Efficiency of introducing a steam screw-rotor machine to the heating power plant circuit

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Abstract. The aim of the work is to increase the efficiency of the Nizhnekamsk CHPP-1 (combined heat and power plant) by introducing a steam screw-rotor machine (SSRM) into the thermal circuit. It is proposed to exclude the passage of steam from the exit of the turbine through the pressure reduction and desuperheating station (PRDS) for own needs. Superheated steam is diverted to be sent to a steam screw-rotor machine installed parallel to the PRDS. This technical solution will allow to obtain steam used in low pressure deaerators, as well as electricity for own needs of the CHPP. The article presents the operating parameters, as well as the calculation results of the backpressure turbine. A feasibility study was carried out for the introduction of SSRM into the plant's thermal circuit: the equivalent fuel and electricity savings for own needs were calculated, as well as the payback period of the project for introducing a steam screw-rotor machine. In the course of the calculations, the following results were obtained: a decrease in the specific consumption of equivalent fuel for the production of 1 kWh of electricity - by 1.9 g; saving of equivalent fuel during the implementation of the SSRM will be 13 tons per year, which also entails a reduction in emissions into the environment; Electricity production for own needs is 8100 kWh, the payback period for the project to introduce a steam screw machine in the thermal circuit of a thermal power plant is 5 years.

1 Introduction

The aim of the work to find out the possibility of parallel production of 0.12 MPa auxiliary steam at the Nizhnekamsk CHPP-1 and 1250 kW of electric energy with a frequency of 50 Hz supplied to the CHPP auxiliary electric bus. To achieve this goal, it is proposed to introduce a steam screw-rotor machine into the thermal circuit of the heating power station, as well as evaluate the economic effect of this technical solution [1-2].

Steam is used from the extraction of cogeneration turbines is used at the Nizhnekamsk CHPP-1 to obtain 0.12 MPa steam for heating demineralized water in low pressure deaerators (LPD). In winter, with a lack of extraction from these turbines, steam is used from

regulated industrial steam extraction of the counter-pressure turbine. Superheated steam passes after the turbine through a pressure reduction and desuperheating station PRDS 14/1.2 (the parameters are shown in Table 1) with its pressure and temperature reducing there. To exclude the steam reduction and to use the existed differential pressure, it is proposed to introduce a steam screw-rotor machine (SSRM) in parallel with PRDS 14/1.2. This technical solution will allow simultaneously receiving 0.12 MPa steam and 1,250 kW of electrical energy [3-7].

The SSRM is developed in Russia. It is a unique equipment without any foreign analogues. The design of the SSRM, its assemblies and systems is covered with about 25 patents in Russia and abroad [8].

Table 1. Technical parameters of the PRDS

Name	Rated capacity, t/h	Superheated/desuperheated steam parameters	
		Pressure, atm (MPa)	Temperature, degrees Celsius
PRDS 14/1.2	40	14/1.2 (1.4/0.12)	246/130

The steam screw-rotor machine (SSRM) is a volumetric rotary machine. According to its operation principle, it is an inverted dry screw compressor.

Structurally, the SSRM consists of a housing where two working bodies - rotors are located with sliding bearings, seals and other components and parts. The power unit

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consists of a steam screw-rotor machine (SSRM) and a generator connected through a compensating sleeve and installed on a concrete foundation with supports, the generator frame and base plates [9-12].
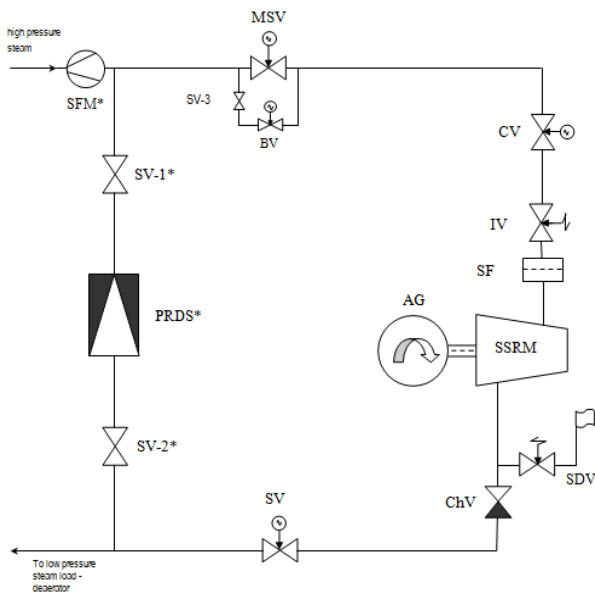

