

Structural and operational optimization of the phase transition accumulator during operation as part of a nuclear power plant based on long-term durability

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Abstract. The purpose of the article is the operational optimization of the heat accumulation system taking into account the requirements of the energy market, daily differentiated tariffs and the influence of a specific operating regime on the main equipment performance using the example of a phase transition accumulator installed at a nuclear power plant. There was developed a three-dimensional model for the non-statutory process of flowing fluids and heat-accumulating material hardening which comes as a result of the heat transfer and the stress field exchange between them. The service life of 3D models with various collector wall thicknesses was calculated. There was performed the calculation of the economic effect and pay-back period for options being compared based on of phase transition accumulator operating cycle, his performance with various collector metal wall thickness. The performance change in the economic analyses is based on the useful lives change while the change in daily operating time is based on the power generation change. As a result, the research shows that the most profitable option for accumulated net income is to use a collector with an accumulator wall thickness of 40 mm and the following operation mode: 5 hours charge + 16 hours discharge.

1. Introduction

Covering irregularities in the electrical loads schedule of the Unified Energy System of Russia is a high priority of today. Combining nuclear power plants with heat energy accumulation systems is one of the possible problem solutions. Accumulation due to the phenomenon of phase transition is a promising direction [1-3]. The combination of nuclear power plants with a heat accumulator will make it possible to ensure the operation of reactor plants with the same installed capacity during recession hours of electric loads by reducing the generated electricity during accumulation process. It will also provide additional electricity during peak and half-peak hours due to the use of accumulated night energy [4].

LiNO₃, LiF, NaNO₃, LiCl are widespread as heat accumulation materials for accumulators [5, 6]. However, the melting point of the presented materials does not allow their use in pure form in the considered energy complex. It is possible to use an alloy consisting of LiNO₃ and NaCl to obtain the required operating parameters of the accumulator. [7-9].

The new design of the heat accumulator with phase transition material was developed to provide the possibility of use the heat accumulation system in the required conditions (patent of the Russian Federation No. 179855) (figure 1).



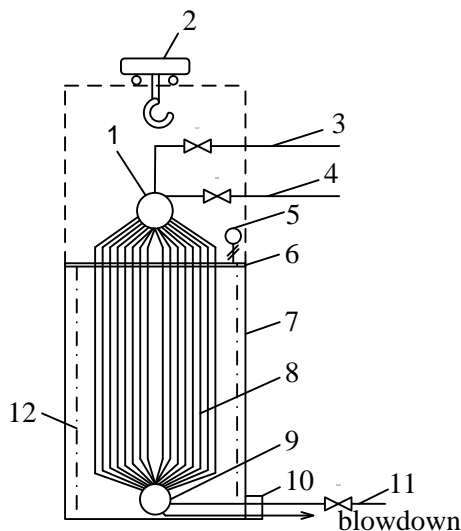


Figure 1. Design of phase transition accumulator. 1 – overhead collector; 2 – overhead traveling crane; 3 – steam conductor; 4, 11 – pipeline; 5 – breathing hole; 6 – tube sheet; 7 – jar; 8 – metal heat exchange tube bundle; 9 – bottom collector; 10 – downtake tube; 12 – glass tubes, in which the parameters control sensors of the heat-accumulating material are located.

Main steam is directed through steam conductor 3 to the overhead collector 1 during charging. Then it is distributed through the metal heat exchange tube bundle 8 and gives off heat to the accumulation material. After that, the steam condenses, merges into the bottom collector 9 and is directed into the main cycle through the pipeline 11.

During the discharge process, feed water is supplied to the bottom collector 9 through the pipeline 11. Then, it is evenly distributed over the heat exchange metal tubes 8. Heated feed water through a pipeline 4 from the overhead collector 1 is directed into the main feed water line in front of the steam generators.

