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Cooperation of a Steam Condenser with a Low-pressure Part of a Steam Turbine in Off-design Conditions

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Abstract A steam condenser is an important component of a power plant, in which the heat of condensation is discharged to the environment. Changes of inlet temperature and mass flow rate of cooling water affect the steam pressure, which has a significant impact on the efficiency and power generated in the low-pressure (LP) part of the steam turbine. On the basis of data obtained from a simulator of the steam condenser and the actual measurement data from a 200-MW power plant, an analysis was performed of how the inlet cooling water temperature, the cooling water mass flow rate, and the steam mass flow rate affect the steam condenser effectiveness, the heat flow, the steam pressure in the condenser, and the efficiency and power of the LP part of the steam turbine. In the case of heat exchangers with a condensation zone, e.g. in a regenerative heat exchanger, the maximum value of the effectiveness ε means obtaining the maximum value of the heated fluid temperature at the outlet. Since the role of the steam condenser (providing the lowest possible vacuum) is slightly different from the role of a classical heat exchanger, increasing the value of ε does not mean better performance of the steam condenser. An even greater disparity exists in the evaluation of the performance of a system comprising the steam condenser and the LP part of the steam turbine. It was therefore suggested to evaluate the performance of the steam condenser and the LP part of the steam turbine using the parameter of efficacy, defined as: $\delta=(1-\varepsilon)=\delta t_{min}/\Delta T_{max}$. Moreover, for practical purposes, the relation (6) was given for the power of the LP part of the steam turbine as a function of the cooling water mass flow rate and its temperature at the inlet to the steam condenser. Knowing the characteristics of the LP part of the steam turbine and of the steam condenser, one can optimize operating conditions of the system.

Keywords: *steam condenser effectiveness, low-pressure part of the steam turbine, steam condenser efficacy*

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1. Introduction

Condensers are the largest heat exchangers in power plants, where the steam flowing from the low-pressure (LP) part of the steam turbine is condensed. To cool down the steam, water, taken from rivers, lakes or cooled in cooling towers, is most often used. Condensers are normally shell and tube heat exchangers. The cooling water flows inside the tubes, and the steam condenses on their outer surface. The application of the condenser allows to close the thermal cycle and transfer the heat of condensation to the environment [1,10]. A diagram of the steam condenser, its location in the heat system, the notation used and a sample temperature distribution along the heat transfer surface are shown in Figure 1. Within the steam condenser, the cooling water temperature at the inlet (T_{c1}) and outlet (T_{c2}) of the condenser, the cooling water mass flow rate ($\dot{m}_w$) and the steam pressure (p_h) are most often measured.

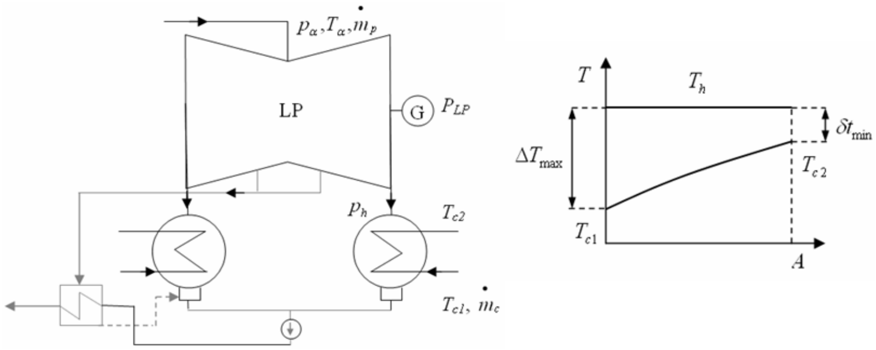

Figure 1. A location of the steam condenser in the heat system with a sample temperature distribution

The steam mass flow rate ($\dot{m}_p$) is usually calculated from the energy balance. For water-cooled condensers with river or lake water, the temperature at the inlet to the condenser varies in summer and winter months. The cooling water mass flow rate can be adjusted by setting the blade angle in a pump [5,8,14]. Changes in the cooling conditions and the inert gas removal efficiency affect the performance of the steam condenser [4,8,12,13] and the condensing steam pressure [2,5,10,14,16,17], which in turn affects the operating conditions of the LP part of the steam turbine, and the internal power it achieves [11].

