The influence of air inflow in the vacuum system of a cogeneration steam turbine plant on its energy performance

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Abstract. The article considers the issue of the influence of air inflow in the vacuum system of a cogeneration steam turbine plant on its energy performance. The authors give a brief description of characteristics of a steam turbine condenser. On the example of the T-110/120 turbine plant, they estimate the power loss factor of a low pressure section (LPS) depending on air inflow in a vacuum system on a heat schedule operating mode with steam consumption of 20 t/h. The authors underline a significant influence of air inflow on the amount of power produced by the turbine plant. Moreover, the authors evaluate the power loss of LPS depending on air inflow in the vacuum system on one of the operation modes on the electrical schedule. They demonstrate that an increase in air inflow leads to quite large (hundreds of kilowatts) power losses.

1. Introduction and a mathematical model

One of the problems of long-term performance of steam turbines is deviations from the standard values of vacuum in their condensers. These deviations often happen due to long working hours of turbines and defects leading to increased air inflow in their condensers. Such inflow is especially characteristic for cogeneration steam turbines with an extended vacuum system [1-3]. Therefore, it seems relevant to find the direct connection of air inflow to the condenser with changes in power generated by low pressure sections (LPS) of turbine plants, and conduct a feasibility study of various operating modes on this basis.

The connection between the pressure in the condenser and the power generated by the plant is known and can be found in the scientific literature and regulatory and technical documentation [4-8]. However, these methods do not allow one to determine the direct effect of air inflow in a vacuum system on the energy performance of a turbine plant.

We propose a mathematical model of a condenser, which makes it possible to obtain dependences of the pressure in the condenser on the amount of air in the condensing steam [9-10]. This model was obtained as a result of an analysis of regulatory characteristics of condensers of cogeneration steam turbines, existing calculation methods for condensers [11–12], a generalized characteristic of variable modes of operation of a condenser [13], and experimental studies [1-3].

A distinctive feature of the proposed mathematical model is that it is based on the fact that the dependence of the saturation temperature at a condenser pressure on the flow rate of the steam \( t_c = f(D_c) \) can be represented as a linear function having a turning point with coordinates \( t_c^* \) and \( D_c^* \) (see. figure 1) The existence of two characteristic sections is explained by the interdependence between the pressure in the condenser and the suction pressure of the main ejector [14, 15]. During the operation of the condenser within the left branch of the characteristic, this relationship is most significant and has a great impact on the processes of heat and mass transfer.
**Figure 1.** Calculated characteristics of the condenser KG2-6200 of the turbine plant T-110/120-130. There is one ejector EP-3-200. The cooling water flow rate is $W = 16000$ t/h, the heat exchange surface is $F = 6200$ m$^2$, the purity coefficient $a = 0.7$.

- Condenser characteristics with standard air inflow $G_{\text{air}} = 15.8$ kg/h;
- Characteristic of the condenser with air inflow $G_{\text{air}} = 63.2$ kg/h;
- Conditional characteristics of the condenser during the condensation of pure steam.

During the operation of a condenser with steam loads corresponding to the right branch of the characteristic, the influence of the ejector on the pressure is minimal.

The mathematical model used in this work has been verified and has been successfully used for several TEPs for several years in solving practical problems. It allows one to calculate the pressure in the condenser for the given air inflow in the condenser within the working branch of the characteristics of the ejector.

**2. Research results and discussion**

Further we consider the method of finding the dependencies between air inflow in the vacuum system and the pressure in the condenser when steam passes into the condenser within the left branch of its characteristics using the turbine plant T-110/120-130.

Figure 1 shows the characteristics $t_c = f(D_c)$ of the condenser KG2-6200 of the turbine plant T-110/120-130 with two levels of air inflow into the condenser: a standard condenser ($G_{\text{air}} = 15.8$ kg/h) and a condenser four times higher ($G_{\text{air}} = 63.2$ kg/h).

The data presented in Figure 1 show that an increase in air inflow displaces the values of $D_c^*$ towards higher values, and almost all operating modes of the condenser become limited by the ejector at cooling water temperature $t_{1w} = 5$ °C.

Figure 2 shows the dependence of the pressure in the condenser as a function on the amount of air inflow to the condenser in the cogeneration steam mode with closed control diaphragms of low pressure parts with a total ventilation pass of 20 t/h.
Figure 2. Relationship between the pressure in the condenser KG2-6200 and the air inflow in the vacuum system when the turbine plant T-110/120-130 is operating in the cogeneration recovery mode. The cooling water flow rate is $W = 8000$ t/h, the heat exchange surface of the condenser is $F = 6200$ m$^2$. The regulating diaphragms of the low-pressure cylinder are closed, $G_{clp} = 20$ t/h. The pressure in the lower heat extraction is 100 kPa.

