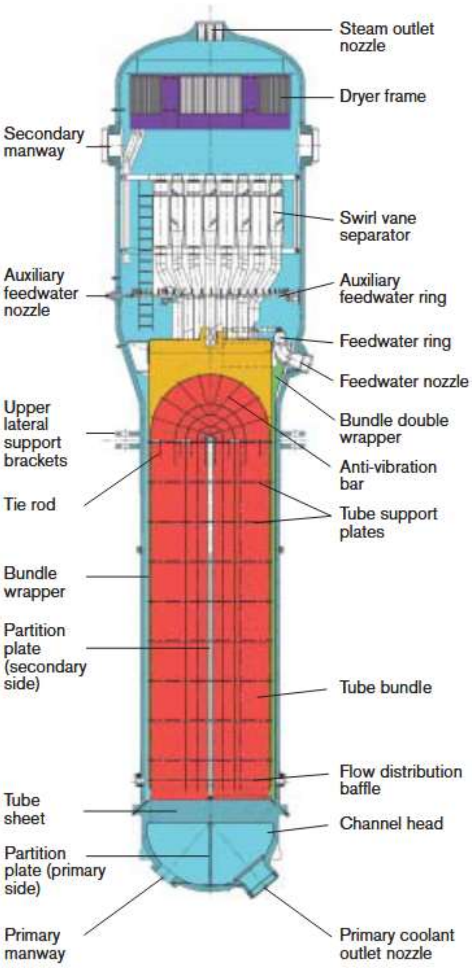

Figure 1. EPR steam generator [4]

The basic data of the analyzed steam generator are presented in Table 1.

Table 1. Basic data for steam generator in a nuclear unit type EPR [9]

EPR unit steam generator	value
Heat transfer surface area	7960 m^2
Tube outer diameter	19.05 mm
Wall thickness	1.09 mm
Number of tubes	5 980
Material of tubes	Alloy 690 TT
Saturation pressure at nominal conditions	77.2 bar
Feed water temperature	230 °C
Steam mass flow rate	658 kg/s
Inlet water temperature to the steam generator- primary loop	329.9 °C
Inlet water mass flow rate to the steam generator- primary loop	5568 kg/s

For a steam generator with economizer, the water supplied to the steam generator on the secondary side is distributed only on half of the circuit (cross-section A-A in Figure 2 [4]). The feed water flows down the steam generator (the so-called cold leg) then turns back and is heated to a saturated state in the economizer. The height of the economizer is determined by the dashboard. Only above the height of the dashboard is the mixing of two streams of water flowing in the hot leg and cold leg parts. In the case of steam generators without an economizer, the feed water supplied to the steam generator on the secondary side is distributed around the entire circumference (cold water) and mixed with the water falling from the steam separators and hot water dryers at the height of the water supply on the secondary side of the steam generator.

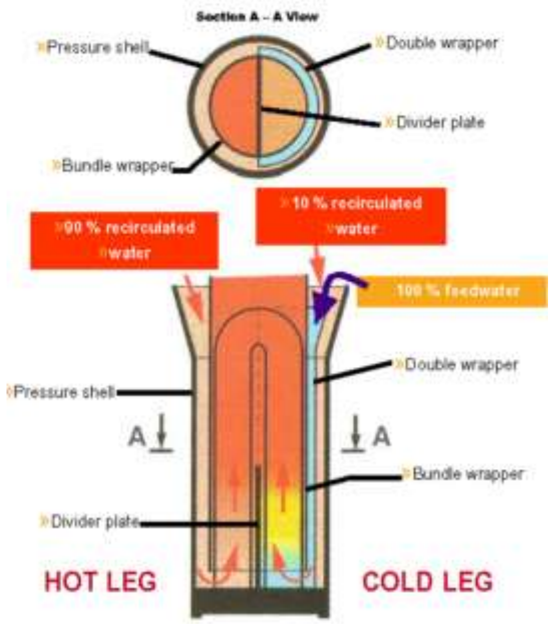

Figure 2. Economizer in steam generator for nuclear power plant type EPR [4]

Figure 3 shows the temperature distribution for a steam generator without and with an economizer [10]. For a steam generator without an economizer, along the length of the generator tubes, the temperature difference decreases, which at the beginning is 35 °C and at the end of the tube length is about 5°C. The temperature difference between the "heating" and the "heated" medium is the driving force behind the heat transfer. At the end of the length of the tubes in the steam generator, the transmitted heat flux is reduced, and therefore it is reasonable at this point to use the economizer to increase the heat flux. For a steam generator with an economizer, the feed water is only partially mixed directly with saturated water falling from separators and steam dryers and is then heated to saturation in the economizer, which is located in the "cold leg" section. The feed water, after reaching the saturation conditions at the outlet from the economizer, is mixed with saturated water from the "hot leg" stream. The use of an economizer causes an increase in the average temperature difference of the fluids, which increases the transferred heat flux at the end of the tubes (Fig. 3). In a steam generator with an economizer, heat transfer takes place in two zones: in the part related to heating the feed water to the saturation state in the economizer and in the part where the phase change occurs. By using an economizer, the average water temperature increases on the primary side of the circuit for the part where the phase change occurs, which allows the vapor pressure to increase. A similar phenomenon occurs in the steam condenser, where as the temperature of the cooling water at the inlet to the steam condenser increases (which translates into an increase in the average water temperature), the pressure of the condensing vapor in the steam condenser increases.