This article analyses how changes in water temperature at the inlet to the condenser and the cooling water and steam mass flow rates affect the steam condenser effectiveness, the heat flow, and the pressure in the steam condenser, and how changes in these values affect the efficiency and electrical power output of the LP part of the steam turbine.

For heat exchangers with a phase change of one fluid, the heat exchanger effectiveness is defined as [2,6,7,13]

$$\varepsilon = \frac{T_{c2} - T_{c1}}{T_h - T_{c1}} = 1 - e^{-\frac{kA}{m_c c_w}} \tag{1}$$

where: k – overall heat transfer coefficient, A – heat transfer surface area, c_w – water specific heat, $\dot{m}_w$ – mass flow rate of cooling water, T_h – steam temperature, T_{c1} – water temperature at the inlet to the steam condenser, T_{c2} – water temperature at the outlet of the steam condenser (Figure 1).

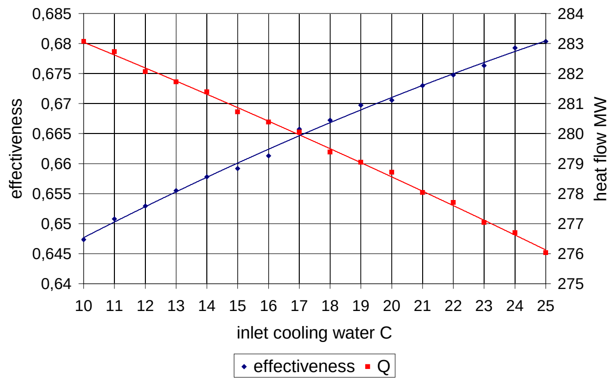

Figure 2. Change in the steam condenser effectiveness and heat flow as a function of water temperature at the inlet to the steam condenser

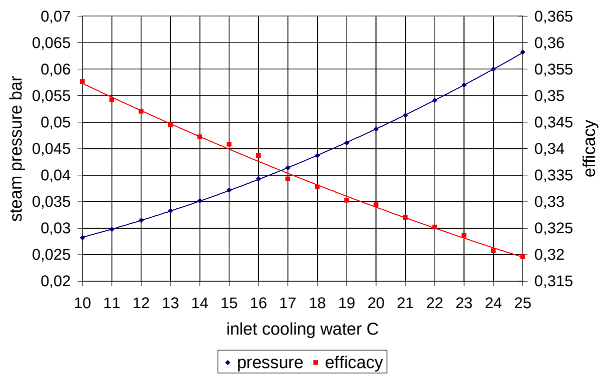

Figure 3. Steam pressure and efficacy of the steam condenser as a function of water temperature at the inlet to the steam condenser

For steam condensers, the parameter ε is not an unambiguous measure for assessing their role in the cooling system of a power plant. From a comparison between Figure 2 and Figure 3, it can be seen that the increase in the steam condenser effectiveness is followed by an increase in the steam pressure in the condenser. Higher pressure means the deterioration in the performance of the steam condenser, whose main task is to receive heat from the condensing steam and ensuring the lowest possible vacuum in the steam condenser. It appears that a better parameter to evaluate the steam condenser performance is the difference δ=1-ε. An increase in the value of the parameter δ corresponds to a decrease in the steam pressure in the steam condenser, and lower vacuum means higher power of the turbine. Given that $\delta t_{min}=T_h-T_{c2}$ and $\Delta T_{max}=T_h-T_{c1}$, we can express a modified effectiveness of the condenser, called efficacy, with the relation:

$$\delta = 1 - \varepsilon = \frac{\delta t_{\min}}{\Delta T_{\max}} = e^{-\frac{kA}{m_c c_w}} \tag{2}$$

where: δt_{min} – terminal temperature difference, ΔT_{max} – maximum temperature difference, ε – steam condenser effectiveness, δ – efficacy of the steam condenser.

