EFFICIENCY OF OPERATION OF 300 MW CONDENSING THERMAL POWER BLOCKS WITH SUPERCRITICAL STEAM PARAMETERS IN SLIDING PRESSURE MODE

by

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The previous research of the application of sliding pressure has shown certain advantages in the operation of high-power condensing blocks with supercritical steam parameters in sliding pressure mode in comparison to the one with constant pressure. The maintenance of stable temperature regime and thermal expansion of turbine elements, prolongation of service life of materials of steam pipes and heating surfaces of the boiler due to the decrease in pressure of the working medium are only some of those advantages. On the other hand, the operation mode of a condensing block with sliding pressure is characterized by the change in cost-effectiveness. The result of this change is mainly due to the decrease of steam throttling in the turbine's balancing valves and the increase of its internal action in a high pressure turbine, then also due to reduced steam consumption of the feed turbo pump just like a drop in the feed water pressure at the steam boiler inlet. A model has been developed within the framework of this study that follows such changes and their graphical interpretation is provided. The analysis results show that switching 300 MW blocks from the constant to the sliding pressure regime in the 30-60% load range increases the block efficiency respectively by 6.70-1.05%.

Key words: *supercritical steam parameters, sliding pressure mode, mathematical model, assessment of efficiency*

Introduction

Non-stationary operating conditions determine turbine characteristics with regards to regulation. They are divided into those occurring in normal exploitation and those occurring in emergency conditions, when, due to the activation of the protection system, the steam turbine gets abruptly switched off [1]. During the exploitation of steam turbines, a controlled or spontaneous change of one or more drive parameters may occur, which will also result in the change of value of the remaining parameters. If steam turbines are intended to drive of electric generators, the basic task of the steam turbine regulation process is the automatic adjustment of the number of revolutions in each loaded machine, with as little difference as possible from the normal drive revolution number, which should have a parallel fitting with other ma-

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chines when idle and the ability to achieve any load in the course of unchanged frequency in the transmission grid, as well as prevention of the increase of revolution number beyond the limit value of the safety regulator when there occurs abrupt relief (turbine runaway) [2].

One of the major requirements for the operation of thermal power plant blocks is a sufficiently wide regulation spectrum of loads, which is equally dependent on maximal and minimal load that the block can safely operate with. The research related to minimal load that has been done by now has shown the necessity for additional modeling and analyzing the load decrease by regulating a block with sliding or combined pressure. Also, during the launch, the block should operate with sliding steam parameters. Therein, high safety and maneuverability must be maintained, with the time necessary to launch the block being as short as possible. Important criterion of the launch is the loss of fuel, so that particular attention is being paid to the analysis and introduction of rational methods when starting the blocks [3].

The analysis of the problem of sliding pressure application has revealed the advantages of large power blocks operating with sliding steam parameters. In operating regimes with nominal pressure of steam maintained in front of main valves, load decrease is achieved by closing turbine regulation valves, which worsens its maneuver properties, safety and efficiency [4, 5]. Owing to this, the operating regime with nominal pressure nowadays is used mostly for blocks which are not able to operate with sliding pressure. Also, due to safety reasons associated with boiler heating surfaces, the block with sliding pressure can very often reliably operate up to a particular loading [2, 6].

The analysis of previous research regarding the application of sliding pressure in high-power energy blocks (installed power greater than 200 MW) shows certain advantages such as maintaining stable temperature regime and thermal dilatation of turbine elements, extending life span of steam pipeline materials and life span of boiler surfaces due to the decreased pressure of the medium [7]. On the other hand, the introduction of sliding pressure is also related to certain problems, which mostly relate to safety of boiler operation (unallowable heat and hydraulic non-linearities in boiler screens, problems with circulation in boiler panels or coils, worsening operation safety of small screens of the boiler, and boiler failure) [8]. The previous research concerning this matter has shown that higher power blocks with supercritical pressure can optimally use turbines with nozzle steam distribution, where the block operates with constant pressure of fresh steam in the range of high loads (up to 0.7-0.9 of nominal) whereas, in the range of lower loads, it operates with sliding pressure of fresh steam with completely open regulation valves of turbines [5].

In turbine blocks with 300 MW nominal power, the analysis of sliding pressure regime, together with its operation, is conducted with first four regulation valves completely open for loads from 220-240 MW [8]. When the block load decreases in sliding pressure regime, the pressure in the whole tract of the boiler decreases, along with the change of hydraulic characteristics of the panel, temperature regime of boiler screens and boiler operation regime as a whole, which requires additional special research [3]. With partial loads, the decrease in steam pressure in front of the turbine leads to the decrease in available heat drop in comparison to state of the steam in front of the main valves and behind the high-pressure cylinder (HPC) [9]. In order to determine the most economical manner of power regulation, it is necessary to analyze thermodynamic efficiency of the plant with various regulation programs. Since the change of power regulation program does not influence energy losses in the turbine bearings and the generator and consequently does not influence the mechanic efficiency of the turbine and the efficiency of the generator, to analyze the block efficiency with different power regulation programs, the research must focus on the change of efficiency of the thermodynamic cycle, the internal efficiency of the turbine, the coefficient which involves the impact of regenerative heating of feed water and the coefficient of its energy consumption [4].

