On the possibility of obtaining ultra-supercritical steam parameters at Nuclear Power Plants with fast neutron reactors using non-nuclear steam superheating

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Abstract. Nuclear and thermal power plants constitute the largest part of Russia’s power grid (about 67%). Today the world thermal power industry has already begun the transition to ultra-supercritical steam parameters, which makes it possible to increase the efficiency and reduce fuel consumption, and, accordingly, the discharge of harmful substances into the environment. Nuclear power plants (NPPs) need to increase their performance to keep up with other electric energy producers in the market. One of the ways to increase the energy efficiency of nuclear power plants with fast reactors is to improve the thermodynamic cycle. The paper presents computer-simulated steam-cycle arrangements for NPPs with a BN-1200 reactor using non-nuclear superheating of steam, as well as steam compression to obtain super-supercritical steam parameters, and an assessment of the efficiency of using these cycle arrangements.

1. Introduction

One of the most important indicators of the efficiency of nuclear power plants is the share of useful heat used by consumers from consumed part (released during a chain reaction of nuclear fuel fission). Since the overwhelming majority of nuclear power plants operating in the world use thermal neutron reactors, this predetermines relatively low initial parameters of water vapor for steam turbine plants (since the choice of pressure in the primary circuit of light water thermal reactors of high power (15.7 MPa) is associated with a limitation temperature, equal to 350 °C for cladding of fuel elements made of zirconium alloys) and leads to low values of thermal efficiency (30-35%) [1].

Fast neutron reactors operating in Russia (BN-600, BN-800 and the project of BN-1200) currently use liquid sodium, the temperature of which at the outlet from the core is about 550 °C (the boiling point of sodium is about 878 °C). This makes it possible to generate superheated steam of high parameters (P=13 MPa, t=505 °C) in steam generators, which significantly increases the thermodynamic efficiency of nuclear power plants. Due to this, the thermal efficiency of nuclear power plants with fast reactors is about 10% higher than that of thermal reactors [2].

The fast neutron reactor system with a sodium coolant and a closed nuclear fuel cycle (NFC) is included in the list of proposed nuclear power systems of the fourth generation, which are characterized by increased indicators in the field of ensuring sustainable development, safety and reliability, as well as competitiveness.

This paper presents the results of modeling various variants of thermal schemes of the BN-1200 reactor (standard cycle, standard cycle with initial fired steam superheating, cycle with compression and one-stage intermediate, cycle with compression and two-stage intermediate fired steam superheating) using
CAD United Cycle. The aim of the work is to determine the most efficient variant of modification of the cycle arrangement of a nuclear power plant with BN-1200 reactor (by using compression and non-nuclear fired steam superheating to instruct ultra-supercritical steam parameters) from a thermodynamic point of view.

2. Materials and Methods

2.1. Research Subject

Today several methods are known to increase the energy efficiency of nuclear power plants by using both nuclear and non-nuclear steam superheating.

The Increasing of the efficiency of the NPP cycle by using nuclear steam superheating has been successfully used in the AMB-100 and AMB-200 channel type reactors, however, it has not received further development, mainly due to the need to use high-temperature steels for the reactor core, reducing the efficiency of using uranium fuel [3].

Non-nuclear steam superheating was used at the Indian Point NPP (USA), however, due to the thermodynamic inefficiency of using superheated low-pressure steam, it did not bring the expected results.

However, in heat power engineering, due to the development of power engineering technologies and the creation of high-temperature steam turbines and compressors, it became possible to widely use thermodynamic cycles at ultra-supercritical steam parameters (P=30 MPa, t=650 °C), which makes it possible to consider the possibility of achieving super-supercritical steam parameters both at NPPs with thermal and fast neutron reactors [4, 5].

Previously, the authors carried out calculations to determine the most thermodynamically effective modification of the cycle arrangement of a nuclear power plant with a VVER-1200 reactor (the article is being published in the international scientific journal «Alternative Energy and Ecology»). In the case of light water reactors (LWR), it also becomes possible to lower the parameters of the primary and secondary circuits, with subsequent compression and fired steam superheating. Lowering the initial steam parameters at the LWR will increase the depth of nuclear fuel burnup and reduce the thickness of the reactor vessel [6].

Modeling of cycle arrangements carried out by the authors showed that in the case of a VVER-1200 reactor, the cycle arrangement with compression (up to 30 MPa) and single intermediate fired steam superheating (up to 650 °C) has the highest thermodynamic efficiency, while the steam leaves the steam generator with the following parameters: t=250 °C, P=3.98 MPa).

