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Research Article

Computational and experimental justification for increasing the performance of the regenerative heat exchanger in the steam generator blowdown system of the AES-2006 project (RU V-392M)*

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Abstract

The article discusses the design and operation modes of the regenerative heat exchanger (RHE) in the steam generator (SG) blowdown and drainage system (LCQ) at Novovoronezh NPP-II 1 and 2 (Project AES-2006).

The results of mathematical modeling of the RHE operating modes are presented in order to identify the causes of its low efficiency.

Based on the results of the commissioning of the SG blowdown and drainage system at NvNPP-II 1, as well as the thermohydraulic calculations of the RHE operating modes, the authors put forward assumptions regarding changes in the rerouting of the piping (Volnov et al. 2017, Yaurov et al. 2017). According to their proposals, the RHE piping was upgraded at NvNPP-II 2.

The upgrading in the RHE piping was implemented first at NvNPP-II 2 at the stage of installing the systems and, after the expected result was confirmed, it was applied in April 2020 at NvNPP-II 1.

In addition, the authors carried out a comparative analysis of the results of testing the thermohydraulic characteristics of RHEs of the blowdown and drainage system for NvNPP-II 1 (before upgrading, after upgrading in scheduled maintenance 2020) and NvNPP-II 2.

These improvements made it possible to achieve more efficient operation of the RHE in the SG blowdown and drainage system and the system as a whole.

Keywords

AES-2006, blowdown, steam generator, upgrading, regenerative heat exchanger, piping, rerouting, RU V-392M, operation

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Design of the regenerative heat exchanger in the blowdown system

The regenerative heat exchanger (RHE) is part of the blowdown and drainage system of the steam generators (SGs) at Novovoronezh NPP-II 1 and 2 and is designed to cool the blowdown (boiler) water from the SGs, before it undergoes special water treatment (SVO-5), and to subsequently heat the purified blowdown water returning to the SGs in different operating modes of the unit (Lukasevich et al. 2004, Shchelik et al. 2006, Zhukov and Lukashov 2010, RB-002-16 2016, Volnov et al. 2017, Yaurov et al. 2017, 2021).

The heat exchanger is a vertical type apparatus, consisting of two removable covers, a body, nozzles, supports, sling devices, cylindrical multi-pass coils (located inside the body between two tube sheets). A general view of the heat exchanger is shown in Fig. 1.

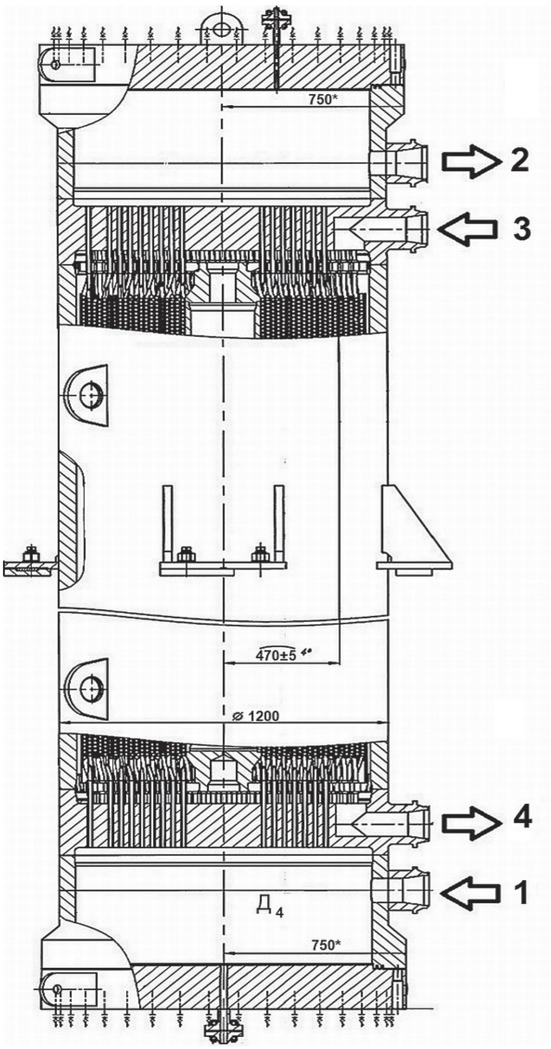

Figure 1. Design of the regenerative heat exchanger in the SG blowdown and drainage system: 1 – supply of the cooled medium from the SG; 2 – supply of the cooled medium from the RHE to the blowdown aftercooler; 3 – supply of the purified coolant from SVO-5 for heating; 4 – return of the purified and heated coolant to the SG

The medium being cooled from the SGs (for purification) is supplied "from the bottom up" through the tubular space, and the heated purified medium (from SVO-5) is supplied "from the top down".