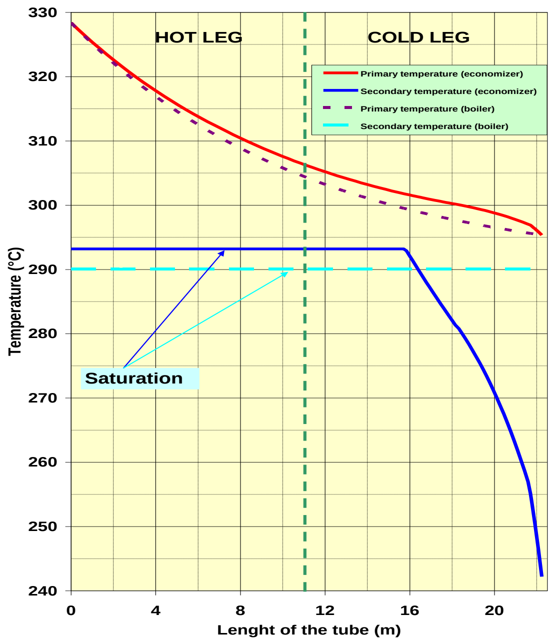

Figure 3. Temperature distribution in steam generator with and without economizer [10]

3 Mathematical model of the steam generator

In the model of the steam generator, the energy balance, the relations on the heat transfer coefficients for water on the primary side and for steam on the secondary side, the dependence on the heat transfer coefficient and Peclet's law [111, 1211, 1313.

The energy balance for the steam generator is

$$\dot{m}_{wp}\left(h_{wp\_in} - h_{wp\_out}\right) = \dot{m}_s\left(h_s - h_{steam\_out}\right) \tag{1}$$

where:
$\dot{m}_{wp}$ – mass flow rate of cooling water flowing inside the tubes (primary circuit), kg/s,
h_{wp_in} – enthalpy of water at the inlet to the steam generator (primary circuit),
h_{wp_out} – enthalpy of water at the outlet from the steam generator (primary circuit),
$\dot{m}_s$ – water mass flow rate supplied to the steam generator on the side of the secondary circuit (supply),
h_s – enthalpy of water at the steam generator inlet (secondary circuit, supply),
h_{steam_out} – vapour enthalpy at the outlet from the steam generator (secondary circuit).

The Nusselt number for water from the side of the primary circuit was determined from the criterion relation for turbulent flow

$$Nu_{wp} = 0.023 Re_{wp}^{0.8} Pr_{wp}^{1/3} \tag{2}$$

where:

Nu_{wp} – the Nusselt number for water flowing inside the tubes,
Re_{wp} – the Reynolds number for water flowing inside the tubes,
Pr_{wp} – the Prandtl number for water flowing inside the tubes.

The heat transfer coefficient from the water side was determined from the Nusselt number

$$h_{wp} = \frac{Nu_{wp}\lambda_{wp}}{d_i} \tag{3}$$

where:
h_{wp} – heat transfer coefficient for the water side,
λ_{wp} – thermal conductivity coefficient for water,
d_i – inner diameter of the steam generator tube.

From the vapor side, the temperature difference between the wall temperature and the vapor saturation temperature was determined from the conventional relation for fully developed subcooled boiling – Jens and Lottes correlation [1, 13]

$$\Delta T = 25(q)^{0.25} e^{-\frac{p}{62}} \tag{4}$$

where:
ΔT - the difference between the wall temperature and the vapour saturation temperature, ^{o}C,
q – heat flux per heat transfer surface area (heat flux), MW/m^2,
p – fresh steam pressure, bar.

Given the dependence (4), the heat transfer coefficient on the vapour side is

$$h_b = \frac{q}{\Delta T} = \frac{1}{25}(q)^{0.75} e^{\frac{p}{62}} \tag{5}$$

The dependence on the transferred heat flux (Peclet's law) has the form

$$\dot{Q} = UA\Delta T_{ln} \tag{6}$$

where:
$\dot{Q}$ – flux of transferred heat in the steam generator, W,
U – heat transfer coefficient, W/(m^{2}K),
A – heat transfer surface area, m^2,
ΔT_{ln} – logarithmic mean temperature difference, ^{o}C.