With these parameters, according to the results of calculations, the electric power of the installation increased by 50% and amounted to 1749.09 MW with the capacity of the standard cycle arrangement being 1200 MW; The net efficiency increased by 20% and amounted to 0.429 while the efficiency of the standard cycle arrangement was 0.355. Also, due to a decrease in the parameters of the primary circuit to P=8 MPa and t=275 °C, the nuclear fuel burn-up of the reactor increased by 3% and amounted to 44.70 MW-day/kgU with a value of the standard scheme of 43.44 MW-day/kgU.

Since the use of compression and fired steam superheating to achieve ultra-supercritical parameters has proven its effectiveness in modeling cycle arrangements of light-water reactors [7], it is obvious that it is necessary to analyze the possibility of their application to fast neutron reactors [10-11].

When developing, designing and creating thermal power plants and nuclear power plants, knowledge of the quantitative and qualitative laws inherent in the systems under consideration is necessary [8-16]. This information can be obtained using mathematical modeling methods.

To solve the problems of modeling cycle arrangements of nuclear power plants, the authors used the United Cycle CAD software package, designed to solve problems and determine the best structure and composition of the equipment of a heat-and-power facility and calculate stationary operating modes.

This package has the following features:
- a highly detailed representation of the cycle arrangement being simulated;
- an advanced graphical design and visualization environment;
- models of machinery elements adjusted and refined over the years;
highly accurate heat and mass balance sheet;
- a multi-level testing system at each step of operating mode simulation, calculation, and analysis.

2.2. Research Objective
Prior to simulation, the following initial parameters were set: the live steam temperature was taken equal to 505 °C, and the pressure to 16.30 MPa. Steam flow rate was set to 4796.10 t/h.

Several potential cycle arrangements were then designed in the United Cycle CAD system to be calculated further. The following arrangements were considered:
- BN-1200 cycle arrangement with standard parameters;
- BN-1200 cycle arrangement with standard parameters and initial fired steam superheating (to 650°C);
- arrangement with compression (to 30 MPa) and single intermediate fired steam superheating (to 650°C);
- arrangement with compression (to 30 MPa) and two intermediate fired steam superheatings (to 650°C).

Initially, cycle arrangements were calculated with no regard for regenerative heating. Later, however, net efficiency was determined for all arrangements, and regenerative heating was additionally calculated for the standard arrangement and for those with lower initial parameters and highest efficiency to determine the final net efficiency including regeneration.

3. Results
Based on the results of the calculations, an analysis of the effectiveness of using various options for cycle arrangements was carried out. Figure 1 and Figure 2 shows electric output and efficiency values obtained as a result of calculations.

**Figure 1.** Net electric output: I – cycle arrangements excluding the regenerative feed water heating system; II – cycle arrangements including regenerative feed water heating system. 1 – BN-1200 cycle arrangement with standard parameters; 2 – BN-1200 cycle arrangement with standard parameters and initial fired steam superheating; 3 – arrangement with compression and single intermediate fired steam superheating; 4 – arrangement with compression and two intermediate fired steam superheatings.
Figure 2. Net cycle efficiency. Numeric designations of the arrangements are similar to those in Figure 1.

Also, to estimate the share of nuclear power in the total output of the station, nuclear power utilization factor, $\xi$, was additionally calculated as:

$$ \xi = \frac{Q_{SG}}{Q_{SG} + \Sigma Q_b} \quad (1) $$

where $Q_{SG}$ is the steam generator thermal output, $\Sigma Q_b$ is the total thermal output of the steam boilers in the arrangement. The results are shown in Figure 3.

Figure 3. Nuclear power utilization factor. Numeric designations of the arrangements are similar to those in Figure 1.

From the analysis of cycle arrangements excluding regeneration, it can be seen that circuit 4 has the highest efficiency and the highest electric power (thermal circuit with compression and two intermediate fire superheats of steam). At the same time, the contribution of the nuclear component to the total power
of the installation for this scheme is the smallest of all the calculated options, however, despite this fact, it remains quite high.

The process of steam expansion in a turbine for all variants of the cycle arrangements, except for the standard one, takes place in the region of deep ultra-supercriticality, which has a positive effect on the thermodynamic efficiency of the cycle. The transition to moist steam is carried out only in the last stages of the low-pressure cylinder, which is due to the operating conditions of the condenser, where superheated steam should not enter under normal conditions.

For further analysis, in the United Cycle CAD system, the authors modeled and calculated variations for cycle arrangements 1-4, taking into account the inclusion of a regenerative feed water heating (RFWH) in the turbine system (Figure 1 and Figure 2).