Fig.1. Thermal circuit if the SSRM
SSRM – steam screw-rotor machine, AG – electrical generator, CV – control valve, MSV – main steam valve, BV – bypass steam valve, SV – steam valve, IV – emergency isolation valve, ChV – check valve, SDV – steam dump valve, SF – steam filter, SFM – steam flow meter, PRDS – pressure reducing and desuperheating station

2 Methods

The used methods include computational mathematics, heat and mass transfer theory, methods of technical and economic calculations in the power energy industry, and thermodynamic analysis of power plants. Application software packages were used for calculations and plotting graphical dependencies.

A thermal calculation of the backpressure turbine was performed to determine the parameters of the steam at the inlet to the steam screw-rotor machine. The calculation followed the method presented in [13-15]. The calculation results are shown in Table 2.

Table 2. Steam parameters at the extraction stages

Control point	P_s, MPa	T_s, °C	h_s, kJ/kg
0 (steam parameters at the turbine inlet)	12.75	555	3485
0'' (steam parameters at the 1st turbine stage)	12.4	552	3485
1 (steam parameters in the 1st regenerative steam extraction)	3.03	353	3122
2 (steam parameters in the 2nd regenerative steam extraction)	1.95	299	3024
3 (steam parameters in regulated industrial steam extraction)	1.4	246	2926

The feasibility study of the SSRM implementation carried out in accordance with the following method:
Determination of SSRM electric power:

$$N_{el} = D \cdot (h_1 - h_2) \cdot \eta = 11{,}3 \cdot (2926 - 2741) \cdot 0{,}62 = 1273 \ \text{kW} \quad (1)$$

where
h_1 is steam enthalpy at the SSRM inlet, kJ/kg;
h_2 is steam enthalpy at the SSRM outlet, kJ/kg.
D is the steam flow rate thought the SSRM, kg/s.
Complete heat consumption for the turbine unit P-100-130/15:

$$Q_t = D_0 \cdot (h_0 - h_f) = 208{,}3 \cdot (3485 - 993{,}3) = 519021 \ \text{kW} \quad (2)$$

where
h_0 is steam enthalpy at the turbine inlet, kJ/kg;
h_f is feedwater enthalpy at the HPH, kJ/kg.

Heat consumption for the auxiliary loads when using the PRDS or SSRM:

$$Q_{pr} = D_p \cdot (h_{se} - h_d) - D_{PRDS} \cdot (h_3 - h'_{PRDS}) =$$
$$= 175{,}52 \cdot (2926 - 624{,}8) - 11{,}1 \cdot (2926 - 2741) = 401853 kW \quad (3)$$

Dpr is steam flow rate for the production, kg/s;
hse is steam parameters in regulated industrial steam extraction, kJ/kg;
hd is the feedwater temperature after the deaerator, kJ/kg;
DPRDS is the steam flow rate at the PRDS, kg/s;

Heat consumption of the power generating turbine using PRDS or SSRM:

$$Q_t^{el} = Q_t - Q_{pr} = 519021 - 401853 = 117168 \ \text{kW} \quad (4)$$

The efficiency factor of power generation when using PRDS:

$$\eta_{prds} = \frac{N_{el}}{Q_t^{el}} = \frac{111322}{117168} = 0.95 \quad (5)$$

The efficiency factor of power generation of the power unit when using PRDS:

$$\eta = \eta_{prds} \cdot \eta_{pg} \cdot \eta_{tr} = 0.95 \cdot 0.93 \cdot 0.986 = 0.87 \quad (6)$$

Specific consumption of equivalent fuel for power generation when using PRDS:

$$b_e^g = \frac{123}{\eta} = \frac{123}{0.87} = 141.38 \ \frac{g}{kW \cdot h} \quad (7)$$

The efficiency factor of power generation when using SSRM:

$$\eta_{SSRM} = \frac{N_{el} + N_{SSRM}}{Q_t} = \frac{111322 + 1250}{117168} = 0.96 \quad (8)$$

The efficiency factor of power generation of the power unit when using SSRM:

$$\eta = \eta_{SSRM} \cdot \eta_{pg} \cdot \eta_{rr} = 0.96 \cdot 0.93 \cdot 0.986 = 0.88 \quad (9)$$

Specific consumption of equivalent fuel for power generation when using SSRM:

$$b_e^g = \frac{123}{\eta_c^3} = \frac{123}{0.88} = 139.77 \ \frac{g}{kw \cdot h} \ . \quad (10)$$

The difference in the specific consumption of equivalent fuel for power generation with using PRDS and SSRM:

$$\Delta b_{\text{e}}^{\text{g}} = 141,38 - 139,77 = 1.61 \ \frac{\text{g}}{\text{kw} \cdot \text{h}} \qquad (11)$$

The planned operation of the SSRM is 6,480 hours per year.