The main characteristics of the heat exchanger are presented in Table 1.

Table 1. Main Characteristics of the Heat Exchanger in the SG Blowdown System

Parameter	Value
Outer diameter of the heat exchange pipes and their thickness, mm	15×1.5
Total number of the heat exchange pipes, pcs.	488
Heat exchange surface area (according to the outer diameter of the pipes), m^2	310
Outer diameter and thickness of the body in the central part, mm	1200×65

The main parameters of the heat exchanger are presented in Table 2.

Table 2. Main Parameters of the Heat Exchanger in the SG Blowdown System

Parameter	Value
Temperature of the cooled medium at the RHE inlet, from special water treatment in the SG (intertubular space), °C	50
Temperature of the cooled medium at the RHE outlet, from special water treatment in the SG (intertubular space), °C	237–251
Medium pressure, MPa	6.9
Temperature of the cooled medium at the RHE inlet, from the SG (tubular space), °C	285
Temperature of the cooled medium at the RHE outlet, from the SG for special water treatment (tubular space), °C	≥ 100
Medium flow rate, t/h	140

Characteristics of the regenerative SG blowdown heat exchanger at NvNPP-II 1 based on the results of the commissioning work

The commissioning work of the SG blowdown system showed the low performance of the RHE system at NvNPP-II 1 (Volnov et al. 2017, Yaurov et al. 2017, 2021). At nominal flow rates in the blowdown system, significantly low blowdown and feed water temperatures were observed before and after the RHE. A set of measures aimed at cleaning the tubular and intertubular space of the heat exchanger did not at all increase its performance.

Table 3 presents the results of commissioning of the RHE in the SG blowdown system at NvNPP-II 1 (before upgrading). Since the SG blowdown system at NvNPP-II 1 and 2 is closed, the flow rates of the cooled (blowdown) medium are equal to those of the cooling (feed) medium. The measurement error was no more than ± 2.0% for the temperature and no more than ± 4.5% for the flow rate.

Table 3. Results of Commissioning of the RHE in the SG Blowdown System (Before Upgrading)

Parameter	Test results		Design data
Blowdown flow rate at the RHE inlet (from the SG), t/h	148.2	60.0	140
Temperature of the cooled medium at the RHE inlet, from the SG (tubular space), °C	281.2	280.0	285.0
Temperature of the cooled medium at the RHE outlet, from the SG for special water treatment (tubular space), °C	144.4	205.0	≤ 100
Temperature of the cooling medium at the RHE inlet, from special water treatment in the SG (intertubular space), °C	62.08	60.0	50
Temperature of the cooling medium at the RHE outlet, from special water treatment in the SG (intertubular space), °C	212.12	156.0	237–251

The measured temperature changes in the tubular and intertubular space of the RHE at NvNPP-II 1 for a flow rate of 60 t/h and 148.2 t/h are shown in Fig. 2a, b, respectively.

The design temperature changes in the tubular and intertubular space of the RHE are shown in Fig. 2c.

Mathematical simulation of heat exchanger operating modes

The authors of this article have previously put forward an assumption about the reasons for low temperatures before and after the RHE, namely, the low flow rate of the coolant in the intertubular and tubular space of the heat exchanger (0.34 m/s and 0.63 m/s) for the design flow rates of the medium in the system (Volnov et al. 2017, Yaurov et al. 2017, 2021). In the design (current) scheme for connecting the RHE piping (the medium being cooled from the SG in the tubular space is supplied “from the bottom up”, the heated medium in the intertubular space is supplied “from the top down”), the directions of forced and free (convection) movement of the medium are opposite. In the case of low flow rates of boiler water, this phenomenon significantly reduces the heat exchanger performance (Rassokhin 1987, Margulova 1994, Trunov et al. 2001, Andrushechko et al. 2010).

The calculations were carried out using the Ansys program (CFX thermohydraulic module) (Snegirev 2009, Bruyaka et al. 2010). The purpose of the calculation was to determine the coolant rate in the RHE tubes for the design scheme of the heat exchanger piping.

To estimate the rate in the heat exchange tubes of the regenerative heat exchanger, a 3D model was built (Fig. 3) and a thermohydraulic calculation was carried out for the RHE nominal operating mode (flow rate = 140 m^3/h). The RHE piping has a design configuration: the supply of hot water from the SG to the tubes is “bottom-up”.