The values of steam parameters obtained by calculating the standard BN-1200 cycle arrangement in United Cycle software were found to match the design values (the difference did not exceed 5%), which suggests that calculations made with the software are reliable.

4. Discussion

Parameters of extraction and parameters before the condenser for each variant of the cycle arrangement, with the exception of the standard one, were selected based on the need to obtain the maximum efficiency as a result of calculations. According to the results of calculations, the highest efficiency (45.79%) and the highest power (2145.36 MW) is obtained by using the cycle arrangement with compression and single intermediate fired steam superheating. At the same time, in order to increase the thermodynamic efficiency, it was decided to lower the steam pressure at the end of the expansion process in the LPC to from 0.052 to 0.031 kgf/cm², to reduce the final steam moisture from 9.73 to 6.2%, and also to exclude HPH-6 from the RFWH system (the feed water after passing HPH-5 is sent directly to the steam generator). This version of the cycle arrangement is shown in Figure 4.

![Figure 4](image-url)

**Figure 4.** Cycle arrangement with compression and single-stage fossil-fired superheating, created in United Cycle software: I, II, III, IV, V, VI, VII, VIII – the turbine compartments; D – a deaerator; DP – a drain pump; C – a condenser; CP – a condensate pump; HPH-5 – a high-pressure heater; SG – a steam generator; LPH-1, 2, 3, 4 – the low-pressure heaters, FWP – a feed water pump; E – an ejector; EG – an electric generator.
Other options for cycle arrangements are of less interest, since they have much lower efficiency compared to the standard circuit. Figure 5 shows h-s chart of the steam expansion process in a turbine for a standard cycle arrangement and for an arrangement with compression and single-stage fossil-fired superheating.

![h-s Chart]

**Figure 5.** The h-s chart of the steam expansion process in a turbine: A – initial parameters of a cycle arrangement with compression and intermediate fired steam superheating; 2 – initial parameters of the standard BN-1200 cycle arrangement. The numbers in the figure indicate the characteristic points of the expansion process.

The numerical values of the thermodynamic parameters (pressure and temperature) at these characteristic points are given in table 1.

| Table 1. Parameters of points on the diagram. |
|---------------------------------------------|
| **Point number** | **P, kg/cm²** | **T, °C (Y, %)** |
|------------------|---------------|-----------------|
| **Cycle arrangement with compression and intermediate fired steam superheating** | | |
| 1                | 163           | 505             |
| 2                | 300           | 632.53          |
| 3ₐ               | 41            | 321.82          |
| 4ₐ               | 41.2          | 650.1           |
| 5ₐ               | 0.031         | 8.17            |
| **Standard BN-1200 cycle arrangement** | | |
| 1                | 163           | 505             |
| 3ₜ               | 5.93          | 4.93            |
| 4ₜ               | 5.81          | 260.79          |
| 5ₜ               | 0.052         | 9.32            |
It can be seen from the chart that the process of steam expansion in a turbine for a scheme with compression and intermediate fire superheating in the region of much higher enthalpies in comparison with the standard thermal scheme, which makes it possible to significantly increase the thermodynamic efficiency of the cycle.

Figure 5 also shows the following characteristic points of the steam expansion process in the turbine:
- 1 indicates steam parameters at the outlet of the steam generator;
- 2 indicates steam parameters at the compressor outlet (only for cycle arrangement A);
- 3_A and 3_B indicate steam parameters at the end of the expansion process in the high-pressure cylinder;
- 4_A and 4_B indicate steam parameters after superheating;
- 5_A and 5_B indicate steam parameters at the end of the expansion process in the low-pressure cylinder.

5. Conclusion
It can be seen from the results that the application of steam compression (up to 30 MPa) and intermediate fired steam superheating after high-pressure cylinder into the cycle arrangement of the BN-1200 reactor leads to the increasing of the electrical power of the installation by 50%, and the increasing of the net efficiency by 5% in comparison with the standard cycle arrangement of the installation, which leads to a significant increase in the thermodynamic efficiency of the cycle, however, to a lower value compared to the numbers that were achieved when using compression and non-nuclear steam superheating in the VVER-1200 cycle arrangement.

Thus, it can be concluded that the use of compression and non-nuclear steam superheating to obtain ultra-supercritical parameters at a NPP with a BN-1200 reactor is a justified measure, since it leads to a significant increase in the electrical power generated by the NPP, as well as efficiency.

Improvement of the thermodynamic cycle of nuclear power plants with fast reactors requires further studying. The authors are going to consider the effectiveness of the use of compression and fired steam superheating using the example of fast neutron reactors with a lead coolant (BREST-OD-300).

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