Investigation of Thermal Economicity of the Turbine During Operation of the Energy Block in the Modes With Variable Load

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Abstract. The maneuverable characteristics of the energy block with the K-1000-60/1500 turbine upon transition to regulation of power by the method of sliding pressure for inclusion the nuclear power plant (NPP) into operation in the variable schedule of electrical loads are determined. The methodical provisions for assessment of indexes of thermal economicity of the block upon transition to sliding pressure are developed, namely, the method of calculation of relative changes in specific heat and fuel consumption by the turbine. Based on the calculation of actual annual change in the heat and fuel consumption by the block, the model for definition of annual economicity of transition to regulation of power by the method of SP in the modes with variable load is received.

1. Introduction

Today Russia is among the countries seeking to develop rapidly nuclear power by means of the developed types of reactors (5% or more per year) and then at achievement of sufficiently high level of their operation to begin introducing fast reactors and implementation close fuel cycle. Therefore, NPPs with water-moderated water-cooled power reactors VVER-1000 are actively pursuing campaigns to extend the lifetime of energy blocks of this type by increase in their reliability and maneuverability.

The replacement of organic fuel by nuclear one causes the necessity of the attraction of larger share of NPPs in the covering of variable (peak) part of the schedule of electrical loads that demands from the NPP of increase in their maneuverability. Along with other measures for improving maneuverability it is important to choose the most economical way to regulate the power of NPP’s energy blocks. At the same time VVER-type reactors are the most adapted to work in the variable modes because of their good self-regulation. In the conditions of increasing propagation of throttling steam distribution in the wet steam turbines sliding pressure of the fresh steam of the second circuit can become important way of increasing of economicity during the work on the under loadings.

2. Problem definition

The purpose of the study is to determine maneuvering characteristics and to assess of economicity of the K-1000-60/1500 turbine during the operation of energy block in the variable mode.

Advantages of the method of sliding initial steam pressure during the operation of turbine in the variable modes are: increase in economicity of energy block due to the growth of thermal drop and efficiency of the high-pressure cylinder; in combination with throttling steam distribution the specific netto heat consumption decreases; the thermal and internal relative efficiency of the turbine increases; the heat costs for intermediate overheating decrease; energy is saved on the drive of the feed pump.
These advantages have turn impact on the manoeuvring characteristics of the turbine and in general on the block of the NPP, namely: maintaining of constant initial temperature of steam causes invariance of temperatures of the majority of the responsible elements of the turbine, this fact defines the possibility of rapid change in load; the durability of the heating and steam-lines surfaces going to the turbine due to less mechanical stress at partial loads increases; decrease of the conditions for heating the high-pressure cylinder, since the supply of steam is carried out around the entire circumference of steamer; decrease in cyclic stresses and unstable magnesia forces in the first-row blades that provides normal loading of the support bearing, acceleration of intake and reduction of start-up losses. According to [1], it’s also provided: undervoltage in the nodes of the reactor compartment; decrease in level of temperature of exhaust branch pipes; reductions in the frequency of overloads of the reactor; the possibility of more rapid exit from "iodine well" by the reactor.

Thermodynamically, the transition to sliding pressure leads to shift of the line of the steam expansion process in h-S diagram to the right. At the same time the isothermal difference of the turbine increases slightly and despite some increase in initial heat content of steam requiring greater amounts of heat costs per unit of steam consumption the specific heat consumption per unit of power is reduced.

In turbines having acute steam intermediate overheating temperature of the secondary superheated steam inevitably decreases with decreasing pressure (and saturation temperature) of fresh steam. The process of steam expansion in the flowing part of the turbine high-pressure cylinder at throttling steam distribution and with the method of sliding pressure is shown in figure 1.