The calculation results showed that the average rate in the RHE tubes was no more than 0.47 m/s.

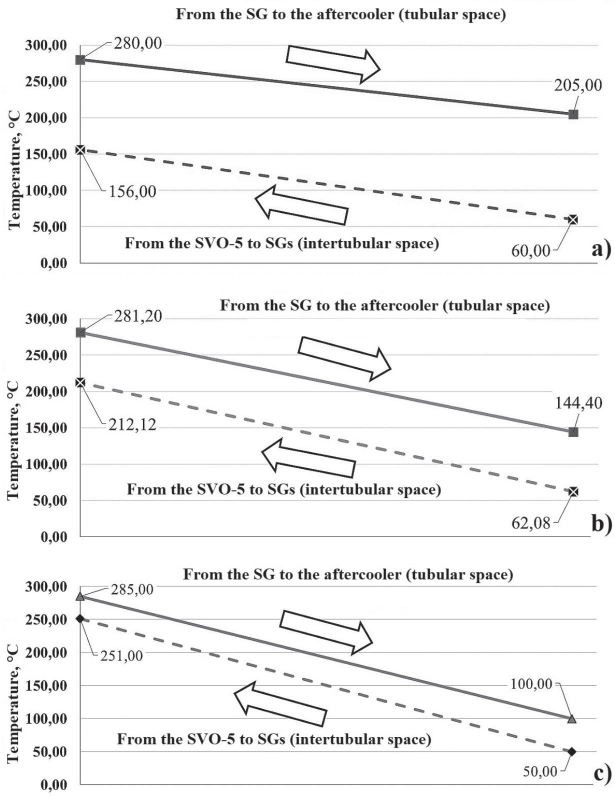

Figure 2. Measured values of temperature difference in the tubular and intertubular space of the RHE in the SG blowdown system. **a.** Flow rate = 60 t/h; **b.** Flow rate = 148.2 t/h; **c.** Design data with a flow rate of 140 t/h

The calculation, in which hot water from the SG to the RHE tubes is supplied “from the top down” (that is, the scheme for connecting the RHE piping proposed by the authors, opposite to the design scheme) showed that the average rate in the RHE tubes would be 0.7 m/s.

Thus, the assumption about the influence of the piping connection scheme on the RHE performance was confirmed.

Operating parameters of the SG blowdown system after upgrading of the RHE piping at Novovoronezh NPP-II 1

The proposed option for rerouting the RHE piping was initially accepted for implementation at NvNPP-II 2 during the installation of the blowdown system, and after the expected result was confirmed during the commissioning of the system, it was applied in April 2020 at NvNPP-II 1 (Fig. 4).

Changing the direction of the flow of the cooled and heated medium increases the heat exchanger performance (Figs 5–7), and also contributes to the sludge washing out of the heat exchange tubes into the lower chamber.

Figs 5–7 present the results of a comparative analysis with the design data of the RHE operation (temperature