The operating conditions of the phase transition accumulator are characterized by intense thermal power cyclic effects on its structural elements. These effects arise due to changes in pressure and temperature of the coolant in transient operation modes. Damage in the form of fatigue cracks can occur during prolonged exposure to stresses in the equipment structural material. Besides, corrosion processes can intensify, which can lead to a loss in its availability. These processes are non-stationary character and lead to changes in the temperature of the metal structural elements. These effects also have a negative impact on the lifetime of the equipment and, therefore, on the lifetime of the accumulation system as a whole.

A large of cycles amount of exposure to excess pressure and heating-cooling occur in the heat exchange tube bundle as the phase transition accumulator is used. These processes lead to the gradual destruction of heat transfer tubes. Despite a large number of studies of thermal accumulators, a full-fledged study of the unsteady process of heat transfer between a heat-accumulating substance and a heat carrier in a phase transition accumulator (used with NPP) absents. Only the thermodynamic efficiency of the accumulator is investigated, and the design life of the accumulator itself is not considered. The task of lifetime researching of the accumulator structural elements, taking into account the unsteady heat transfer process, is urgent and needs to be solved. Research of the lifetime will optimize the design of the accumulator and make more precise the capital investment in the installation. This will have a direct impact on the annual operating costs: repair, depreciation and others. The results of these researches will allow to fully evaluate the economic efficiency of combining nuclear power plants with phase transition accumulators.

The modern technology for studying fatigue life of equipment under thermocycling influences is based on three-dimensional numerical modelling using computational fluid dynamics programs, stress-strain state calculation programs in combination with mathematical models and durability calculation programs. Based on this technology, modelling of the unsteady thermal state of the heat transfer tubes of the phase transition accumulator is carried out.

2. Description of the computation model

The presence of excess pressure inside the collectors and tubes of the phase transition accumulator leads to the occurrence of mechanical stresses in them. Also, cyclic temperature changes are followed by thermal stresses. The following conditions are accepted for calculating the lifetime of phase transition accumulator:

The temperature of the heat accumulating material, water in the tubes, and phase transition accumulator structural elements after charging is equal to 272 °C. During discharge, water having a temperature of 225 °C is supplied to the down collector of the phase transition accumulator, is heated in the phase transition accumulator and at the outlet has a temperature of at least 245 °C. Thus, in the bottom collector, at the beginning of the discharge process, a difference of 47 °C is observed between the water temperature and the metal temperature.

During charging, steam with a temperature of about 275 °C is supplied to the overhead collector of phase transition accumulator, which has a temperature of about 247°C, which leads to a temperature unevenness of 28 °C. Thus, the analysis of the bottom collector during the discharge of the phase transition accumulator is since the difference between the temperatures of the water and the metal at this element is the largest and that leads to greater thermal stresses.

The study of the bottom collector completely (i.e., along its entire length) is not advisable, because along its length all geometric dimensions are constant and the result of the calculations will be similar at any point and the studying only part of the bottom collector allows to reduce the required computing resources and the calculation time.

3 variants of 3D models of the bottom collector part of the phase transition accumulator with the tube bundle part, which differs from each other by the collector wall thickness were built. The stress calculation for the three variants will determine the optimal wall thickness of the collectors in terms of its lifetime. The geometric dimensions of the collector part with the tube bundle part are presented in table 1. For example, figure 2 shows a 3D model of the collector part with tube bundle part.

Table 1. The geometric dimensions of the part of the collector with part of the tube bundle.