Figure 1. The process of expanded steam in the high-pressure cylinder of the turbine at nominal and partial loads at throttling steam distribution and with the method of sliding pressure (dotted line-isotherm corresponds to = const)

At the nominal load of the turbine, the expansion process of the steam is represented by the line AB. When the load is reduced by throttling, the expansion process decreases to the right and is represented by the line CD. During the operation on CD, the steam pressure in front of the turbine must be reduced proportionally to decrease in its expenditure keeping the temperature of the steam in front of the turbine moving along this isotherm to isobar (sliding) and arriving at point E with more enthalpy than in point C. Thus, comparing expansion process of the steam in the high-pressure cylinder of the turbine at partial loads, it’s visible that both the initial and final enthalpies are larger with controlling by sliding pressure. The gain in economicity upon transition by the method of sliding pressure is reached generally due to two factors: increase in the power of the high-pressure cylinder and decrease in the power developed by the turbo-pump [1-3]. In the process of transition to sliding pressure and, therefore, in the process of steam pressure decrease in front of and behind the high-
pressure cylinder, the available heat difference decreases at the same value of the internal relative efficiency of the high-pressure cylinder that leads to increase in the used heat difference. At the same time, the heat costs for intermediate overheating are reduced due to a change in its expenditure. The accounting of the power developed by the turbo-pump is defined based on the principle of load regulation by sliding pressure of the double-circuit NPP, which is carried out by change of the pressure of the feed pump in the presence of regulated turbine drive [2].

3. Results
The assessment of economicity of the turbine in the variable modes at throttling regulation of load and at regulation of load by the method of sliding pressure was carried out according to the absolute specific heat consumption of the turbine.

Absolute specific heat consumption for the turbine (netto) is determined by the following analytical dependence:

$$q^e_t = \frac{Q_0 + \Delta Q_1 + \Delta Q_2 + \Delta Q_3}{N_s}, \text{ MW/MW}$$

(1)

where $Q_0$ - the specific heat consumption of the turbine under the appropriate regime, MW (is determined from the calculation of the thermal scheme and from taking into account reducing of load); $\Delta Q_1$ - the change in the specific heat consumption per the turbine due to the change in the power of the feed pump. It is determined from the dependence:

$$\Delta Q_1 = D_{fp} \cdot V \cdot (p_{fp} - p_{ip}) \eta, \text{ MW},$$

(2)

where $D_{fp}$ - the specific feedwater consumption, kg / s; $V$ - average specific volume of water at the inlet and outlet $V=0,0011\text{m}^3/\text{kg}$; $p_{fp}, p_{ip}$ - inlet and outlet water pressure, MPa. With throttling regulation, this pressure remains constant, with controlling by sliding pressure it varies in proportion to the change in load. $\eta = 0,82$ hydraulic efficiency of the pump; $\Delta Q_2$ - the change in the specific heat consumption per the turbine due to the change in steam enthalpy in front of the high-pressure cylinder. It is determined from the dependence:

$$\Delta Q_2 = D_{0p} \cdot \Delta h_0, \text{ MW},$$

(3)

where $D_{0p}$ - specific steam consumption per the turbine, kg/s; $\Delta h_0$ - increase in steam enthalpy in front of the high-pressure cylinder, KJ / kg; $\Delta Q_3$ - the change in the specific heat consumption per the turbine due to increase in steam enthalpy behind the high-pressure cylinder and to heat reduction for intermediate overheating. It is determined from the dependence:

$$\Delta Q_3 = D^{src}_{0p} \cdot \Delta h_{HPC}, \text{ MW},$$

(4)

where $D^{src}_{0p}$ - the specific steam consumption for intermediate overheating at nominal conditions, kg/s; $\Delta h_{HPC}$ - increase in steam enthalpy behind the high-pressure cylinder, KJ / kg; $N_s$ - the received power of the turbine.

The economic efficiency of the turbine upon transition to the sliding pressure is estimated by the relative change of specific heat per turbine $\delta q^e_t$, the relative change of specific fuel consumption at $\delta h_0$, the actual annual decrease in fuel consumption for electricity generation and the annual effectiveness of transition to sliding pressure during the work in variable mode.

The relative change of specific heat per the turbine with the use of sliding pressure will be:

$$\delta q^e_t = \frac{q^e_t - q^e_{sp}}{q^e_t}$$

(5)

The relative change of specific fuel consumption upon transition to sliding pressure will be:
\[ \delta b_y = \frac{\delta d^t_q}{\eta_c}, \quad (6) \]

where \( \eta_c = \eta_{mp}^o \cdot \eta_{mp}^r \cdot \eta_{mp} \cdot \eta_{mp} \) - efficiency of the station.

The annual efficiency of the transition to sliding pressure during the work in variable mode will be:
\[ \Delta E'_e = \Delta B'_y \cdot Co, \quad (7) \]

where \( \Delta B'_y \) - the annual decrease in fuel consumption; \( Co \) - fuel cost.

