Efficiency investigation of nuclear power plant combination with a system of water and phase-transfer heat accumulators

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Abstract. Combination of nuclear power plants with accumulation installations can be one of the ways to participate in regulating load schedules for the NPP, due to the fact that it allows to store of cheap night time non-peak energy and it's further using during the peak hours of electric load. The use of accumulating systems will allow to optimize the structure of power generating capacities with the possibility of increasing the share of powerful power units and also will reduce emissions into the environment by reducing the share of thermal power plants operating on fossil fuels. One of the most perspective types of batteries are phase transition accumulator. Their use will make it possible to get the steam for an additional turbine without changing the steam flow in the main NPP cycle and will allow to avoid equipment modernization and an increase in its wear. At the same time such accumulators are very expensive. One of the solutions can be a combination of phase transition accumulator and additional steam turbine with inexpensive, in relation to phase transition accumulator, feed water accumulators, which, like the phase transition accumulator, will be charged at night due the energy of main steam. In this case, the phase transition accumulator will work only as a steam generator. In the course of this work, the systemic conditions for the payback of the proposed accumulation system are determined. Net present value is determined in the depending of range of half-peak and off-peak electricity tariffs.

1. Introduction
As the share of nuclear power plants grows, the tendency to grow for the deficit of maneuverable capacities in power systems is observed. Nuclear power plants, as well as other power generating sources operating in power systems, are involved in the regulation of the current frequency in the power system, including the primary regulation. Thus, according to the technical requirements for generating equipment of the Unified Energy System of Russia, nuclear power plants with VVER reactors must participate in the primary regulation of the power system current frequency. The maneuverable characteristics of these NPPs in situations of frequency deviation should ensure a guaranteed power change: for an increase up to 2% and for a decrease up to 8% of the nominal electrical power. For this, the capacity of power units must be maintained at a level of no more than 98%. Realization of this requirement reduces the installed capacity utilization factor of reactors. This factor, together with the high cost of building nuclear power plants, significantly reduces their competitiveness.

One of the ways to increase the maneuverable characteristics of nuclear power plants while maintaining a high installed capacity utilization factor of reactors can be a combination with the heat accumulation system, developed by the authors [1], which includes a phase change accumulator as
well as cold and hot water tanks. Most of the known accumulation systems involve the use of stored heat in the main cycle of a nuclear power plant. This requires costly upgrades to the NPP steam turbine and power generator. The cyclic operation of this installations at an increased load accelerates the wear process of the equipment. In this work, the installation of additional steam turbines together with a heat accumulation system is proposed, which will solve the said problems.

The structure diagram of the combination of a nuclear power plant with a heat accumulation system, developed by the authors, is shown in figure 1.

During the hours when the electrical load is reduced, part of the main steam is taken from the steam generators and directed to the accumulator charging. The feed water of the heat storage system circuit is directed from the cold 7 to the hot water tank 13. The condensate, formed in the phase transition accumulator 2, is directed to the heat exchangers of the first stage 9 for heating the feed water, after this it is directed to the circuit of the main steam turbine. Part of the taken main steam is directed to the second stage heat exchangers for further heating of the feed water. The produced condensate is also directed to the main steam turbine circuit in front of the steam generators. Steam turbines 3 operate in idle mode for 9 hours by taking a small part of main steam.

In the increased load mode, the feed water, which has a nearly of saturated temperature, is directed from the hot water tank 13 to the phase change accumulator 2. The steam, generated in the accumulator 2, is directed to additional turbines for the electricity generate. Condensate is directed into cold water tank 7.

2. Phase transition heat accumulator design
To ensure the operation of the heat accumulation system under the required conditions, the design of the phase transition accumulator was developed, that capable to operate in the steam generation mode (figure 2) [2].