At the beginning of the 1930s methods were elaborated for the power regulation in turbo-generators under the changeable (sliding) pressure of fresh steam and completely open regulation valves. In the middle of the 20th century there were already plants comprising high-power energy blocks with the application of sliding steam pressures [3, 10].

Analysis of Regulation of K-300-240 (LMZ) steam turbine operation within the Republic of Srpska Electric Power System

The basic scheme of condensing 300 MW block is given in fig. 1. The blocks in the Republic of Srpska (TPP Ugljevik and TPP Gacko) also have similar schemes [3].

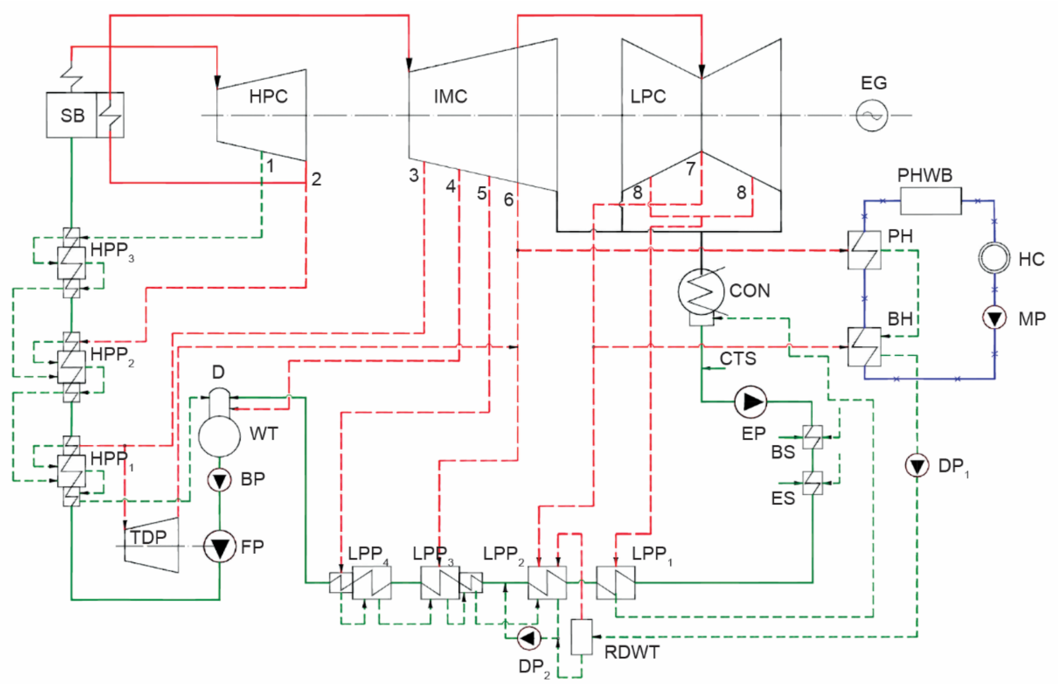

Figure 1. Scheme of condensing TPP with K-300-240-3 LMZ [3]; *SB – steam boiler, HPC – high pressure cylinder, IMC – intermediate pressure cylinder, LPC – low pressure cylinder, EP – extraction pump, CTS – chemical treatment station, RP – reprise pumps, D – deaerator, WT – water tank, LPP – low pressure feed water heater, FP – main feed water pump, DP – drainage pump, TDP – turbo drive pump, HPP – high pressure supply water heater, EG – electric generator, CON – condenser, PHWB – pic hot water boiler, BS – basic sealing, ES – ejector steam, PH – pic heater, BH – basic heater, HC – heating consumer, MP – main pump, BP – boiler pump, RDWT – reservoir of drainage water tank*

These thermal power plants were the only ones at the territory of former Yugoslavia with supercritical steam parameters. Table 1 presents the main parameters of this type of condensing thermal power plant with K-300-240 LMZ steam turbine. The HPC, fig. 1, that is an integral part of the K-300-240 turbine, has a regulation stage, and then follows a group of five stages in the internal part of the casing and six stages in which steam enters after the 180° turn.