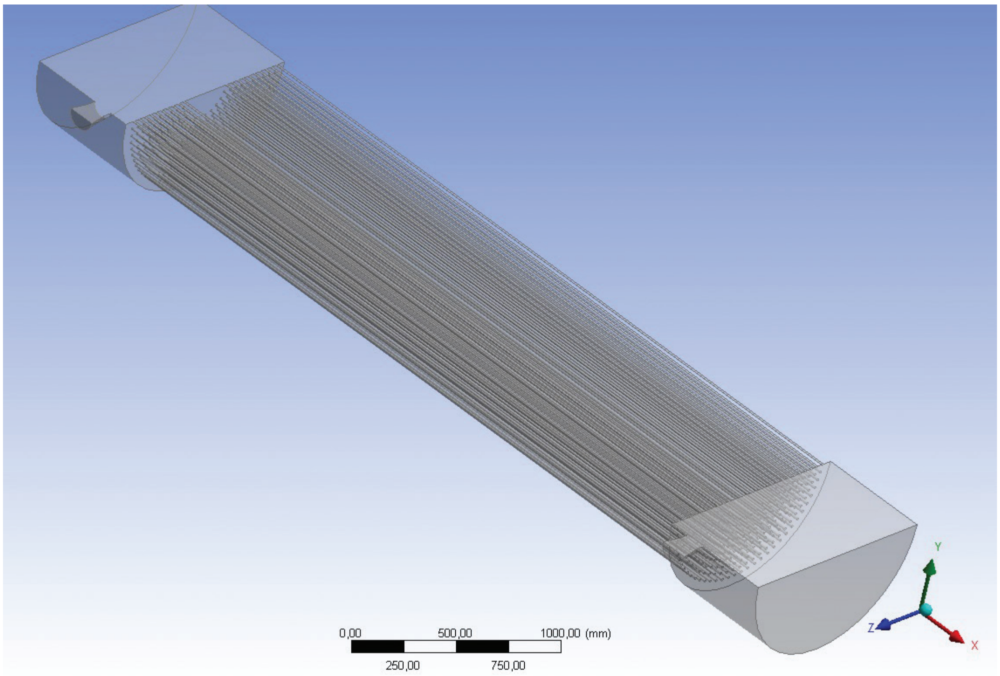

Figure 3. 3D RHE model

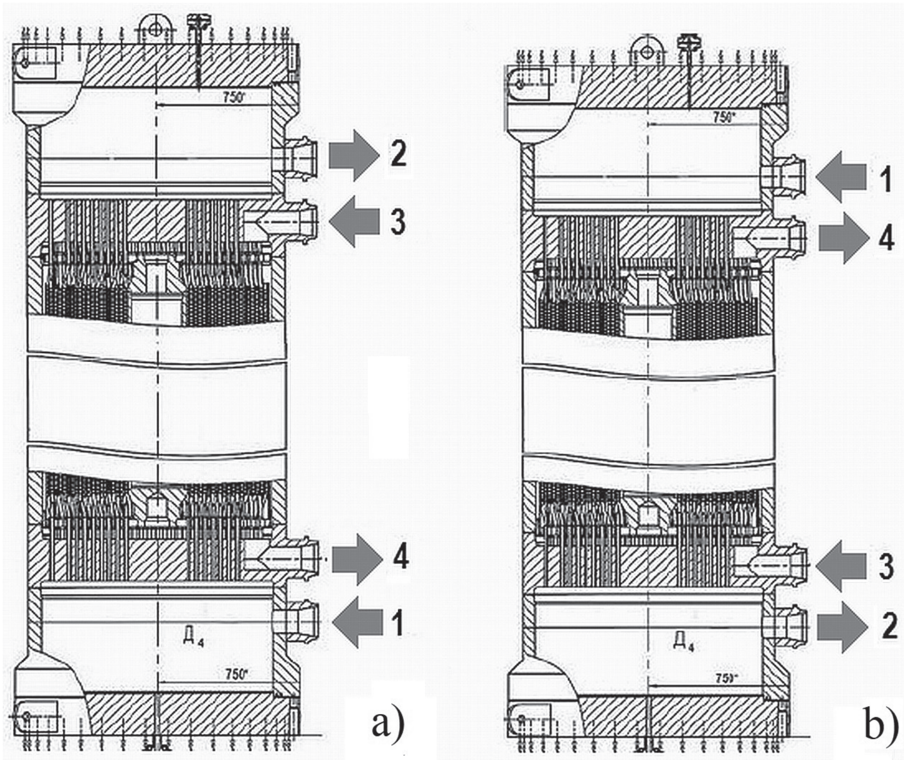

Figure 4. RHE piping of the SG blowdown system: **a.** before upgrading at NvNPP-II 1; **b.** after upgrading in 2020 at NvNPP-II 1 and 2 (1 – supply of the medium being cooled from the SG into the RHE; 2 – supply of the cooled medium from the RHE to the blowdown aftercooler and further to SVO-5; 3 – supply of the purified coolant from SVO-5 to the RHE for heating; 4 – return of the purified and heated coolant from the RHE to the SG)

drops Δt in the tubular and intertubular spaces depending on the flow rates) of the SG blowdown system at NvNPP-II 1 before upgrading and NvNPP-II 1 and 2 after upgrading. The temperature and flow rates of the medium were measured by standard technological (design) means (including thermocouples and orifice gages); the measurement error was no more than ± 2.0% for the temperature and no more than ± 4.5% for the flow rate.

Based on Figs 5–7, it can be concluded that with the current RHE piping configuration at NvNPP-II 1 (after upgrading), the RHE parameters fully correspond to both the calculated (design) values and the RHE parameters at NvNPP-II 2.

