Reserves for increasing electricity production on operating nuclear power plants

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Abstract. Ways to increase electricity production on operation nuclear power plants by means of improving circuit equipment performance are considered. The paper gives specific quantitative examples of underproduction of electric power by individual nodes of the thermal circuit of a nuclear power unit. The authors emphasize the importance of the development of a thermal-hydraulic model of an NPP unit at the stage of data processing of thermal tests with a view to agreeing the energy and material balances of the thermal scheme. This approach allows to increase the accuracy of the analysis of thermal efficiency of energy equipment.

1. Introduction
Currently, the task of increasing power generation at operating nuclear power plants (NPP) is extremely relevant. This is primarily due to global trends in the growth of electricity consumption and energy saving. Around the world, operating organizations are working to increase electricity production at operating NPPs. According to [1] in the United States in the period 1977-2005 due to upgrades of different levels, the electric capacity of operating NPPs was increased by 4,417 MW, which is comparable with the commissioning of 4 new power units. Work on increasing power generation is carried out in different ways: by increasing the reactor's thermal capacity allowed for operation; modernization of the most important equipment in terms of power generation; reducing the measurement error of the thermal power of the reactor and, thereby, its maximum approaching the licensed capacity. Examples of such events include:
− increase in reactor thermal power up to 104% at nuclear power plants with ВВЭР-1000 АО “Контсерт Rosenergoatom”;
− increasing the electric power of the RBMK -1000 units at NPP АО “Контсерт Rosenergoatom” by 32 MW by increasing the length of the blades of the last stage of the K-500-65/3000 turbines [2];
− increase in thermal power of the reactor due to a decrease in the error in determining its thermal power at power unit No. 1 of NPP “Limerick” LCC Exelon from 2% to 0.35% [3].

2. Results and discussion
As practice shows, at present the quality of the work of the thermal-mechanical equipment of NPPs of the Russian Federation is not adequately controlled. The main reasons for this phenomenon are: firstly,
the lack of detailed reporting regarding thermal efficiency; secondly, the use of operational control devices for the calculation of technical and economic indicators (TEI). The current reporting of NPPs in the form of 3-ТЭК actually only states the electrical power and electricity generation by each power unit, and the analysis of the quality of the power unit is practically absent: only a comparison of some characteristics with the standard for this power unit is given. According to the 3-TEK form, it is impossible to compare power units with each other and identify the causes of differences in generation and, thus, identify the reserves for increasing electrical power. It is necessary to pay attention to the fact that, despite the identical reporting form of 3-TEK, the performance indicators of different NPPs are not quite comparable: for example, the thermal losses of the reactor at each NPP are different and lie within 2 ÷ 24 MW. Analysis of operational data shows that the actual electrical power of the power units may vary significantly. This especially applies to power units of different NPPs. The reasons may be:

- various heat output to the working body of the turbine unit;
- different temperature and flow rate of cooling water;
- features of the thermal scheme of a specific power unit;
- conducted equipment upgrades;
- technical condition of the equipment;
- insufficient quality of repair work and level of operation.

As for the use of operational control devices for the calculation of TEI, they have errors that do not meet the requirements relating to the calculation of TEI. In essence, the operational control devices are connected with the system of protection, interlocks and signaling equipment of the unit (mainly turbines). In [4] it is said that the value of the analysis largely depends on the accuracy of the source data. Measurement errors can lead to incorrect conclusions that can be costly.

This article presents the main results of thermal tests at power units of single-circuit NPP with demonstration of the potential for energy saving.

Figure 1 shows the general approach applied in conducting thermal tests and analyzing their results.

![Diagram](image)

**Figure 1.** The general approach when testing a power unit.

Separately, it is worth noting the importance of the adjustment phase of the thermal-hydraulic model, which is, in fact, the final stage of the data processing algorithm and characterizes the integral verification of the laws of thermodynamics throughout the scheme. At this stage, the energy and material balances are consistent according to the scheme and unreliable readings that, for example, lead to unattainable heat transfer coefficients in heat exchange equipment, are identified.
Measurement errors can be both up and down from the true value, so when setting up the model, they partially compensate each other. Figure 2 shows a histogram of the probability density distribution of errors in the verification of the thermal-hydraulic model of a power unit of one of the NPPs (the setting was made for 4 modes of operation).

![Histogram of the distribution of verification errors of the thermal-hydraulic model of the power unit](image)

Inconsistency in the energy and material balances of the thermal scheme leads to incorrect estimates of capacity under-utilization, which essentially reduces the reporting efficiency to zero. The table, for example, presents a comparison of the results of the evaluation of the power unit under-production using a model set up according to test data and station reporting.

Based on the experience of testing, the following main measures can be distinguished, bearing the potential for energy saving:

1. Improving the accuracy of measuring the flow of feed water;
2. Improvement of the work of heat exchange equipment of the regeneration system and heating installations.