Table 1. Condensing TPP with K-300-240-3 LMZ main parameters [3]

Parameter	Mark	Values
Theoretical consumption of heat for production of electric power	q_t	3600 kJ/kWh
Specific increase of the turbine heat consumption in the work of the basic feed pump and constant flow of the cooling water with the temperature of 12 °C	q	7994 kJ/kWh
Heat consumption in the idling speed of the turbine	Q_0	82.6 GJ/h
Efficiency coefficient of heat flow for the block loads that correspond to the sliding pressure regime	η_k	0.93-0.95
Coefficient of the change of extraction power, *i. e.* the coefficient of the steam power change for the first heater behind the feed pump	η_{tt}	0.985-0.970
Gross efficiency coefficient of the boiler plant for the block loads that correspond to the sliding pressure regime	e	0.34
Damping coefficient for the turbo-drive OR-12 pM KTZ, under the steam flow of 40% of the nominal one, switching to the sliding pressure regime is performed by decreasing (fig. 2, line 2)	γ_{pr}	0.889-0.7

Such approach could also be applied to this stage group (5+6), while a significantly lower steam pressure in the regulation chamber could be taken as the entrance pressure in front of the nozzles. That is also a reason why more consideration is given to the thermal process in nozzle (quantity) regulation of K-300-240 turbine, which is built in our thermal power plants.

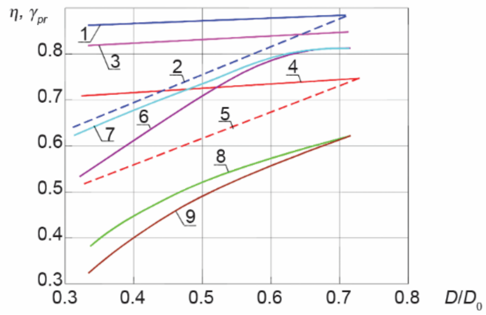

Figure 2. Changing the efficiency of the 300 MW turbo-drive power in TPP Ugljevik and TPP Gacko, as well as the damping coefficient [3, 7]; *1, 2 – damping coefficient for the turbo-drive OR-12 pM KTZ at constant (line 1) and sliding (line 2) pressure, 3 – internal relative efficiency of the turbo-drive flow section, 4, 5 – internal relative efficiency of turbo-drive at constant (line 4) and sliding (line 5) pressure, 6, 7 – efficiency of power plants at constant (line 6) and sliding (line 7) pressure, 8, 9 – efficiency of feed pump at constant (line 8) and sliding (line 9) pressure*

The change of K-300-240 turbine load with the steam flow of less than 67% of the nominal flow is conducted by steam dampening at the regulation valves number 1-4, fig. 3. The necessity of steam throttling under the flows lower than 177 kg/s, along with the decrease of the nominal pressure in front of the turbine, is conditioned by the safety of working blades of the turbine regulation stage, as well as by the need for maintenance of the stable temperature regime HPC under the equations change.

Comparative assessment of the efficiency of a turbine plant at the transfer to the regulation by sliding pressure, compared to the similar regime of regulation by regulating and throttling valves with the constant pressure of fresh steam (expansion line $AB_1C_1E_1$ in fig. 4) is given based on the example of the condensing turbine K-300-240, whose process of steam expansion in HPC is presented in fig. 4.

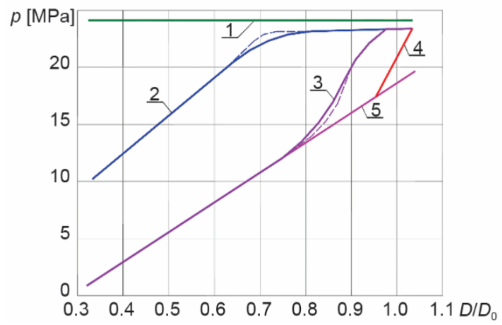

Figure 3. The HPC steam distribution diagram of the turbine K-300-240 [3, 11]; *1 – steam pressure in front of the turbine, 2 – steam pressure behind control valves No. 1-4, 3 – steam pressure behind control valves No. 5 and 6, 4 – steam pressure behind control valves No. 7, 5 – steam pressure in the control chamber*