![Figure 1. The structure diagram of the combination of a nuclear power plant with a heat accumulation system: 1 – steam distribution device; 2 – phase-transfer accumulator; 3 – additional steam turbine; 4 – electric generator; 5 – condenser; 6 – condenser pump; 7, 13 – cold / hot water tank; 8, 14 – booster pump; 9, 12 – first / second stage heat exchangers; 10 – deaerator; 11 – feed-water pump.](image-url)
Figure 2. Phase transition heat accumulator design: 1, 16 – supply / outlet pipeline; 2 – temperature sensors; 3 – blinds; 4, 5 – pipeline; 6 – level sensor; 7 – drum separator; 8 – outlet pipeline; 9 – overhead traveling crane; 10 – a breathing hole; 11 – tube sheet; 12 – jar; 13 – metal heat exchange tube bundle; 14 – collector; 15 – downtake tube; 17 – downpipe; 18 – glass tubes, in which the parameters control sensors of the heat-accumulating material are located.

During charging, main steam is evenly distributed over the metal heat exchange tubes 13, giving off heat to the heat accumulation material. Then the steam condenses. The condensate is accumulated in the collector 14 and directed to the first stage heat exchangers. In case of incomplete condensation of steam in the heat exchange tubes 13, the pipeline 5, connected to the supply pipeline 1, is provided in the upper part of the drum separator 7. Due to this, a cycle is formed, thereby the consumption of main steam from the steam generators is reduced.

In the process of discharging, the feed water is directed from the hot water tank into the collector 14, and is evenly distributed over the heat exchange tubes 13, where the vaporization is. The generated steam is directed from the drum-separator 7 to the steam turbines. By the end of the discharge, the heat exchange between the accumulating material and the working fluid slows down, which is caused by the growth of the crystallized boundary layer. As a result, the entire volume of incoming feed water cannot go to state of steam. The outlet pipeline 4 is provided for the removal of excess water.

Based on the works [3–6], a staggered arrangement of the tube bundle of the phase transition accumulator and longitudinal ribbing of the heat exchange tubes were selected. The chosen design will reduce the number of zones of uneven melting of the accumulating material in the accumulator.

The crystallization temperature of the selected accumulating material should be higher than the required temperature of the working fluid at the outlet of the phase transition accumulator, since the latent heat of the phase transition is released precisely during the crystallization process, and it allows to ensure stable steam parameters. Besides that, the melting point of the material must be lower than the temperature of the main steam used to charge the accumulator. For this heat accumulation system, a material NaOH + NaNO₃ is proposed. Thermophysical characteristics of this [7–9] are shown in table 1.

| Heat accumulation material | The melting temperature, °C | Phase transition heat, kJ / kg | Density, kg / m³ | Heat capacity, kJ / kg·K | Thermal conductivity, W / m²·K | The cost, $/ kg |
|---------------------------|-------------------------------|-------------------------------|-----------------|------------------------|-----------------------------|---------------|
| 59%NaOH+ +41%NaNO₃       | 266                           | 278                           | 1910            | 1.85                   | 0.75                        | 0.52          |
During some number of heating and cooling cycles of the accumulating material, the deterioration of its thermophysical properties is by 2–5%, depending on the mode and intensity of the accumulator. Moreover, the number of such cycles can reach 2000–4000 for some materials without deterioration of properties [10–14].

Cold and hot water tanks have a number of disadvantages: heat loss, high construction cost. However, examples of the efficient operation of such installations exist, for example, in Germany, tanks for storing hot water to 1000 m³ are used. Saving investment in the construction of such tanks is achieved by reducing the consumption of concrete for the construction: the construction of small tanks, allows to have low pressure from the water on the walls of the tank [15]. Also, another problem is known: in the hot water tank when discharging, the pressure drops and water vaporizes. To solve this problem, pumping a nitrogen blanket into the tank is proposed in the work. Such a solution will avoid spontaneous vaporization and create excessive pressure in the hot water tank, which will serve as a boost pressure for hot water supply to the accumulation system circuit during hours of increased load.

The investigation was carried out on the example of combining a heat accumulation system with a nuclear power plant with VVER-1000. To participate in the primary regulation of the current frequency at the power system, according to the requirements of the system operator, the installation of additional steam turbines with a total capacity of 87 MW is required. Then, in the normal mode, they will be able to operate at a reduced power of 65 MW (75% of the nominal power) and, if necessary, supply an additional 22 MW to the power system, which is 2% of the total capacity of the power complex NPP + accumulation system. This level of reduced load is realized with multiple steam nozzle control without significant losses in the efficiency of steam turbines. The power of additional steam turbines is selected so that one of them has a power of 12 MW, which, according to [16], will make it possible to ensure reliable reserve of own needs of two NPP power units. Thus, the capacity of the second turbine will be 75 MW. Additional steam turbines operate in idle mode for 9 hours during the load drop using the small consumption of main steam – 1.18 kg / s and 7.52 kg / s, respectively (0.076% and 0.48% of the total consumption of main steam).