To illustrate the analysis, including the evaluation of the steam condenser efficacy expressed with the equation (2), data obtained from a steam condenser simulator and measurement data for the steam condenser and the LP part of the turbine in a 200-MW power plant were used.

2. Steam Condenser – Data from a Simulator

The steam condenser simulator was developed based on a steady state zero-dimensional model, and relations known in the literature for heat transfer coefficients for water and steam [2,3,5,9] were used.

The input parameters to the simulator are: water temperature at the inlet to the steam condenser, cooling water mass flow rate, and steam mass flow rate. The output parameters are: water temperature at the outlet of the steam condenser, and steam pressure (temperature). The following design parameters of the steam condenser were assumed: cooling water mass flow rate of 7995 kg/s, cooling water temperature of 17°C, steam pressure of 0.0414 bar and temperature of 29.56°C, and steam mass flow rate of 123 kg/s.

By changing these three input parameters, a set of data for off-design operating conditions of the steam condenser was obtained, as illustrated in Figure 2 to Figure 7.

2.1. Change in the Cooling Water Temperature at the Inlet to the Steam Condenser

In the first case, the temperature of the cooling water at the inlet to the steam condenser was changed from 10°C to 25°C, in one degree Celsius increments. The cooling water and steam mass flow rates were constant and equal to the nominal values. The influence of the change in the cooling water inlet temperature on the steam condenser effectiveness and the transferred heat flow is shown in Figure 2, and on the steam pressure and the efficacy of the steam condenser in Figure 3.

The increase in water temperature at the inlet to the steam condenser causes an increase in the effectiveness, a decrease in the heat flow, and an increase in the steam pressure.

2.2. Change in the Mass Flow Rate of Steam Flowing from the LP Part of the Turbine to the Steam Condenser

In the second case, the steam mass flow rate was changed from 70 kg/s to 150 kg/s, in 10kg/s increments.

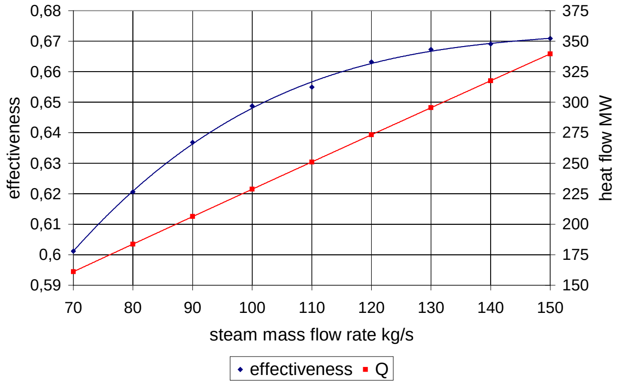

Figure 4. Steam condenser effectiveness and the heat flow as a function of the steam mass flow rate

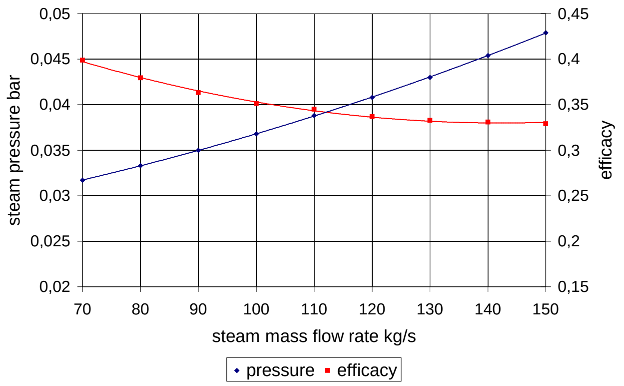

Figure 5. Steam pressure and efficacy of the condenser as a function of the mass flow rate

The temperature of cooling water at the inlet to the steam condenser and its mass flow rate were constant and equal to the nominal values. The influence of the change in the steam mass flow rate on the steam condenser effectiveness and the transferred heat flow is shown in Figure 4, and on the steam pressure and the efficacy of the steam condenser in Figure 5.