Annual savings in specific fuel consumption:

$$\Delta b_{\text{e}}^{year} = \Delta b_{\text{e}}^{\text{g}} \cdot N \ = 1,61 \cdot 8100 = 13.041 \ tons \qquad (12)$$

CHPP auxilirary power generation with SSRM:

$$N = N_{el} \cdot n_h = 1,25 \cdot 6480 = 8100 \ \text{MW} \cdot \text{h} \qquad (13)$$

N_{el} - CHPP auxilirary power generation with SSRM, n_h – running hours.

Saving money per year will be:

$$E = N \cdot P \ = 8100 \cdot 14,71 = 119151 \ \text{USD} \qquad (14)$$

N – power generation per year, thousand kW·h,

P - the price of the auxiliary power energy, USD/MW·h (we take the actual cost of purchased electric power for CH at Nizhnekamsk CHPP-1 for calculation according to 2020 P =14,71 USD/MW·h)

$$\text{Pr} \mathit{ofit} = E - C_{ER} = 119151 - 2629 = 116522 \ \text{USD per year} \qquad (15)$$

where

C_{ER}–costs of the equipment repairs, 2629 US dollar.

3 Results and Discussion

An estimated calculation of the economic efficiency of the SSRM implementation is given in tables 3 and 4.

Table 3. Estimated calculation of the economic efficiency of the SSRM implementation for the period 2020-2026.

Year	2020	2021	2022	2023	2024	2025	2026
Electricity savings on own needs, thousand kWh/year	8100	8100	8100	8100	8100	8100	8100
Price of kWh, including indexation, USD/thousand kWh	14.71	15.17	15.64	16.12	16.62	17.14	17.67
Savings on own needs, thousand USD / year	119151	122877	126684	130572	134622	138834	143127
Average indexation factor for the electricity price	1.031	1.031	1.031	1.031	1.031	1.031	1.031
Average annual repair costs USD	2629	2706	2846	2962	3093	3186	3294
Construction price index growth rate (repairs)	1.043	1.041	1.043	1.04	1.04	1.036	1.034
Total savings, USD/year	166152	120171	123838	127610	131529	135648	139833

Table 4. Estimated calculation for the SSRM implementation feasibility for the period 2027-2030.

Year	2027	2028	2029	2030
Electricity savings on own needs, thousand kWh/year	8100	8100	8100	8100
Price of kWh, including indexation, USD/thousand kWh	18.21	18.78	19.36	19.96
Savings on own needs, thousand USD / year	147501	152118	156816	161676
Average indexation factor for the electricity price	1.031	1.031	1.031	1.031
Average annual repair costs USD	3418	3526	3650	3774
Construction price index growth rate (repairs)	1.034	1.035	1.035	1.033
Total savings, USD/year	144083	148592	153166	157902

Table 5.SSRM payback period

No	Parameter	Value
1	Net present value (NPV), USD	134 117
2	Internal rate of return (IRR), %	14.09
3	Profitability index (PI)	1.19
4	Payback period (PBP), year	4.89

The above calculations show that the payback period of a project to upgrade the thermal circuit of Nizhnekamsk CHPP -1 based on the SSRM will be 5 years. The economic effect in 2020 will be 166,152 USD and will grow from year to year, given the change in the indexation factor.

4 Conclusions

In this paper, we consider the option of upgrading the thermal circuit of the Nizhnekamsk CHPP -1 with the installation of a 1300kW steam screw-rotor machine. The proposed solution will allow getting 0.12 MPa auxiliary steam (including for the LPD) and at the same time additionally generating 1.25 MW of electricity by

eliminating the need for steam throttling through a 14/1.2 atm PRDS. A feasibility study was also carried out for the SSRM into the thermal circuit of the CHPP. Savings of equivalent fuel in case the SSRM implementation were defined along with the plant auxiliary power saving, as well as the payback period of the proposed solution.

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