The heat transfer coefficient was determined from the relation

$$U = \frac{1}{\frac{1}{h_{wp}} + \frac{\delta_m}{\lambda_m} + \frac{1}{h_b}} \tag{7}$$

where:
λ_m – is the thermal conductivity of the steam generator tube material,

δ_m – steam generator tube thickness.

In the case of a steam generator with an economizer, the relation (5) applies to the zone in which the phase change occurs. In this case, to calculate the heat flux per heat transfer surface area q for the relation (5), the heat flux and heat transfer surface area for the phase change zone only shall be taken into account, without taking into account the heat flux transferred in the economizer and its heat transfer surface area. The calculations for the economizer were made as for a counter-current heat exchanger.

4 Results

On the basis of the calculations carried out for the presented model, geometrical and input data to the model, the following values of steam pressure at the outlet were obtained: for a steam generator without an economizer and for a steam generator with an economizer. From the model of the steam generator without economizer, the value of the steam pressure at the outlet was obtained 74. 17 bar and for the model with economizer the steam pressure was 77.2 bar. The pressure difference for these two variants on the basis of calculation simulations was therefore 3 bar. Based on the data shown in Figure 3 taken from the steam generator manufacturer, the vapour temperature difference for a steam generator with and without an economizer is about 3 ^{o}C, which corresponds to a pressure difference of 3 bar. For the presented zero-dimensional mathematical model of the steam generator with and without economizer, the pressure increase is the same as for the data of the steam generator manufacturer. As the steam pressure increases at the outlet from the generator, the power generated by the unit increases. The article [2] presents a mathematical model of a nuclear unit of the EPR type made in the Ebsilon program and presents the characteristics of the power of the unit as a function of steam pressure at the outlet from the steam generator, which shows that the increase in pressure by 1 bar is accompanied by an increase in the power of the unit by about 3 MW. Assuming that the steam pressure increase for a steam generator without and with an economizer is equal to 3 bar, which corresponds to an increase in the power of the unit by 9MW. For the power difference (ΔN_{el}) of the power plant, it is possible to determine the economic profit for n years of operation of the unit in the form

$$Z = \sum_{k=0}^{n} \Delta N_{el} \tau_k c_{el,k} a_t = \Delta N_{el}\, \tau\, c_{el} \sum_{k=0}^{n} a_t \tag{8}$$

where:

n - years of operation of the unit
t- current year (t=0 for the year preceding the first year of operation of the unit)
ΔN_{el}– difference in the power of the nuclear unit resulting from the increase in vapour pressure through the use of an economizer in the steam generator, MW
τ - annual operating time of installed power, h/year
c_{el} - electricity price, PLN/MWh
a_t – discount factor.
Assuming that the price of electricity is fixed each year as well as the operating time of a nuclear power plant is the same, depending on (8), the discount factor for individual years should be added together

$$SE = \sum_{k=0}^{n} a_t = \sum_{k=0}^{n} \frac{1}{(1+d)^t} \tag{9}$$

Assuming a discount rate d of 5% and years of operation of a nuclear power plant n=60 years, the sum of the discount factor for the life of the nuclear power plant SE is equal to 19.93. Ultimately, the gain over 60 years of operation of an EPR nuclear power plant with steam generators equipped with economizers can be recorded as

$$Z = \Delta N_{el}\, \tau\, c_{el} SE \tag{10}$$

It is assumed that the average annual operating time of a nuclear power plant is equal to $\tau = 7000h$, and the price of electricity is equal to $c_{el} = 500\ zł/MWh$.

The profit from the use of an economizer in an EPR power plant with four steam generators amounted to PLN 0.6 billion according to relation (10).

5 Conclusion

The article presents a zero-dimensional model of a steam generator with and without an economizer for a steam generator of a nuclear power plant of the PWR/EPR type, which is based on energy balance, heat transfer coefficients, criterion relations and Peclet's law.

The use of an economizer improves the conditions of heat transfer, which causes an increase in the transferred heat flux in the generator and an increase in steam pressure. Higher steam pressure at the outlet of the steam generator translates into a greater decrease in enthalpy in the turbine and greater power generated by the steam turbine and the efficiency of the entire nuclear power plant.

Based on the calculations, an increase in steam pressure in a steam generator with an economizer of 3 bar was obtained in relation to a steam generator without an economizer. The same pressure rise is given by the steam generator manufacturer for the EPR power plant.

As for the increase in steam pressure at the outlet from the steam generator by 3 bar, there is an increase in the generated electrical power by about 9 MW according to the calculations presented in the article [2]. Based on the economic calculations carried out for 60 years of operation of a nuclear power plant with four steam generators, the profit from the use of an economizer amounted to about PLN 0.6 billion.

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