**Table 1. Comparison of power shortage by the power unit.**

| Thermal circuit node under-production, MW | Separators, steam superheaters | Low pressure compressor | Low pressure heater | Deaerator | Total |
|-----------------------------------------|-------------------------------|------------------------|--------------------|-----------|-------|
| Station reporting                       | 0.36                          | 0.25                   | 0.47               | 0.09      | 1.17  |
| Calculation by CKTI                     | 0.65                          | 0.12                   | 1.08               | 2.44      | 4.29  |

The feedwater flow rate determines the thermal power supplied to the working fluid of the turbines. The change in feed water consumption by 1% leads to approximately the same change in electrical
power. The maximum flow rate of feed water, in addition to the limitations on the turbine capacity, determines the thermal capacity of the reactor, which should not exceed the value specified in the operating license. In Europe and the USA, this problem is solved by installing high-precision ultrasonic flow meters (UFM), which allow to measure the feedwater flow with an accuracy of ± 0.32% [3]. UFMs are used in parallel with regular narrowing devices (ND), such as diaphragms or nozzles, and are used for online calibration of NDs [1]. Moreover, if the discrepancy between the readings of the control system and the remote control device exceeds the permissible value, the thermal power of the reactor is immediately reduced in order to establish the reasons that caused the indicated deviation. Currently, at most NPPs of Russia, mainly diaphragms are used as flow meters; the measurement error of feedwater flow is within 2%. Using the experience of American NPPs, the additional generation of electricity for a 1000 MW power unit will be ~ 16 MW.

The quality of work of heat exchange equipment can be characterized by a heat transfer coefficient. As practice shows and tests carried out, the best regenerative heaters at nuclear power plants have a heat transfer coefficient of ~ 3500 ÷ 3600 W/(m² · K); turbine exhaust steam condensers ~ 3200 ÷ 3500 W/(m² · K). Table 2 provides data on the comparison of the operational performance of heat exchange equipment obtained during the thermal tests of the NPP power unit.

### Table 2. Underproduction of electricity by the unit due to the deterioration of the performance of heat exchange equipment.

| Thermal circuit element | ΔNₑ, MW | Comments |
|-------------------------|---------|----------|
| Low pressure heater-1   | 0.3     | 0.4      | For turbine No.1: heat transfer coefficient 2335 W/(m²*K) vs. standard 3264 W/(m²*K); for turbine No.2: heat transfer coefficient 2222 W/(m²*K) vs. standard 3273 W/(m²*K). |
| Low pressure heater-2   | 0.7     | 0.8      | For turbine No.1: heat transfer coefficient 1423 W/(m²*K) vs. standard 3316 W/(m²*K); For turbine No.2: heat transfer coefficient 1319 W/(m²*K) vs. standard 3326 W/(m²*K). |
| Low pressure heater-3   | 0.7     | 0.3      | For turbine No.1: heat transfer coefficient 1679 W/(m²*K) vs. standard 3411 W/(m²*K); For turbine No.2: heat transfer coefficient 2401 W/(m²*K) vs. standard 3421 W/(m²*K). |
| Low pressure heater-4   | 0.1     | 0.2      | For turbine No.1: heat transfer coefficient 3042 W/(m²*K) vs. standard 3518 W/(m²*K); For turbine No.2 heat transfer coefficient 2846 W/(m²*K) vs. standard 3529 W/(m²*K). |
| Low pressure compressor | 4.8     | 0.1      | For turbine No.2: heat transfer coefficient 2730 W/(m²*K) vs. standard 3221 W/(m²*K), also accounting for muffled pipes; For turbine No.1: accounting for muffled pipes |

Non-condensable gases, which impair the heat transfer from the steam side, have a strong influence on the operation of steam-water heaters. Often, it is poorly organized withdrawal of non-condensable gases and leads to deteriorated performance of heat exchange equipment. In turbine condensers, in
addition to the effective suction of the vapor-air mixture, there is also a strong influence of sediments from the side of cooling water. Currently, the problem of combating sediments in tube bundles is successfully solved by using efficient ball cleaning systems. In regenerative heaters, this problem is not so acute, since reactor-quality water is used, which then goes directly to the reactor, as in single-circuit NPPs or in a steam generator in the case of two or three loop stations.

When analyzing the operation of heat exchange equipment, consideration should be given to the issue of the operation of the heaters of the heat and power plant. Such plants, especially at single-circuit NPPs, were created with enormous reserves of heat performance, therefore, insufficient attention was paid to monitoring their thermal efficiency. Table 3, for example, presents the results of the analysis of the work of a group of boilers for heat supply of one of the nuclear power plants.

Table 3. Analysis of the work of a group of boilers for single-loop heating NPP.

| Parameter                          | Meas. unit | Boiler No. 1 | Boiler No. 2 | Boiler No. 3 |
|------------------------------------|------------|--------------|--------------|--------------|
| Boiler thermal power               | MW         | 6.3          | 7.4          | 4.9          |
| Boiler underheating                | °C         | 0.5          | 0.4          | 0.2          |
| Boiler heat transfer coefficient   | W m²·K     | 120          | 802          | 1297         |
| Standard heat transfer coefficient of the boiler | W m²·K | 1587         | 1696         | 1773         |

As the experience of the studies performed shows, the reduced heat engineering indicators of the operation of heat supply boilers are determined mainly by the deteriorated organization of the removal of non-condensable gases.

3. Conclusion

The example of specific units and equipment of the thermal circuit of a power unit shows the reserves for increasing electrical power. It should be noted that there is the need for regular rapid testing of power units, with the aim of timely determining the deterioration of the thermal performance of equipment, as well as the ability to determine the nature of their flow in time. Another approach, which is actively used in Europe and the United States, is the creation of an independent control system for TEI, which monitors equipment performance in real time and, in the event of overshooting, carries out diagnostics indicating possible causes of the decrease in thermal performance of equipment. It is important to note that such a system does not work with operational control devices, but with special laboratory precision devices.

References

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