	Value
The inner diameter of the heat exchange tubes, D_t^{in} (m)	0.021
Wall thickness of the heat exchange tubes, δ_t (m)	0.002
The distance between the axes of the tubes of the heat exchange surface in the longitudinal and transverse directions of the collector, δd (m)	0.126
The inner diameter of the collector, D_c^{in} (m)	0.8
Collector wall thickness, δ_c (m)	0.03 (a); 0.04 (b); 0.05 (c)
The number of tubes in the row of the collector, in the transverse direction, n (pcs)	18

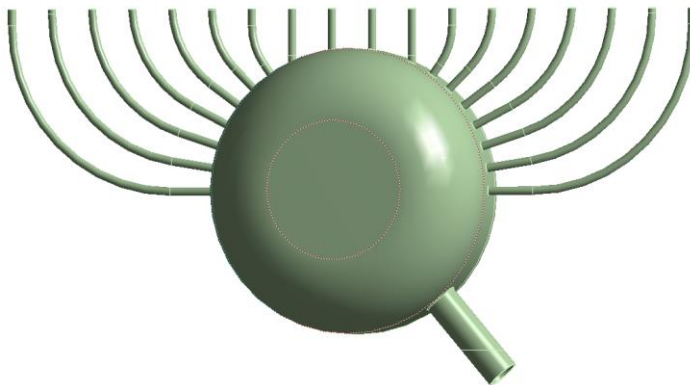


Figure 2. 3D model of the collector and the heat exchange surface of the phase transition accumulator.

In the simulation adopted steel of grade 10. Its physical properties are shown in Table 2.

Table 2. The physical properties of steel of grade 10 depending on temperature.

	Temperature, °C	
	200	300
Density, ρ (kg/m ³)	7800	7765
Elastic modulus, $E \cdot 10^{-5}$ (MPa)	1.99	1.9
Coefficient of thermal expansion, $\alpha \cdot 10^6$ (1/°C)	13.2	13.9
Thermal conductivity, λ (W/(m · K))	53	49.6
Heat capacity, c_p (J/(kg · K))	532	565

Next, an unsteady process of fluid flow and solidification of TAM was simulated. The temperature of the collector metal depending on time was determined.

3. Results and discussion

Based on the data obtained, stresses from temperature non-uniformity and the influence of internal pressure (6.91 MPa) at any point of the calculation model depending on time were determined (figure 3). Figure 4 shows the maximum stresses for all three variants at the corresponding time points. The moment of pressure increases from zero was not simulated, because during this process maximum stresses cannot be achieved.

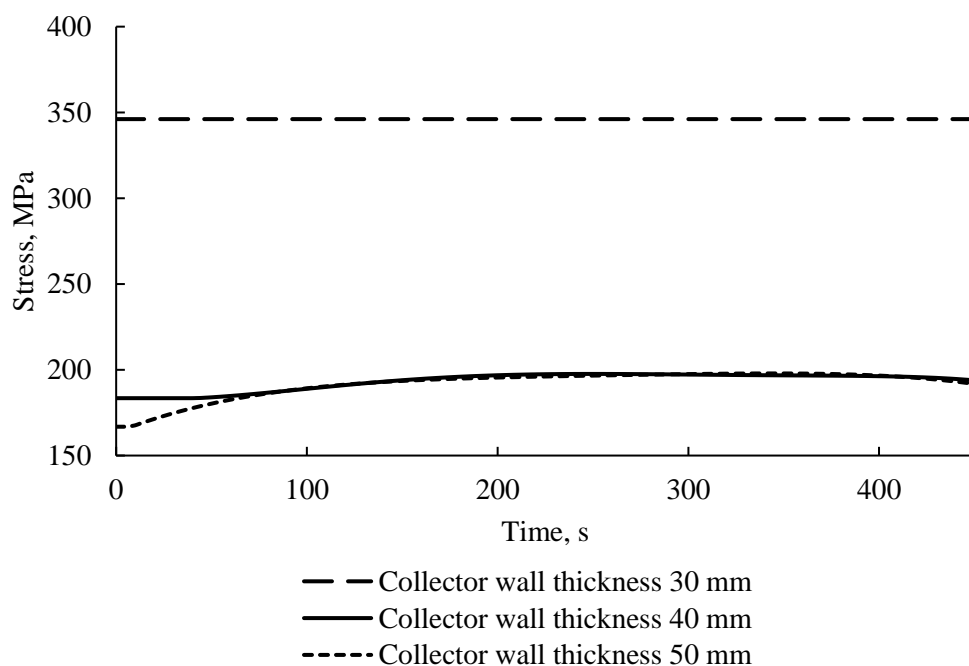


Figure 3. The dependence of the maximum stresses on the time.