- the temperature of the cooling water at the inlet to the condenser $t_{lw} = 35$ °C;
- the temperature of the cooling water at the inlet to the condenser $t_{lw} = 20$ °C;
- the temperature of the cooling water at the inlet to the condenser $t_{lw} = 5$ °C.

Figure 2 shows that the effect of air inflow on the pressure in the condenser is quite significant. So, increasing the suction capacity of air by four times compared with the standard, the pressure in the condenser rises by $\Delta p_c = 1.27$ kPa at $t_{lw} = 35$ °C, by $\Delta p_c = 1.43$ kPa at $t_{lw} = 20$ °C and by $\Delta p_c = 1.54$ kPa at $t_{lw} = 5$ °C.

In this case to analyze the dependence of the power produced by the turbine plant on the size of air inflow in the vacuum system is of great interest. To achieve this goal, it is possible to use the mathematical model of the turbine plant T-110/120-130 [16], developed at the Heat Engineering and Hydraulics Department, Vyatka State University. A distinctive feature of this model [16] is an adequate calculation of the compartments of the LPS (24-25 and 26-27 steps). The calculation includes finding the steam flow rate through a closed SG LPS, determining the degree of opening of the SG (from 0 to 1 inclusive), determining the pressure behind the LPSG, taking into account the actual discharge characteristics of the compartment, obtained by calculation and experimentally. Figure 3 shows the dependence of the power generated by turbine steps of the low-pressure cylinder, depending on air inflow in the vacuum system.

Calculations show that in most cases LPS stages do not produce power and are in the ventilation mode. Their power is observed only at $t_{lw} = 5$ °C and if air inflow is less than 57 kg/h.
Figure 3. Relationship between the power generated by the turbine steps of the low-pressure cylinder of the turbine unit T-110/120-130 in the cogenerating mode on the size of air inflow into the vacuum system. The cooling water flow rate is \( W = 8000 \) t/h, the heat exchange surface of the condenser is \( F = 6200 \) m\(^2\). The regulating diaphragms of the low-pressure cylinder are closed, \( G_{clp} = 20 \) t/h. The pressure in the lower heat extraction is 100 kPa.

- the temperature of the cooling water at the inlet to the condenser \( t_{1w} = 35 \) °C;
- the temperature of the cooling water at the inlet to the condenser \( t_{1w} = 20 \) °C;
- the temperature of the cooling water at the inlet to the condenser \( t_{1w} = 5 \) °C.

A fourfold increase in air inflow, depending on the cooling water temperature, leads to the following power losses: \( \Delta N = 108 \) kW at \( t_{1w} = 35 \) °C, \( \Delta N = 208 \) kW at \( t_{1w} = 20 \) °C and \( \Delta N = 364 \) kW at \( t_{1w} = 5 \) °C.

As an example, we consider the dependencies of pressure and power generated by a LPS on air inflow in a vacuum system on the operating mode of the T-110/120-130 turbine plant according to electrical schedule with heat extraction selections and a steam flow rate in the low-pressure cylinder 80 t/h (see. Figures 4 and 5).

Figure 4. Relationship between the pressure in the condenser KG2-6200 from the air inflow into the vacuum system during the operation of the turbine plant T-110/120-130 in its mode of operation according to the electrical schedule. The cooling water flow rate is \( W = 16000 \) t/h, the heat exchange surface of the condenser is \( F = 6200 \) m\(^2\). The steam consumption in the low-pressure cylinder is \( G_{clp} = 80 \) t/h.

- the temperature of the cooling water at the inlet to the condenser \( t_{1w} = 35 \) °C;
- the temperature of the cooling water at the inlet to the condenser \( t_{1w} = 20 \) °C;
- the temperature of the cooling water at the inlet to the condenser \( t_{1w} = 5 \) °C.
Figure 5. Relationship between the power generated by turbine steps of the low-pressure cylinder of the turbine plant T-110/120-130 on the electrical schedule mode of operation, on the size of air inflow in the vacuum system. The cooling water flow rate is W=16000 t/h, the heat exchange surface of the condenser is F =6200 m2. The steam consumption in the low-pressure cylinder is Gclp = 80 t/h.

--- the temperature of the cooling water at the inlet to the condenser $t_{1w} = 35 \, ^\circ\text{C}$;
- - - - - - the temperature of the cooling water at the inlet to the condenser $t_{1w} = 20 \, ^\circ\text{C}$;
- - - - - - the temperature of the cooling water at the inlet to the condenser $t_{1w} = 5 \, ^\circ\text{C}$.