As the calculations of thermodynamic processes have shown, during the night off-peak hours main steam is taken from the steam generators for 5 hours to charge the phase transition accumulator and second stage heat the feed water of the heat accumulation system with a flow rate of 274 kg / s and 96 kg / s (17.5% and 6.1% of the total consumption of main steam), respectively. During hours of increased load, hot feed water with a temperature of at least 258 °C and a flow rate of 81.6 kg / s is directed from the hot water tank to the phase-transfer heat accumulator within 15 hours.

3. Economic effects
For systems that allow NPP to participate in the primary regulation of the current frequency in the power system without loss in power 2%, it is advisable to take into account the economic effect of operating with a constant full load of reactor units. The effect obtained depends on the selected operating mode and electricity tariffs.

In the present work, the positive systemic economic effect of replacing manoeuvrable power generating plants, operating on fossil fuel, by the heat accumulation systems with additional steam turbines was also taken into account. Natural gas, that is not used due to this substitution, can be sold. The cost of export natural gas is taken at the level of 170 $/1000 m³ according to the annual financial report of Gazprom for 2019. Taking into account the order of the government of the Russian Federation № 705-p this corresponds to 85 $/1000 m³ in federal budget. It is assumed in the work, that 50% of the profit, received by the state (25% of natural gas export sales), will be paid to NPP to increase the share of accumulation units in the energy system in the form of facilitation payments.

According to [16], one multifunctional steam turbine with a capacity of 12 MW is capable of providing reliable reserve for the auxiliary needs of two NPP power units. The safety level of nuclear power plants, required by the IAEA, will be performed, when a multifunctional steam turbine and a three-channel emergency power supply system with diesel generators work together [16]. Thus, the
refusal to install expensive heat exchangers of the passive heat removal system (PHRS) becomes acceptable.

The economic effect of combining a nuclear power plant with a heat accumulation system can be represented as a function of the net present value:

\[
NPV = -I_{HAS} + I_{PHRS} + \sum_{i=1}^{T} [(R_i - C_i + C_{i}^{PHRS}) \cdot (1 + E)^{T_i - T_{i+1}}],
\]

where: \( K_{HAS} \) – capital investment in a heat accumulation system, \$; \( K_{PHRS} \) – investment in heat exchangers PHRS, \$; \( C_{i}^{PHRS} \) – change in annual operating costs for safety systems when replacing PHRS heat exchangers, \$; \( R_i \) – the results of the annual use of the heat accumulation complex at the NPP (sale of electricity at the cost of the peak tariff), \$; \( C_i \) – annual operating costs of the heat accumulation system, \$; \( E \) – discount rate; \( T_i / T_n / T_{i} – first / last for the billing period / current year of the investigation, respectively.

The average cost of PHRS heat exchangers was taken as \$ 16.8 million per power unit in accordance with the design documentation for the supply of PHRS equipment to Kursk NPP-2 and Akkuyu NPP. Additional costs, such as: purchase of regulating devices, control systems for PHRS floodhatches, thermal insulation of PHRS heat exchangers, are estimated at \$ 3.75 million. The total cost of installing PHRS heat exchangers for one NPP power unit will thus amount to \$ 20.6 million.

Additional operating costs for maintaining constant readiness arise when using PHRS heat exchangers. According to [17], the annual operating costs range from \$ 0.05 m to \$ 0.27 m, depending on the climatic conditions of the NPP construction. In this paper, for calculations, the annual operating costs are assumed to be \$ 0.14 million and the annual inflation rate is 3%.

Since there is no information on the operating phase transition accumulators in open sources, the assessment of their cost consists in the search and analysis of existing analogues of heat exchangers, similar in design. Table 2 shows some preliminary cost of the main units of the investigated installation.

According to [7-9, 18, 19], the cost of the selected heat accumulation material is assumed to be \$ 1.8 / kg. This cost includes: the cost of accumulating material (0.52 \$ / kg), delivery, customs payments and other deductions, as well as loading the material into the complex.