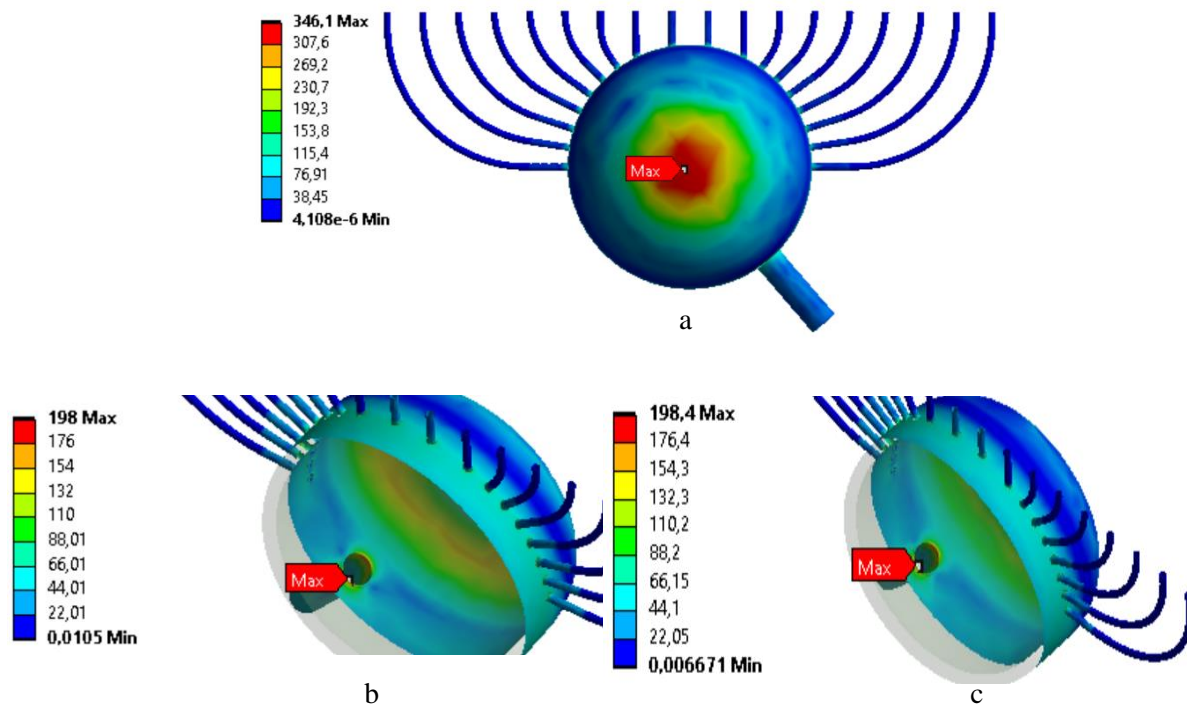


Figure 4. Stress field in 3D models with different collector wall thicknesses, MPa: a – 30 mm; b – 40 mm; c – 50 mm.

Based on the previously obtained data, figure 5 presents a graph of the dependence of the maximum stresses in the calculation model per cycle on its thickness.