According to the above methodological provisions the assessment of thermodynamic indexes of the block of the K-1000-60/1500 turbine is carried out during the operation in the variable modes. The calculations of the specific heat consumption are carried out at throttling regulation and at regulation of the block’s power by the method of sliding pressure. The results of the calculations are presented in Tables 1-3.

### Table 1. The calculation of economicity of the turbine at throttling regulation

| Index | Dimension | Variable power mode (in shares) |
|-------|-----------|--------------------------------|
| \( \Delta Q_1 \) | MW | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  | 1      |
|       | | 28.27 | 33.92 | 39.58 | 45.23 | 50.89 | 0     |
| \( \Delta Q_2 \) | MW | 121.2 | 107.7 | 94.23 | 71.79 | 40.38 | 0     |
| \( \Delta Q_3 \) | MW | 0.2156 | 0.2102 | 0.185 | 0.152 | 0.097 | 0     |

### Table 2. The calculation of economicity of the turbine at regulation by the method of sliding pressure

| Index | Dimension | Variable power mode (in shares) |
|-------|-----------|--------------------------------|
| \( \Delta Q_1 \) | MW | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  | 1      |
|       | | 13.83 | 20.33 | 28.08 | 37.07 | 47.08 | 0     |
| \( \Delta Q_2 \) | MW | 90.19 | 88.88 | 70.08 | 59.58 | 30.98 | 0     |
| \( \Delta Q_3 \) | MW | 0.3324 | 0.3234 | 0.2992 | 0.2242 | 0.2336 | 0     |

### Table 3. The change in economical upon transition from throttling regulation to throttling regulation with sliding pressure

| Index | Dimension | Variable power mode (in shares) |
|-------|-----------|--------------------------------|
| \( \delta q^c_e \) | % | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  | 1      |
|       | | 1.614 | 1.297 | 0.818 | 0.271 | 0.116 | 0     |
| \( \delta b_y \) | g / kWh | 4.966 | 3.989 | 2.518 | 0.834 | 0.358 | 0     |
| \( \Delta B'_y \) | kg / h | 2.979 | 2.872 | 2.116 | 0.801 | 0.386 | 0     |
| \( \Delta B'_y \) | kg / year | 464.77 | 448.02 | 330.01 | 124.98 | 60.23 | 0     |
| \( \Delta E'_e \) | million rubles / year | 14.873 | 14.337 | 10.561 | 3.999 | 1.928 | 0     |

Apparently from the carried-out calculations (table 1-3) the absolute values of heat consumptions and specific heat consumptions are lower at regulation of power of the block by the method of sliding pressure that allows to make a conclusion that the fuel consumption per the installation is reduced. The calculation of the change in the economicity of the block showed that the gain from the transition to sliding pressure that is higher than more deeply unloading of the block on power. Thus, with the
block power $\bar{N}=0.9$ the relative indexes of economicity is: $\delta q^t = 0.116$, $\delta b_e = 0.359$ g / kWh, $\Delta E_e = 1.928$ million rubles / year, and with the block power $\bar{N}=0.5$ these indexes reach their maximum values: $\delta q^t = 1.614$, $\delta b_e = 4.969$ g / kWh, $\Delta E_e = 14.873$ million rubles / year.

The gain established in this work in thermal economicity allows to judge that the method of sliding pressure can find application at regulation of power of the double-circuit NPPs. However at the same time it is necessary to conduct in more detail a research on examination and estimates of the changes arising in work of reactor part of the scheme.

4. Conclusions

1. Increase in economicity of energy blocks of the NPP during the operation at partial loads can be reached by using sliding pressure of fresh steam. Increase in economicity in this case is achieves due to the growth of thermal difference and efficiency of the high pressure cylinder, to decrease of heat costs for overheating and to saving energy on the drive of the feed pump;

2. The change in the heat consumption per the turbine due to the change in the power of feed pump, to the change in the heat consumption per the turbine, to increase in steam enthalpy in front of the high pressure cylinder, to increase in steam enthalpy behind the high pressure cylinder and to decrease in heat for intermediate overheating is defined;

3. The assessment of economic efficiency of the turbine upon transition to sliding pressure is carried out.

References

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