The increase in the steam mass flow rate causes an increase in all the analysed variables: the steam condenser effectiveness, the transferred heat flow, and the steam pressure in the condenser.

2.3. Change in the cooling water mass flow rate

In the third case, the cooling water mass flow rate was changed from 6,000 kg/s to 10,500 kg/s, in 500 kg/s increments. The cooling water temperature and the steam mass flow rate were constant and equal to the nominal values. The influence of the change in the cooling water mass flow rate on the steam condenser effectiveness and the transferred heat flow is shown in Figure 6, and on the steam pressure and the efficacy of the steam condenser in Figure 7.

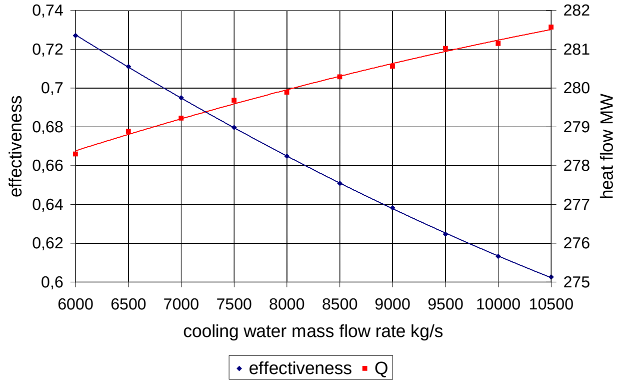

Figure 6. Steam condenser effectiveness and the heat flow as a function of the cooling water mass flow rate

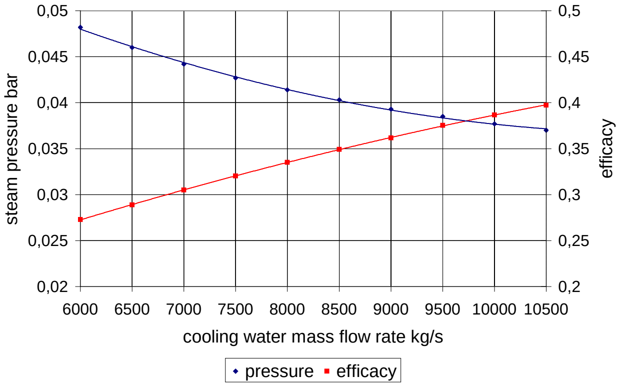

Figure 7. Steam pressure and the efficacy of the steam condenser as a function of the cooling water mass flow rate

The increase in the cooling water mass flow rate causes a decrease in the steam condenser effectiveness, an increase in the transferred heat flow, and a drop in the steam pressure in the condenser. From among the parameters analysed, the steam pressure in the condenser is the one that has the biggest impact on the performance (efficiency and power output) of the LP part of the steam turbine. With the increase in the steam pressure, which was observed in the first case (the cooling water temperature at the inlet to the condenser increasing) and the second case (the steam mass flow rate increasing), the actual enthalpy drop should decrease, because steam expands to a higher pressure. Due to the "shorter" expansion curve, less losses are generated, hence the efficiency of the LP part of the steam turbine should increase. The correctness of this thesis was verified based on actual data for the 200-MW power plant.

3. Steam condenser – measured data

On the basis of hourly average data obtained from a Distributed Control System (DCS) of a national power plant, an analysis of changes in the parameters of the system comprising the steam condenser and the LP part of the steam turbine was performed for two months: January and July. These two months were chosen due to a significant change in the cooling water temperature at the inlet to the steam condenser in winter and summer seasons.

Using these data, the effect of the increase in the cooling water temperature on the performance of the steam condenser and the LP part of the steam turbine was analysed.