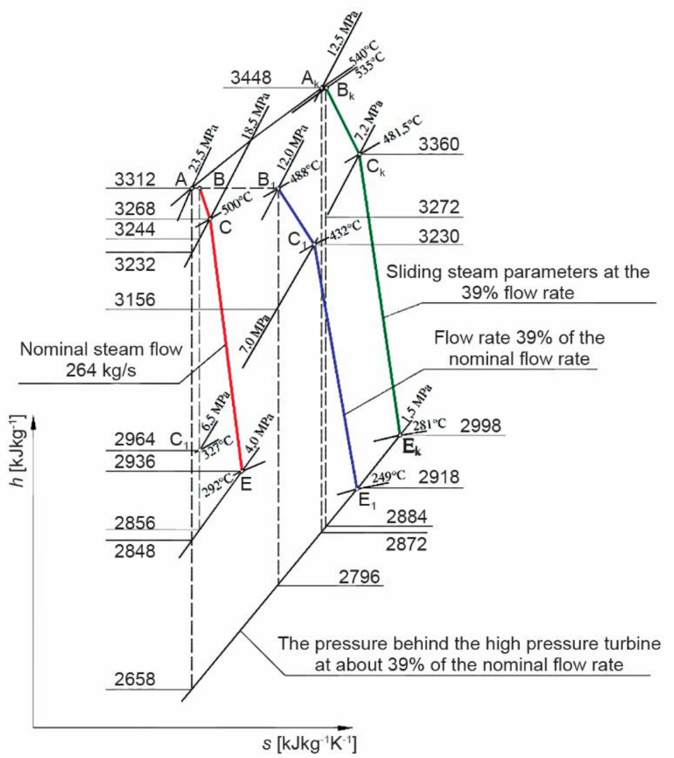

Figure 4. The h-s diagram for steam expansion process in HPC of the turbine K-300-240 [5, 11]; *ABCE – at the nominal regime, $AB_1C_1E_1$ – for the steam flow at 39% of the nominal (103 kg/s) and constant initial pressure before the steam turbine, $A_kB_kC_kE_k$ – steam flow at 39% of the nominal with sliding initial pressure, BC_1' – is the isentropic enthalpy drop at the regulatory level of nozzle distribution of vapor flow rate and 39% of nominal vapor flow*

It is the case of the energy block with supercritical steam parameters and steam superheating. Transition to the turbine operation regime with sliding pressure is presented by the line $A_kB_kC_kE_k$ with the steam flow of 39% of the nominal one in fig. 4. Steam parameters in front of the turbine are 12.5 MPa and 540 °C with enthalpy of 3448 kJ/kg. Steam pressure and temperature in front of the regulation (first) stage amounts to 12.3 MPa and 535 °C, of course with the same enthalpy, with throttling by a regulation valve amounting to around 0.2 MPa. Isentropic heat drops with the steam status in front of the stop valves amounts to 576 kJ/kg, and in front of the regulation stage 564 kJ/kg. Isentropic and used heat drops of the regulation stage amount to 176 kJ/kg, *i. e.* 88 kJ/kg, so that the internal efficiency coefficient of the regulation stage is increased to 0.487-0.5. The used heat drop in HPC reached the value of

450 kJ/kg, which is 56 kJ/kg more than in the regime with constant steam pressure in front of the turbine. Analyzing the diagram in fig. 4, we may also observe some other interesting characteristics in the regime with sliding pressure: steam temperature at the exit from HPC increased to 249-281 °C, internal efficiency coefficient increased to 0.763-0.798 which is connected with the increase of volume flow at the increased temperature in the streaming part of HPC, and internal efficiency coefficient of HPC amounts to 0.781 (fig. 5) [3, 5].

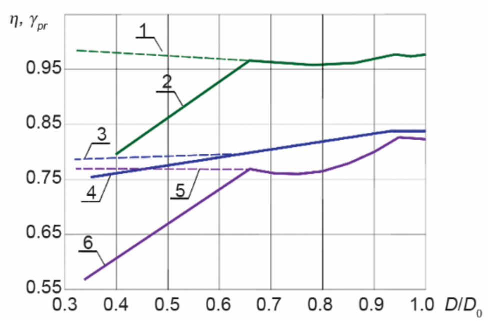

Figure 5. Internal efficiency coefficient η_{oi} and dumping coefficient γ_{pr} [11]; *1, 2 – dumping coefficient γ_{pr} at sliding (line 1) and constant (line 2) pressure, 3, 4 – internal efficiency coefficient of flow part η_{oi} at sliding (line 3) and constant (line 4) pressure, 5, 6 – HPC internal efficiency coefficient η_{oi} at sliding (line 5) and constant (line 6) pressure*

Mathematical model of efficiency for the steam block in the sliding pressure regime and results analysis

The changeable operating conditions also result in changing values of other driving parameters (change of velocity, reactivity, steam flow, degree of stage expedience, *etc.*), and the work of the turbine in such conditions represents changeable operating conditions of the steam turbine [10]. Since operation safety is one of the primary factors in the course of exploitation of steam turbines, stability in operations should be provided in all domains foreseen for functioning of the thermal steam turbines. In constant live steam pressure operation mode, steam pressure is maintained constant through variation of control stage admission section. In sliding live steam operation mode, the quantitative and qualitative control with control stages is aborted. In this case, inlet turbine areas remain constant, and the live steam pressures will naturally result, function of the live steam flows (turbine loads) [2]. The constant live steam parameter versus sliding live steam parameters is an old problem.