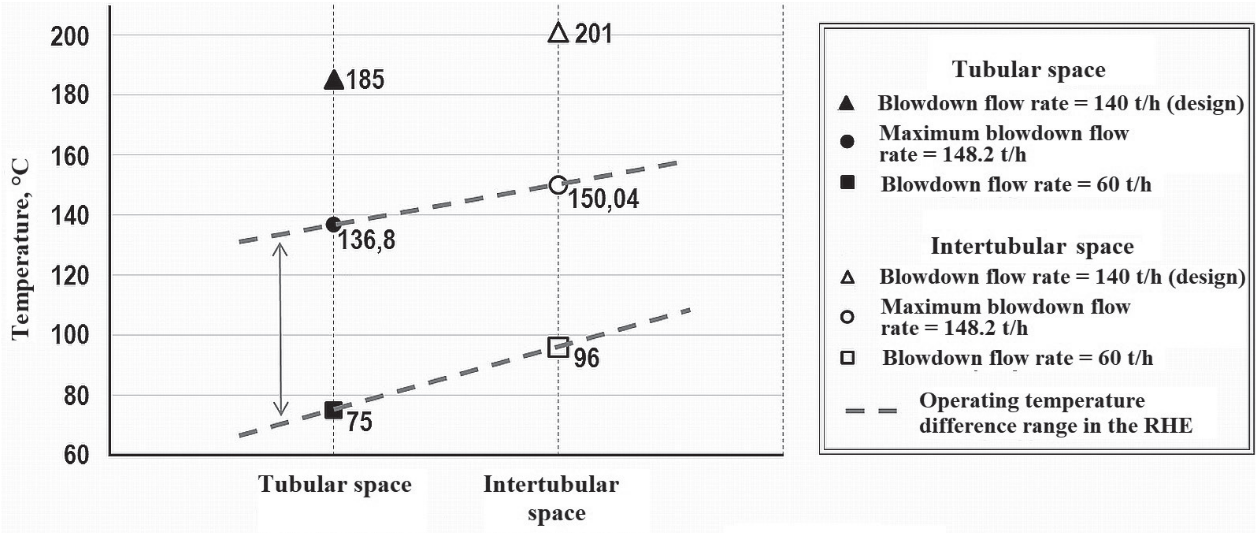

Figure 5. Temperature difference Δ*t* in the tubular and intertubular space of the RHE at NvNPP-II 1 before upgrading

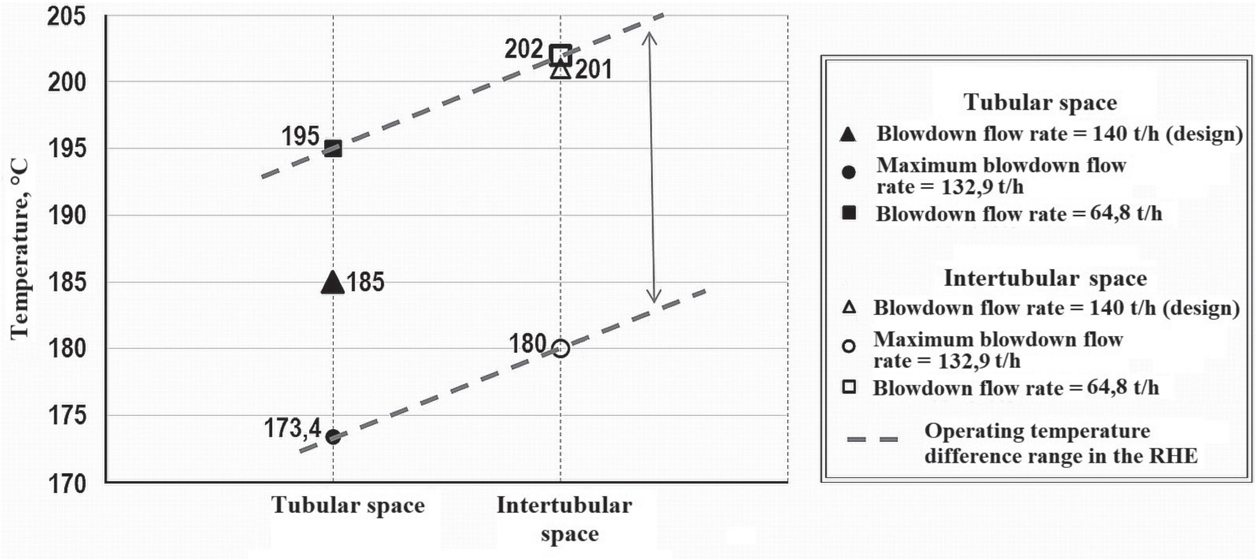

Figure 6. Temperature difference Δ*t* in the tubular and intertubular space of the RHE at NvNPP-II 1 after upgrading during scheduled maintenance 2020