Figure 8 shows the range of changes in the cooling water temperature at the inlet to the steam condenser for January and July. The cooling water temperature varied between 9 and 14°C in January, and between 20 and 26°C in July. The average increase in water temperature at the inlet to the steam condenser for July, as compared to January, is about 10°C, which means considerable variation in the operating conditions of the steam condenser. With the increase in the cooling water temperature at the inlet to the steam condenser, an increase in the steam temperature (and the corresponding pressure) is observed (Figure 9).

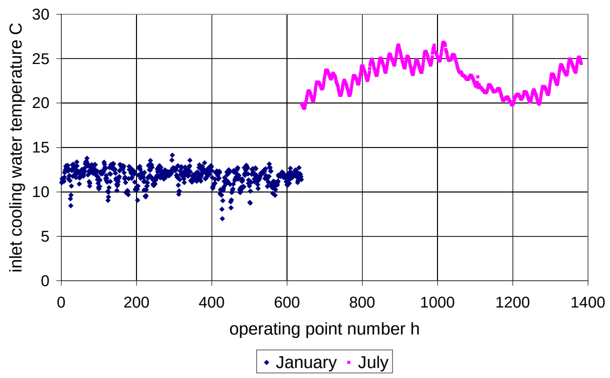

Figure 8. Change in the cooling water inlet temperature in January and July

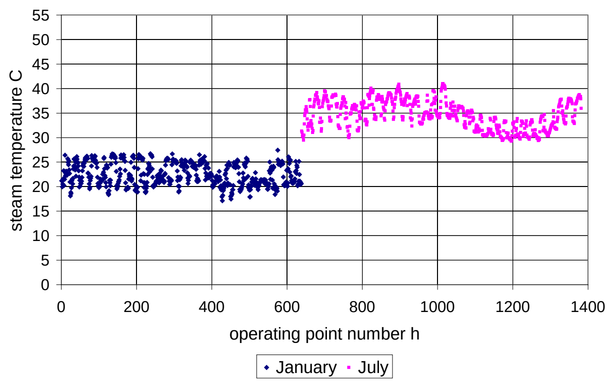

Figure 9. Change in the steam temperature (pressure) in the condenser in January and July

Following the increase in the steam temperature in the condenser, the steam in the LP part of the turbine expands to a higher pressure, so the enthalpy drop is smaller (Figure 10). At the same time, smaller losses are generated in particular groups of stages, resulting in an increase in the efficiency of the LP part of the turbine (Figure 11). With the increase in the steam pressure, the quality (dryness) of the steam is also increasing (Figure 12). The values of the efficiency of the LP part of the turbine, presented in Figure 11, are relatively high, perhaps because of the way of balancing the whole turbine set, according to which the balance of the LP part is a closure of the entire turbine. The influence of changes in the cooling water parameters (including the inlet temperature according to Figure 8) on the steam condenser effectiveness is shown in Figure 13.