The cost of the design of the heat accumulator is taken from the calculations of the materials cost and 100% mark-up for their delivery and installation.

According to the TURBOPAR group of companies for 2018, specific capital investments in a 12 MW steam turbine unit will amount to about \$ 646.1 / kW, a 75 MW turbine – \$ 416.9 / kW. In this case, we take into account the costs of condensers and electric generators of additional steam turbines, modernization of the transformer cooling system, input of high-voltage transformers, modernization of the conductors cooling, modernization of the automation control system of the technological process and assembly of all installations [17].

Experience in the design of accumulation tanks for hot and cold water [15] allows to determine the preliminary investment in their construction. The cost of building a 1000 m³ tank in 2004 is estimated at \$ 150 / m³, then, taking into account inflation of 3%, the cost of building 1 m³ in 2019 will be about \$ 265 / m³. For calculations, the delivery and installation of heat-insulating materials are taken into account in the form of a surcharge of 30% of the cost of the tank.

The use of a nitrogen blanket is proposed to prevent instant boiling of feed water of the heat accumulation system circuit in a thermally insulated hot water tank. For this, the installation of a stationary or mobile nitrogen compressor station with an additional booster compressor is necessary. According to [20, 21], the preliminary cost of such equipment based on the volume of a thermally insulated hot water tank is estimated at \$ 1.35 million, including delivery and installation. Electricity consumption for the operation of the unit will be about 0.2 MW / h. Thus, the annual cost of its operation will average about \$ 0.0017 million annually. Additionally, it is necessary to estimate the investment in the construction of the building. An earthquake-resistant foundation is necessary for the building, since multifunctional steam turbines provide an additional reserve for the NPP’s own needs. Based on the
required standards, the cost of installation such a building is assumed to be 20% of the cost of the heat accumulation system.

Electricity tariffs depend on the time of day, region and a range of factors. As consumption at night is reduced, the off-peak electricity tariff becomes significantly cheaper. Under these conditions, the operation of many power generating plants becomes economically unprofitable. The reduction in the selling electricity tariff reaches $0 / kW·h for some regions. For calculations, the range of off-peak electricity tariffs is accepted: 0 – 0.015 $ / kW·h.

Variants of the dynamics of the selling tariff for semi-peak electricity were accepted to calculate the resulting effect from the sale of electricity during the hours of increased load in the power system, based on data from sources from European countries, the USA and the Russian Federation [22–25] (figure 3). The discount rate was adopted at the rate of 11.28% [17].

![Figure 3. Forecast dynamics of the selling tariff for semi-peak electricity](image)

The results of the economic analysis of combining an NPP power unit with a VVER-1000 with the developed heat accumulation system are shown in table 2 and figure 4.

| Equipment                                                                 | Value, $ million |
|---------------------------------------------------------------------------|------------------|
| Accumulation material                                                     | 44.9             |
| Metal heat exchange tube bundle with collector                            | 10.3             |
| Phase transition accumulator jar with thermal insulation                  | 0.66             |
| Drum separator                                                            | 0.23             |
| The main structural elements of the phase transition accumulator + 20% for delivery and installation | 13.4             |
| Hot and cold water tanks + 30% for thermal insulation, delivery and installation | 3.04             |
| Nitrogen compressor station                                               | 1.35             |
| The total cost of the nitrogen compressor station + 20% for delivery and installation | 1.62             |
| Steam turbine 12 MW                                                       | 8.8              |
| Steam turbine 75 MW                                                       | 40.1             |
| Modernization of electrical facilities and automated process control system of the station | 7.58             |
| Construction of building (accepted 20% of the capital investments in the construction of the heat accumulation system) | 13.4             |
| **Total investment**                                                      | **125.3**        |
As seen from figure 4, the system does not receive positive accumulated income for the lowest semi-peak electricity tariff.

4. Conclusion
The heat accumulation system, developed by the authors, with hot and cold water tanks at NPPs with VVER provides reserve for the NPP's own needs due to the use of additional steam turbines, which makes it possible to abandon the installation of expensive PHRS heat exchangers and related equipment; provides the full payback of the system and additional profit under some conditions, due to the generation of electricity in the normal mode.

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