The data presented in Figure 4 show that in the considered mode, the effect of air inflow on the pressure in the condenser is weaker than in the case of operating modes with closed LPS diaphragms. It can be explained by a lower relative air content in the steam. In this case:

\[
\Delta p_c = 0.94 \, \text{kPa at } t_{1w} = 35 \, ^\circ\text{C},
\]
\[
\Delta p_c = 1.19 \, \text{kPa at } t_{1w} = 20 \, ^\circ\text{C} \text{ and } \Delta p_c = 1.42 \, \text{kPa at } t_{1w} = 5 \, ^\circ\text{C}.
\]

The results of calculations carried out on the mathematical model of the turbine plant T-110/120-130 show that the power generated by the turbine steps of the low-pressure cylinder is: with standard air inflow - from $N=1370 \, \text{kW at } t_{1w} = 35 \, ^\circ\text{C} \text{ – up to } N=4520 \, \text{kW at } t_{1w} = 5 \, ^\circ\text{C}$; with fourfold increased air inflow - from $N=970 \, \text{kW at } t_{1w} = 35 \, ^\circ\text{C} \text{ up to } N=3600 \, \text{kW at } t_{1w} = 5 \, ^\circ\text{C}$.

Figure 6 shows the dependence of the power loss with increasing air inflow into the vacuum system. The data show a significant increase in power losses of the turbine plant with an increase in air inflow in the vacuum system, reaching respectively at $t_{1w} = 35 \, ^\circ\text{C} \text{ – } \Delta N = 406 \, \text{kW}$, at $t_{1w} = 20 \, ^\circ\text{C} \text{ – } \Delta N = 707 \, \text{kW} \text{ and at } t_{1w} = 5 \, ^\circ\text{C} \text{ – } \Delta N = 928 \, \text{kW}$. It is equivalent to the additional consumption of reference fuel, respectively: $\Delta B = 109.6 \, \text{kg/h}$, $\Delta B = 190.8 \, \text{kg/h}$ and $\Delta B = 250.6 \, \text{kg/h}$.

Additional calculations show that in a number of operating modes of a turbine plant, power losses can reach significantly larger values than in this example: $t_{1w} = 35 \, ^\circ\text{C} \text{ – } 800 \, \text{kW}$, at $t_{1w} = 20 \, ^\circ\text{C} \text{ – } 1000 \, \text{kW}$, and at $t_{1w} = 5 \, ^\circ\text{C} \text{ – } 1100 \, \text{kW}$.

3. Conclusion

1. On the basis of a mathematical model of a condenser and a mathematical model of a turbine plant, the authors have proposed a method that allows to establish the interdependence between air inflow in the vacuum system of a turbine plant and the power produced by the turbine steps of the LPS.
Figure 6. Relationship between the increasing power losses in the low-pressure cylinder from air inflow into the vacuum system of the turbine plant T-110/120-130 on the operation mode according to the electrical schedule. The cooling water flow rate is $W=16000$ t/h, the heat exchange surface of the condenser is $F=6200$ m$^2$. The steam consumption in the low-pressure cylinder is $G_{clp}=80$ t/h.

- the temperature of the cooling water at the inlet to the condenser $t_{1w}=35$ °C;
- the temperature of the cooling water at the inlet to the condenser $t_{1w}=20$ °C;
- the temperature of the cooling water at the inlet to the condenser $t_{1w}=5$ °C.

2. On the example of the turbine plant T-110/120, the power loss factor of the LPS is estimated depending on air inflow in the vacuum system during the operation mode according to the heat schedule with steam consumption in the low-pressure cylinder of 20 t/h. The significant influence of air inflow in the range of their change from 15.8 to 63.2 kg/h on the amount of power produced by the turbo plant has been established. For example, when the temperature of the cooling water at the inlet to the condenser is $t_{1w}=35$ °C, the loss of electricity supply from the turbine per day can be up to 2500 kW·h, and at $t_{1w}=5$ °C – up to 8500 kW·h.

3. For the turbine plant T-110/120, the power loss factor of the LPS was estimated depending on air inflow in the vacuum system during one of the operation modes according to the electrical schedule. It is shown that with an increase in the air inflow, power losses are quite large and can reach hundreds of kilowatts. In this case, the maximum possible additional fuel costs will be:

- $\Delta B=109.6$ kg/h at $t_{1w}=35$ °C,
- $\Delta B=190.8$ kg/h at $t_{1w}=20$ °C and
- $\Delta B=250.6$ kg/h at $t_{1w}=5$ °C.

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