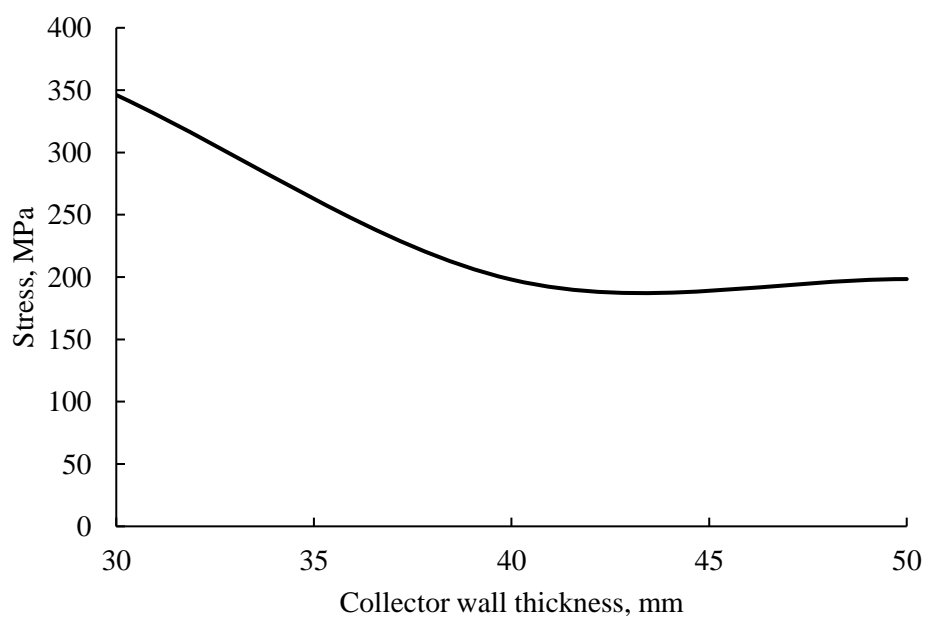


Figure 5. The dependence of the maximum stresses in the calculation model per cycle on its thickness.

It is proposed to use the methodology for calculating equivalent operating hours to estimate the lifetime of the tube bundle of the phase transition accumulator [10]. Equivalent operation hours are determined by the following formula:

$$T_{eq} = a \cdot n + \tau_{sum} + b \cdot \tau_p \quad (1)$$

where a is the coefficient taking into account low-cycle fatigue of the metal for start-up; n is the number of start-ups; τ_{sum} is the total operating time; b is the coefficient taking into account long-term strength when operating equipment with temperatures above the base level; τ_p is the operating time in excess of the base temperature level.

To determine the coefficient a in formula (1), a calculation was made for cyclic fatigue. The purpose of this calculation is to determine the thermomechanical stresses and the number of cycles to failure of the element. The formula for finding the coefficient a is as follows:

$$a = \frac{T_{life}}{N_f} \quad (2)$$

where T_{life} is the lifetime of the element; N_f is the number of cycles to failure.

Finding the coefficient b involves the calculation of long-term strength during operation of the equipment above the basic characteristics. This coefficient can be found by the following formula:

$$b = \frac{T_{life}}{\tau_f} \quad (3)$$

where τ_f is the time to failure of the element during operation of the equipment in excess of the base temperature, which can be defined by the long-term strength equation.

According to the strength calculation standards for stationary boilers and steam and hot water pipelines (RD 10-249-98), the maximum stress amplitudes at wall thicknesses of 30, 40, and 50 mm are 173.1 MPa, 99 MPa, and 99.2 MPa, respectively. Figure 6 shows the dependence of the number of cycles to failure on the stress amplitudes at a temperature of 272 °C, which is the maximum temperature of the metal in the cycle under consideration.

As can be seen from Figure 6, the maximum number of cycles to failure for different collector wall thicknesses is 14,600, 170,000, and 169,000 cycles, respectively.

To calculate the coefficient a , it is necessary to know the factory life of the phase transition accumulator. It was decided to take the accumulator lifetime equal to the guideline life of heat exchangers. According to [11], the guideline life of heat exchangers is 30 years.

Thus, based on the previously presented data, the coefficients a for different collector wall thicknesses are 18, 1.5, and 1.6 hours per start-up, respectively.