The main theoretical advantages of the second operation mode are pressure losses due to lamination disappearing and steam turbines internal efficiencies (including control stages) are high for different loads [2, 9]. Another advantage of sliding parameter operating mode is that efforts through high pressure components of steam turbines are reduced [2]. Using sliding parameter operating mode assures greater flexibility, faster transition between diverse loads compared to constant live steam operating mode, and metal fatigue into acceptable limits. The sliding live steam parameter operation was analyzed with a mathematical model which allows steam thermal circuit computation [5]. When switching to the regime of regulation of the steam turbine with sliding pressure, due to the increase of the used heat drop in the HPC, the increase of power amounts to $\Delta N = \Delta H\, D$, where ΔH represents the increase of the used heat drop (fig. 6), and D – flow of steam in the turbine. At the same time, the use of the turbine heat increases by $\Delta Q = q_t\, \Delta H\, D$, where q_t represents theoretical specific consumption of heat for the production of electric power.

In order to compensate for the increase of the turbine power by this value in the regime of constant pressure, the change of use of turbine heat should be:

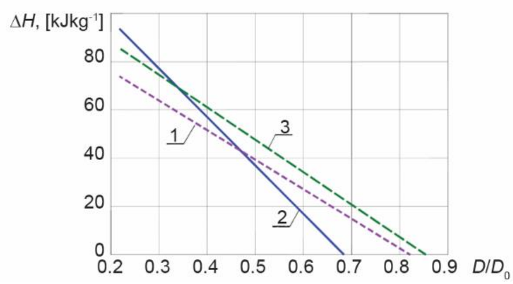

Figure 6. Increase of used heat loss in HPC [3, 11]; *1 – steam turbine K-800-240 LMZ, 2 – steam turbine K-300-240 LMZ, 3 – steam turbine T – 250/300-240 TMZ*

$$\Delta Q = q \Delta H D \tag{1}$$

where q is the specific heat consumption of the turbine.

The difference of consumption of the turbine heat for the same block power with the change of the program of regulation amounts to:

$$\Delta Q = (q - q_{\mathrm{t}}) \Delta H D \tag{2}$$

The overall consumption of the turbine heat in that case amounts to:

$$Q = Q_o + q N \tag{3}$$

where Q_o is the heat consumption in the idling speed of the turbine, and N – the block power.

The relative change of efficiency of the block in switching from the nominal to the sliding pressure is determined by:

$$\Delta q_1 = \frac{(q - q_{\mathrm{t}}) \Delta H D 100}{(Q_o + qN) \eta_k \eta_{\mathrm{tt}}} \tag{4}$$

where η_k is the gross efficiency coefficient of the boiler plant, and η_{tt} – the efficiency coefficient of heat flow.

The calculation according to eq. (4) shows that the efficiency increase of the 300 MW block due to the increase of utilization of heat drop consumption in the HPC of K-300-240 plant when switching from the constant to the sliding pressure for the steam flows by 60-30% of the nominal flow, amounts to 0.78-4.5%, respectively, fig. 7, line 2, [5].

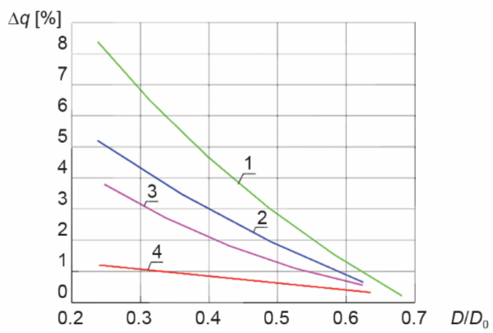

Figure 7. Change in efficiency in the 300 MW blocks in TPP Ugljevik and TPP Gacko when switching to the sliding pressure regime; *1 – total increase of efficiency; 2 – increase of efficiency due to the increase of internal steam work in the HPC; 3 – increase of efficiency due to the decrease of steam consumption for the turbo-drive of the feed pump; 4 – decrease of efficiency due to the decrease of water heating in the pump and increase of steam consumption in the high pressure heater (HPP$_3$)*

In changing the manner of regulation, a significant effect on the heat efficiency of energy blocks lies also with the change of energy consumption for driving the feed pump, as well as the change of efficiency of the regenerative heating of the feed water. Since the feed pump power is $Np = DH_p\eta_p^{-1}$, where D – the feed pump capacity (equivalent flow of steam in the turbine), H_p – the pump exertion, and η_p – efficiency coefficient of the pump. Neglecting the change of the water speed in the connections and geometric loss, the pump exertion amounts to $H_p = \Delta p_p \rho^{-1}$, where Δp_p is the difference in the water pressure in front and behind the pump, and ρ – the water density. The change of the feed pump power when the block switches to the work regime with the sliding pressure is conditioned by the decrease of exertion and change of the feed pump efficiency [5]:

$$\Delta N_p = D\left(\frac{H_p^{\text{con.pr}}}{\eta_p^{\text{con.pr}}} - \frac{H_p^{\text{sl.pr}}}{\eta_p^{\text{sl.pr}}}\right) \tag{5}$$