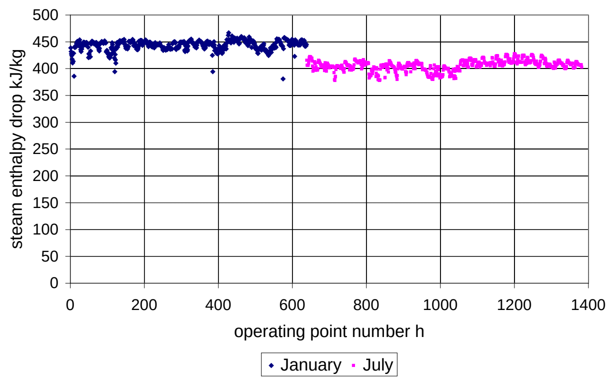

Figure 10. Steam enthalpy drop in the LP part of the turbine

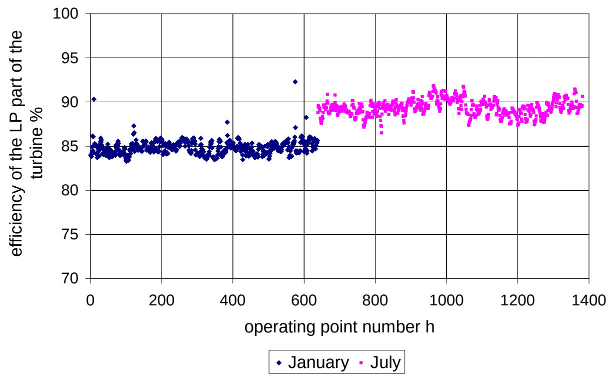

Figure 11. Change in the efficiency of the LP part of the turbine

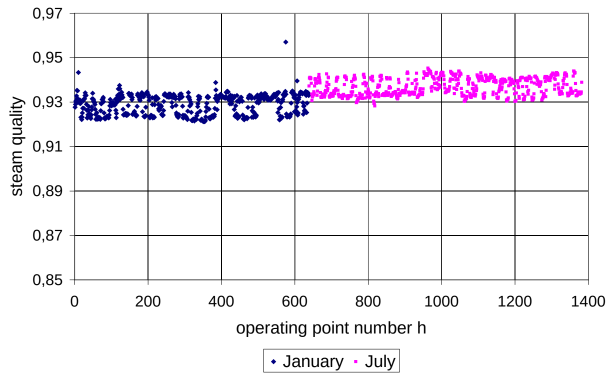

Figure 12. Change in the steam quality (dryness) at the outlet of the LP part of the turbine

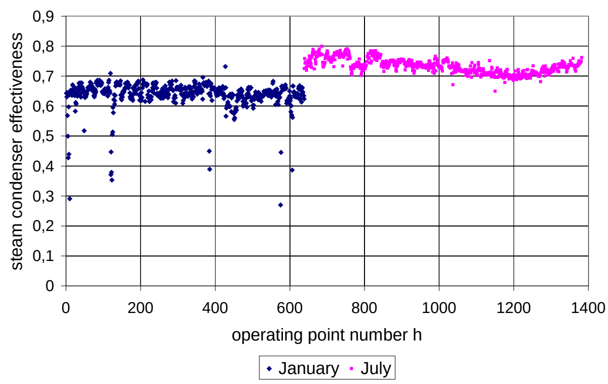

Figure 13. Change in the steam condenser effectiveness due to the increase in the cooling water inlet temperature

Figure 14 to Figure 16 present the changes in the performance of the steam condenser and the LP part of the turbine in the two periods. Figure 14 shows the change in the mass flow rate of steam flowing from the LP part to the steam condenser. The steam mass flow rate varied from 270 to 450 t/h, i.e. within 60 and 95% of the power range of the power plant. Figure 15 illustrates the change in the heat flow transferred in the condenser, and Figure 16 shows the change in the power of the LP part of the turbine, which varied from 30 to 55 MW. The nominal power of the LP part of the steam turbine is around 60 MW [10].