Figure 7 shows a graph of the dependence of the equivalent operation hours for a year on the collector wall thickness for three variants of accumulator operating cycles:

- Variant 1 - Operation for 292 days a year for 2 cycles (1 charge for 5 hours + 1 discharge for 6 hours) per day.
- Variant 2 - Operation for 292 days a year for 2 cycles (1 charge for 5 hours + 1 discharge for 12 hours) per day.
- Variant 3 - Operation for 292 days a year for 2 cycles (1 charge for 5 hours + 1 discharge for 16 hours) per day.

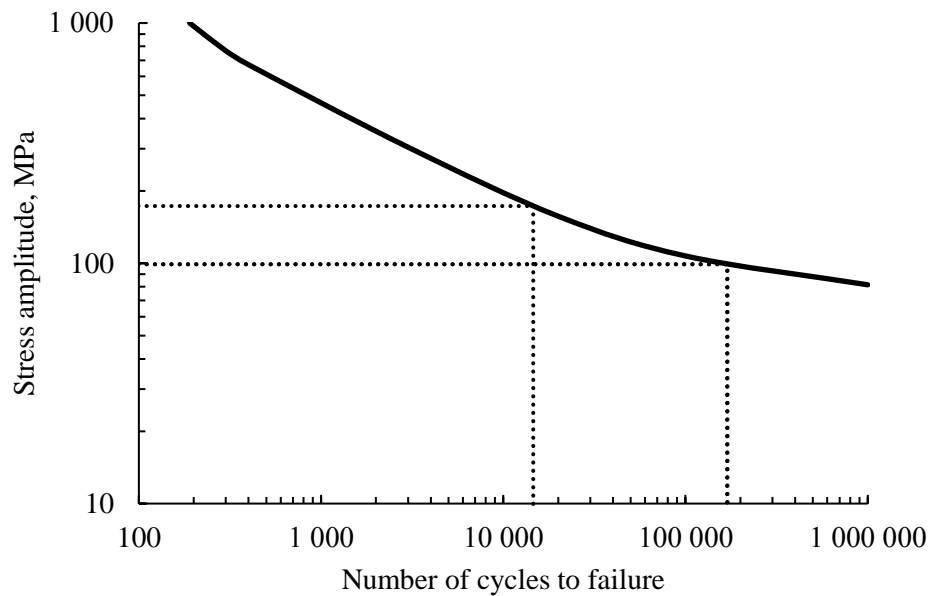


Figure 6. Dependence of the number of cycles to failure on the stress amplitude for carbon steels.