In case the good quality and efficiency of the pump exertion regulation is provided by the change of drive turbine revolution number in the blocks with the turbine drive of the feed pump, the effect of power decrease for the feed pump drive is realized to the full extent. In the course of unchanged feed pump capacity, the decrease of the number of revolutions causes the decrease of the pressure drop in the flow part, as well as of the losses due to friction. For those reasons, it is necessary to conduct the transfer of the block to the sliding pressure regime with partial loads by the increased efficiency of the feed pump. For the 300 MW nominal power blocks with the steam flow of 40%, a switch from the nominal to the sliding pressure brings about the increase of the feed pump efficiency by 0.6-0.67, fig. 2, which enables an additional loss in the block efficiency increase [11]. The decrease of energy consumption for compression of water in the feed pump leads to the decrease of feed water enthalpy at the entrance into the first heater behind the pump and to the increase of heat brought to the heater by the steam from extraction. The value of the additionally brought heat equals the change of power consumed by the pump and is determined by eq. (5).

The increase of steam flow through the heater causes the decrease of steam flow from the point of extraction to the condenser, *i. e.* the decrease of main turbine power by $\Delta N=\Delta N_p e$, where e is the coefficient of the change of extraction power. Since the process of steam expansion after the eventual superheating does not depend on the regime of block power regulation, the effect in the regime of sliding pressure on the change of the working conditions of the system of regenerative feed water heating lies only with the extractions on the HPC. According to the Stodol-Fliegel equation, steam parameters from the extraction with the unchanged consumption of turbine steam in the regime of sliding pressure meet the requirement [3, 11]:

$$\frac{p^{\text{con.pr}}}{p^{\text{sl.pr}}}\sqrt{\frac{T^{\text{con.pr}}}{T^{\text{sl.pr}}}} = 1 \tag{6}$$

where $p^{\text{con.pr}}$, $p^{\text{sl.pr}}$, $T^{\text{con.pr}}$, and $T^{\text{sl.pr}}$ are pressures and absolute steam temperatures from the extraction with the constant and sliding steam pressure, respectively.

The increase of steam temperature in the flow part of the HPC when switching to the sliding pressure regime brings about the increase of steam enthalpy from the extraction for the heaters. Under the unchanged steam pressure for heating, this will cause the decrease of its flow through the heaters, which, to a certain degree, lowers the efficiency of the system of regenerative heating of the feed water (heating of the feed water is realized to a greater extent at the cost of the heat for superheating the steam) [11]. Equally, the loss of heat in the condenser is also higher. At the same time, the increase of steam temperature in the flow part of the HPC, under the unchanged flow, results in the increase of pressure and temperature of the saturated steam for heating, and also accordingly to the growth of the feed water temperature behind the heaters. This contributes to the increase of steam consumption in the heaters and decreases the loss of heat in the condenser. The increase of the efficiency process of the regeneration system under the sliding pressure also contributes to the increase of feed water enthalpy under the decrease of the water pressure with the unchanged temperature.

The analyses conducted in the research presented in [5, 11] show that under the sliding pressure there is a slight decrease of the steam extraction for heating from the HPC, since the increase of steam enthalpy for heating is not fully compensated by the increase of the feed water enthalpy originating from the growth of steam pressure from the extractions and intensification of the heat exchange in the heat exchanger. The analyses conducted in the research presented in [1-6, 9-11] show that under the sliding pressure there is a slight decrease of the steam extraction for heating from the HPC, since the increase of steam enthalpy for heating is not fully compensated by the increase of the feed water enthalpy originating from the growth of steam pressure from the extractions and intensification of the heat exchange in the heat exchanger. Therefore, due to that, the decrease of the block efficiency under the load of 50% does not go beyond 0.03%, so that in practical engineering calculations this value cannot be completely neglected. Because of the changes in the working conditions of the system of regenerative heating of the feed water when switching from the regime with constant pressure to the regime with sliding pressure, change of the turbine power will be conditioned only by the increase of the quantity of heat brought by the heating steam in the first heater behind the feed pump. The drop of efficiency in doing so will be determined by:

$$\Delta q_2 = \frac{eD\left(\frac{H_{\rm p}^{\rm con.pr}}{\eta_{\rm p}^{\rm con.pr}} - \frac{H_{\rm p}^{\rm sl.pr}}{\eta_{\rm p}^{\rm sl.pr}}\right)q\cdot 100}{(Q_o + qN)\eta_k\,\eta_{\rm tt}} \tag{7}$$

The calculation by using eq. (7) shows that there is a decrease of efficiency of 300 MW block when switching to the regime of sliding pressure due to the increase of heat consumption in the first heater behind the feed pump with the steam flows of between 60% and 30% of the nominal flow, with the adequate value of 0.19-0.98%, fig. 7, line 3, [5, 11].