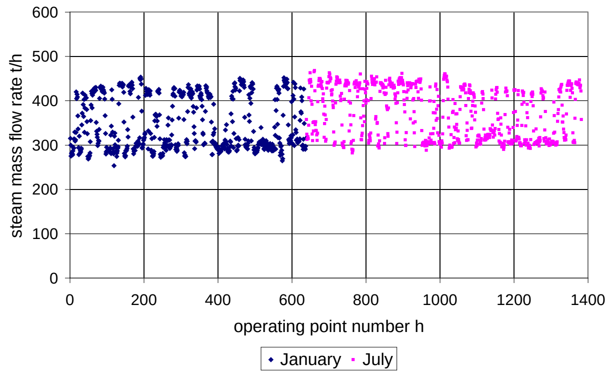

Figure 14. Change in the steam mass flow rate

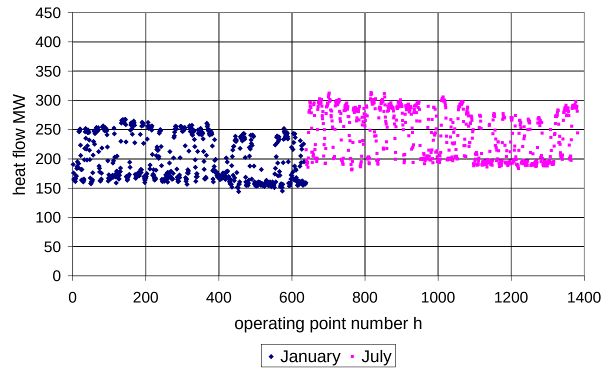

Figure 15. Change in the heat flow transferred in the steam condenser

According to the analysis carried out based on the data from the steam condenser simulator, the increase in the cooling water inlet temperature should cause a decrease in the heat flow transferred in the steam condenser (Figure 2). In contrast, in Figure 15 an increase in the transferred heat flow is observed, which can be explained by a slight increase in the steam mass flow rate (Figure 14); this corresponds to the second case for the data obtained from the steam condenser simulator (Figure 4). The final result of the increase in the cooling water inlet temperature (Figure 8) is a decrease in the actual power of the LP part of the turbine (Figure 16).

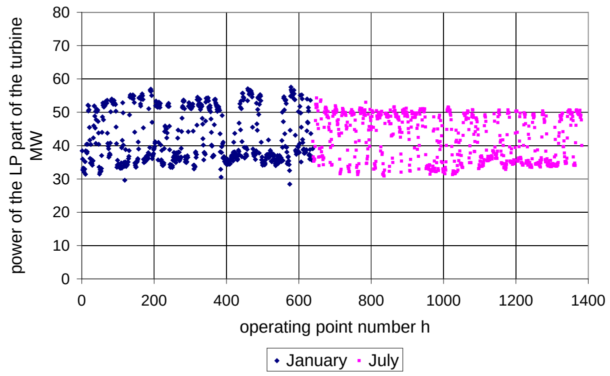

Figure 16. Change in the power of the LP part of the turbine

The power of the LP part of the turbine is

$$P_{LP} = \dot{m}_p \Delta h_s \eta_{LP} \tag{3}$$

where: Δh_s – isentropic enthalpy drop, η_{LP} – efficiency of the LP part of steam turbine.

By analysing the changes in the power of the LP part of the turbine (3), one can see that it mainly depends on the inlet and outlet parameters of the LP part of the turbine which are related to the working parameters of the steam condenser [18,19]. The steam pressure in the condenser is a function of the following parameters [15,16]:

$$P_{LP} = f\left(\dot{m}_p, p_\alpha, T_\alpha, p_h\right), \; p_h = f\left(T_{c1}, \dot{m}_w, \dot{m}_p\right) \tag{4}$$

where: p_α, T_α – inlet steam pressure and temperature to the LP part, of steam turbine.

Assuming that the steam pressure and temperature at the inlet to the LP part of the turbine and the cooling water mass flow rate vary within a narrow range, one can finally write

$$P_{LP} = f\left(T_{c1}, \dot{m}_p\right) \tag{5}$$

The power of the LP part of the turbine as a function of these two parameters with indicated trend lines is presented in Figure 17. The increase in the cooling water temperature at the inlet to the steam condenser of about 10°C causes a decrease of around 5 MW in the power of the LP part of the turbine. The power of the LP part of the steam turbine is a linear function of the steam mass flow rate [18,19], which is confirmed in Figure 17. Directional coefficients of the trend lines of the two months analysed, January and July, are similar in value, which implies that the power of the LP part of the turbine is also a linear function of the cooling water temperature at the inlet to the condenser.