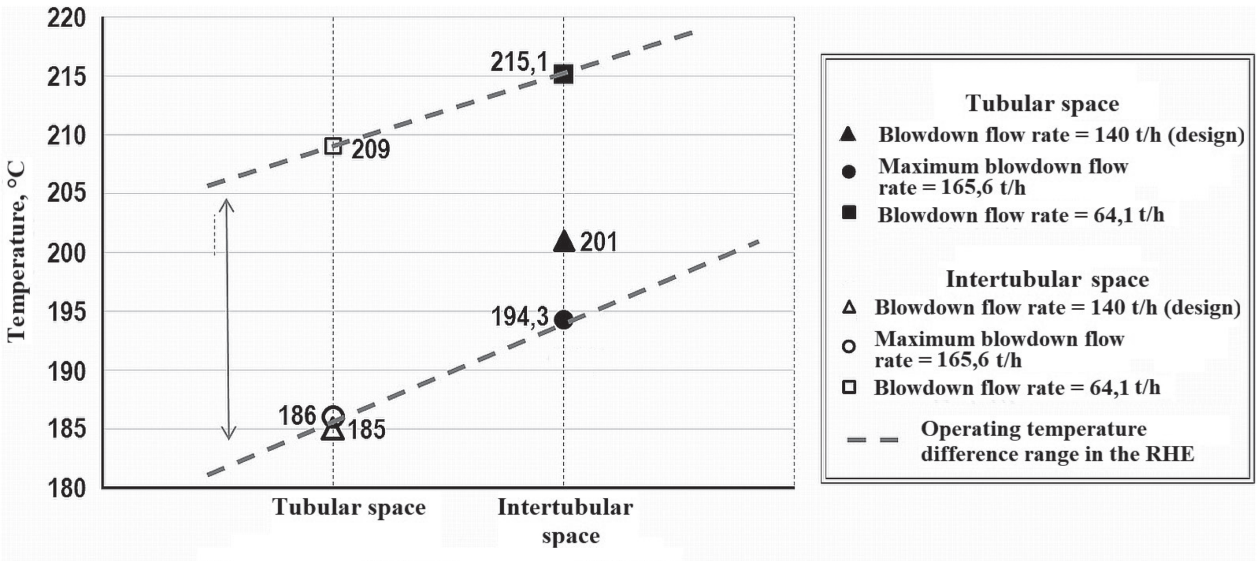

Figure 7. Temperature difference Δ*t* in the tubular and intertubular space of the RHE at NVNPP-II 2

The results of testing the new RHE connection configuration at NvNPP-II 1 showed that the RHE of this power unit provides the temperature difference in the tubular and intertubular space as close as possible to the design (calculated) data.

Conclusions

The commissioning of the SG blowdown system at NvNPP-II 1 revealed insufficient RHE performance in terms of ensuring temperature differences in the tubular and intertubular space.

Based on the results of the commissioning of the RHE in the SG blowdown system at NvNPP-II 1, according to the proposals made by the authors of this article (with a confirmed thermohydraulic calculation of the heat exchanger), with the recommendations of the developers of the system and the RHE manufacturer taken into account, the RHE piping at NvNPP-II 2 was rerouted so that the medium being cooled from the SG in the tubular space is supplied "from the top down" and the heated medium in the tubular space is supplied "from the bottom up" (forced and convective movement of the medium coincide).

The results of testing this RHE connection configuration at NvNPP-II 2 showed that the RHE of this power unit provides the temperature difference in the tubular and intertubular space as close as possible to the design (calculated) data.

- The test results of the new RHE connection configuration at NvNPP-II 1 showed as follows:
- The RHE also provides temperature differences in the tubular and intertubular space as close as possible to the design (calculated) data; and
- The expected (calculated) result from the RHE upgrading was confirmed.
- Changing the RHE connection scheme made it possible as follows:
- To reduce the temperature difference between the feed water pipelines and the blowdown water return pipes to the SG;
- To reduce the heat load on the blowdown aftercooler and, as a result, reduce the heat load on the intermediate circuit system of normal operation consumers; and
- To ensure the design modes of operation of the SG blowdown system and the intermediate circuit system of normal operation consumers.

According to the test results, it was decided to modernize the RHE piping at NvNPP-II 1 as well.

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