Under the decrease of the power consumed by the feed pump, there is also a decrease of flow through the turbo-drive pumps, and there is an increase of the steam flow through the stages of the basic turbine at the part from extraction to introduction of the used steam from the turbo-drive, during which the increase of the basic turbine power will be lower than the decrease of power for driving the feed pump due to the worsening of the internal relative efficiency coefficient of the turbo-drive and increase of the steam flow for heating through the first heater of high pressure. Worsening of the internal relative coefficient of turbo-drive efficiency is explained by the decrease of the damping coefficient $\gamma_{\rm pr}$, fig. 2, line 2. The internal relative efficiency coefficient of the turbo-drive flow part practically does not depend on the program of block power regulation and is located at the level of 0.88-0.82 in the load diagram for 100-40%. When switching from the constant to the sliding pressure, the internal relative efficiency coefficient of the turbo-drive flow part decreases to 0.715-0.565.

The change of power when switching from the constant to the sliding pressure regime also changes due to the increase of the steam flow through the stages of the part from extraction to introduction of the used steam from the turbo-drive. The decrease of the turbine power due to the extraction for the turbo-drive is determined according to:

$$\Delta N = N_{\mathrm{p}} \frac{\eta'_{oi}}{\eta_{oi}} \tag{8}$$

where η'_{oi} and η_{oi} are internal relative efficiency coefficients of the turbine part and feed pump turbo-drive.

It is important to point out that for the K-300-240 LMZ, T-250/300-240 TMZ, and K-800-240 LMZ turbines, the extraction of steam for the turbo-drive is performed from the IPC, whose η_{0i} practically does not depend on the steam flow and the power regulation program and is located at the level of 0.905-0.915, fig. 2, line 5, [5, 11].

When the block switches from the normal to the sliding pressure regime, eqs. (5) and (8) indicate that the increase of the turbine power is due to the decrease of the consumption of steam for the feed pump turbo-drive:

$$\Delta N = D\eta'_{oi}\left(\frac{H_{\mathrm{p}}^{\mathrm{con.pr}}}{\eta_{\mathrm{fp}}^{\mathrm{con.pr}}} - \frac{H_{\mathrm{p}}^{\mathrm{sl.pr}}}{\eta_{\mathrm{fp}}^{\mathrm{sl.pr}}}\right) \tag{9}$$

where η_{fp} is the efficiency coefficient of the feed plant, without mechanical losses $\eta_{\mathrm{fp}} = \eta_{oi}\, \eta_{\mathrm{p}}$, fig. 2, line 9, [5, 11].

The analysis of the change of efficiency coefficient of the feed plant shows that η_{fp} decreases when switching to the sliding pressure regime. When the steam flow is 42% of the nominal flow, η_{fp} of the 300 MW blocks decreases to 0.368-0.329 [5]. The decisive influence on weakening of η_{fp} lies with the decrease of γ_{pr} of the feed pump turbo-drive.

The increase of efficiency due to the decrease of turbo-drive steam consumption when switching to the sliding pressure regime is determined on the basis of:

$$\Delta q_3 = \frac{D\eta'_{oi}\left(\dfrac{H_{\mathrm{p}}^{\mathrm{con.pr}}}{\eta_{\mathrm{fp}}^{\mathrm{con.pr}}} - \dfrac{H_{\mathrm{p}}^{\mathrm{sl.pr}}}{\eta_{\mathrm{fp}}^{\mathrm{sl.pr}}}\right) q \cdot 100}{\left(Q_o + qN\right)\eta_k\, \eta_{\mathrm{tt}}} \tag{10}$$

The calculation according to eq. (6) shows that, when the 300 MW block with the turbine K-300-240 LMZ (manufactured by Leningradsky Metallichesky Zavod, Russia) switches to the sliding pressure regime, it brings about the increase of the block efficiency due to the decrease of the consumption of steam of the feed pump turbo-drive for the flows through the turbine of 60-30% of the nominal flow of the respective 0.45-3.2%, fig. 7, line 4.

The total change of the block efficiency when switching from the constant to the sliding pressure regime represents a sum of right-hand sides of eqs. (4), (7), and (10), taking into account the sign (positive or negative) of the effect of components on the change of efficiency:

$$\Delta q_{\mathrm{TOT}} = \Delta q_1 - \Delta q_2 + \Delta q_3 \tag{11}$$

Equation (11) shows that switching the 300 MW blocks with the turbines K-300-240 LMZ from the constant to the sliding pressure regime in the load range of 60-30% increases block efficiency respectively by 1.07-6.72%, fig. 7, line 1, [5, 11]. For example, LMZ under critical parameter steam turbine K-210-130 runs better with sliding parameter operation, the heat consumption being reduced by 1.6%, [2].