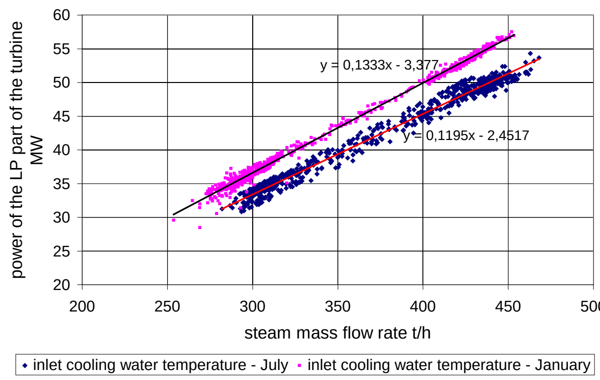

Figure 17. Power of the LP part of the turbine as a function of the cooling water temperature at the inlet to the condenser and the steam mass flow rate

Therefore, it is proposed to provide the power of the LP part of the turbine as a linear function with respect to the steam mass flow rate and the inlet cooling water temperature to the condenser in the form

$$P_{LP} = a_1 \dot{m}_p + a_2 T_{c1} + a_3 \tag{6}$$

The coefficients in the equation (6) were determined by means of the least squares method. A comparison between the power of the LP part of the turbine as obtained from DCS and calculated from the proposed equation (6) is presented in Figure 18. Points in Figure 18 are arranged along a straight line $y = x$, which indicates a good accuracy and correctness of the proposed equation (6).

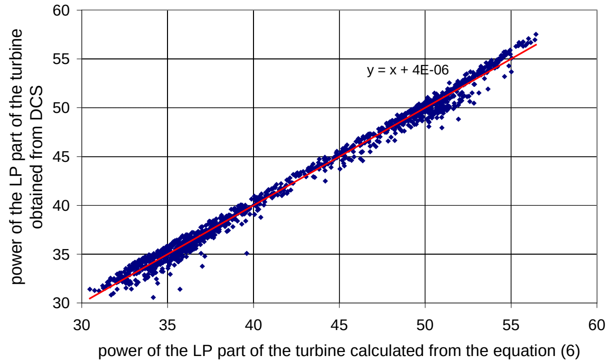

Figure 18. Comparison between the power of the LP part of the turbine as obtained from DCS and calculated from the equation (6)

4. Conclusions

The changes in water-side parameters affect the characteristic parameters which describe the condenser performance, such as the effectiveness, the transferred heat flow, and the steam pressure, which has a significant influence on the performance (efficiency and power) of the LP part of the turbine.

Based on the data obtained from the steam condenser simulator, changes in the condenser effectiveness, the transferred heat flow, and the steam pressure in the condenser were analysed for three cases: for the change in the cooling water temperature at the inlet to the condenser, for the change in the cooling water mass flow rate, and for the change in the steam mass flow rate. The effect of these three parameters on the characteristic values that describe the steam condenser performance is presented in Table 1.

With the increase in the steam condenser effectiveness, an increase in the steam pressure and a decrease in the power of the LP part of the turbine is observed. This is the case when the water temperature at the inlet to the condenser is increasing, and when the steam mass flow rate is increasing. With the increase in the steam temperature/pressure, we can see some positive effects, such as an increase in the efficiency of the LP part of the turbine (Figure 11), and an increase in the quality (dryness) of steam (Figure 12), but also strongly negative effects, such as a lower actual drop in the steam enthalpy (Figure 10) leading to the lower power of the LP part of the turbine (Figure 16). Thus, according to the authors, the steam condenser effectiveness is not a good parameter to describe the performance of the steam condenser nor the system comprising the steam condenser and the LP part of the turbine. Such a parameter, however, may be the proposed efficacy of the steam condenser δ whose increase means better vacuum (Table 1).

Table 1. Effect of the change in the inlet cooling water temperature, and the steam and cooling water mass flow rates on the characteristic values describing the performance of the condenser

Parameter	Heat exchanger effectiveness ε	Heat flow $\dot{Q}$	Pressure in the steam condenser p_h	Efficacy of the steam condenser $\delta=(1-\varepsilon)$
$T_{c1}\uparrow$	↑	↓	↑	↓
$\dot{m}_p\uparrow$	↑	↑	↑	↓
$\dot{m}_c\uparrow$	↓	↑	↓	↑

Moreover, for practical purposes, the relation (6) was given for the power of the LP part of the steam turbine as a linear function of the cooling water mass flow rate and its temperature at the inlet to the steam condenser with three constant coefficients.

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