Conclusion

With throttling regulation, the efficiency coefficient decreases at lower steam flows due to throttling losses in the regulation valve. Therefore, we can say that the internal power of HPC in the regulation by sliding pressure is higher than in the throttling regulation. It is shown that the increase of the efficiency of the block operation in the sliding pressure regime originates at the cost of the decrease of steam damping in the regulation turbine valves and increase of the internal exertion of the steam in the HPC an decrease of the steam consumption for the drive of the feed turbopump. It is also shown that when switching to the sliding pressure regime with 300 MW block there is a slight decrease of the efficiency due to the decrease of water heating in the feed turbopump and increase of the steam flow through the regenerative HPP_3 by around 0.23-0.72%. It is established that the decrease of the block load will increase the efficiency gain when it operates in the sliding pressure regime. Therefore, in the load range of 40-80% of the nominal value, the gain amounts to 8-3%.

Nomenclature

D – steam flow, (equivalent feed pump capacity) [kgs^{-1}]
e – coefficient of extraction power change
H – the available heat drop, [$kJkg^{-1}$]
h – steam enthalpy, [$kJkg^{-1}$]
N – characteristic power, [kW]
p – steam pressure, [Pa]
Q – heat consumption, [kJh^{-1}]
q – specific increase of the turbine heat consumption, [$kJkW^{-1}h^{-1}$]
s – entropia, [$kJkg^{-1}K^{-1}$]
T – steam absolute temperature, [K]

Greek symbols

γ – throttling coefficient
Δ – difference of or relative change, [%]
η – efficiency coefficient

Superscripts

′ – steam status in front of the first stage of HPC
con.pr – refers to the work regime with constant pressure
sl.pr – refers to the work regime with sliding pressure

Subscripts

o, reg – nominal and regulated value of the parameters
oi – internal relative efficiency
fp – feed plant, without mechanical losses
p – pump
pr – for the turbo-drive OR-12 pM KTZ
t – thermal power, theoretical consumption of heat
TOT – total change
tt – heat flow

References

[1] Liu, W., *et al.*, Variable Condition Calculation Method for Thermal Power Units Sliding Pressure Operation, *International Journal of Computer and Electrical Engineering*, *5* (2013), 2, pp. 211-215
[2] Darie, G., *et al.*, Sliding Pressure Operation of Large Conventional Steam Power Units, *Proceedings*, WSEAS International Conferences: 5th IASME/WSEAS International Conference on Heat Transfer, Thermal Engineering and Environment (HTE '07), 5th IASME/WSEAS International Conference on Fluid Mechanics and Aerodynamics (FMA '07), Vouliagmeni, Athens, 2007, pp. 299-303
[3] Miličić, D., Milovanović, Z., *Steam Turbines*, Monograph Library, Energy Machines 3, Faculty of Mechanical Engineering, University of Banja Luka, Banja Luka, Republic of Serpska, B&H, 2010

[4] Shcheglyaev, A. V., Smelnitsky, S. G., *Regulirovanie Parovyh Turbin* (Regulation of Steam Turbines – in Russian), Gosenergoizdat, Moscow, 1962

[5] Milovanović, Z., *et al.*, Optimization of K-300-240 (LMZ) Steam Turbine Functioning under Changeable Operating Conditions within Republika Srpska Electric Power System, *Proceedings*, 18th Symposium on Thermal Science and Engineering of Serbia (Eds: M., Laković Paunović, M., Stojiljković), Sokobanja, Serbia, 2017, pp. 207-220

[6] Luo, X., *et al.*, Modeling and Optimization of a Utility System Containing Multiple Extractions Steam Turbines, *Energy*, *36* (2011), 5, pp. 3501-3512

[7] Trukhniy, A. D., *et al.*, *Atlas Konstrukciy Parovyh Turbin* (Atlas of Constructions of the Turbine Details – in Russian), Textbook for Universities, 3rd ed., MPEI Publication, Moscow, 2007

[8] Lezyerovich, A., S., *Steam Turbines for Modern Fossil Fuel Power Plants*, Taylor & Francis Group, CRC Press, New York, USA, 2008

[9] Jakovljević, I., Perčić, M., Dependence of Changes in Pressure of Superheated Steam upon Reducing Heat Drop in the Throttling Regulation of Steam Turbines, *Engineering Review*, *35* (2015), 2, pp. 205-210

[10] Souza, G. F. M., *Thermal Power Plant Performance Analysis*, 1th ed., Springer Series in Reliability Engineering, London, 2012

[11] Misak, J., Work with Sliding Pressure of Large Energy Blocks in Stationary and Start-up Regimes, Report No. 35, Power Utility of the Bosnia and Herzegovina, Mining and Thermal Power Plant Ugljevik, Ugljevik, Bosnia and Herzegovina, 1985

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