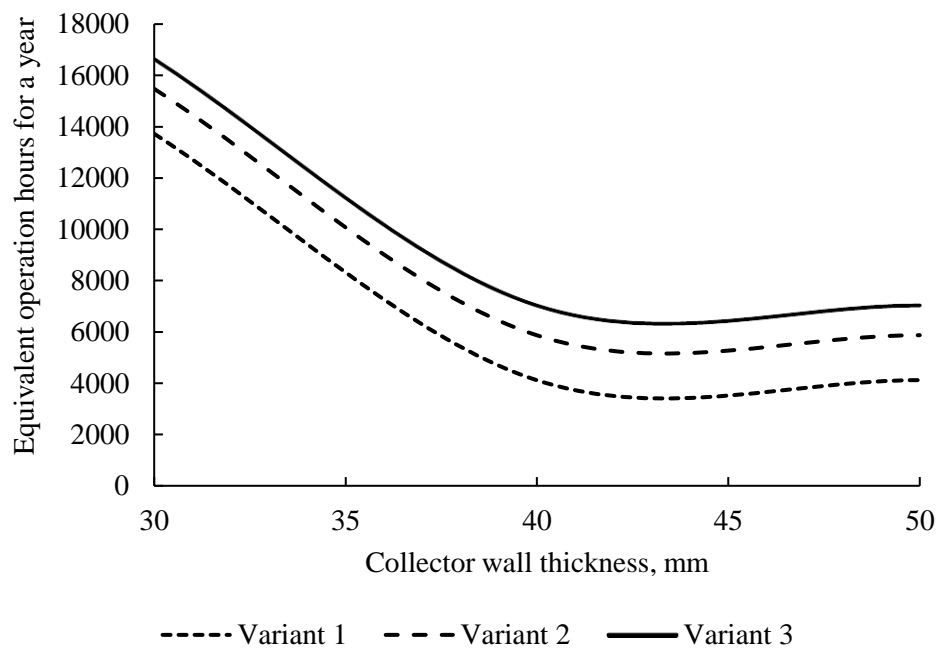


Figure 7. Dependence of the equivalent operation hours for a year on the collector wall thickness and duration of operation per day.

It should be noted that an increase in the collector wall thickness leads to an increase in temperature non-uniformity inside the collector wall. This appears in an increase in stresses in the cycle (figures 3-5), and leads to an increase in the equivalent operation hours for a year, but this begins to appear when the collector wall thickness is more than 40 mm (figure 7).

The economic effect and payback period were calculated to compare different variants for accumulator operating cycles and different accumulator lifetime at different collector wall thicknesses. The need to compare and search for the optimal solution is since with a smaller thickness of the collector wall, there is less investment and useful life. With a larger wall thickness, on the contrary, more investment and longer useful life. An economic calculation for a collector with a wall thickness of 50 mm is not necessary. Obviously, economic indicators will be worse than those of a collector with a wall thickness of 40 mm due to the lower useful life and greater steel intensity of the structure.

The increase in nuclear fuel prices and electricity tariffs was taken from the Forecast of the Ministry of Economic Development for the long-term socio-economic development of the Russian Federation to calculate the accumulated net income and payback period. The investment in the phase transition accumulator is estimated as follows. Since the structure of the accumulator without taking into account the heat accumulation material contains mainly pipes of different diameters and lengths, the cost of the accumulator design is accepted as the retail cost of these pipes with a margin of 10% for delivery and assembly. The cost of heat accumulation material is accepted to be 3.1 \$/kg [12-15]. The dollar rate in the calculations was taken equal to 65 rubles. Based on the data of the TURBOPAR group of companies, the relative capital investment in a low-power steam turbine plant is about \$ 640/kW. The increase in the equipment cost and spends was adopted in the form of inflation, for calculations equal to 3%. The results of the economic calculation are shown in table 3.

Table 3. The results of the calculation of accumulated net income and payback period for different variants for using the phase transition accumulator.

	Variant 1		Variant 2		Variant 3	
Collector wall thickness, (mm)	30	40	30	40	30	40
Capital investment in accumulator design, (\$ million)	0.4	0.5	0.4	0.5	0.4	0.5
Useful life, (years)	19	64	17	45	16	37
Amortization for the accumulator design (in the first year of operation), (thousand \$)	22.5	7.7	24.6	10.8	26.2	13.8
Accumulated net income (time horizon – 60 years), (\$ million)	73.1	76.1	217.0	225.9	312.9	325.7
Payback period, (years)	11.9	12.0	9.1	9.2	8.3	8.4

4. Conclusion

The operational optimization of the heat accumulation system was carried out taking into account the requirements of the energy market, daily differentiated tariffs and the influence of a specific operating regime on the lifetime of the main equipment using the phase transition accumulator installed at nuclear power plants as an example. The paper assesses the effect of cyclic and long-term loads on the lifetime of the collector and tube bundle of the accumulator with different collector wall thicknesses as a result of thermomechanical influences. As calculations showed, a thickness of 40 mm is the most optimal for the collector wall in terms of lifetime. It is shown that the accumulator lifetime depends on its operating mode. As a result of the economic calculation, it was determined that the most profitable option is to use collectors with a wall thickness of 40 mm in the design of the accumulator and an operating mode: 5 hours charge + 16 hours discharge in the half-peak part of the electric load graph.

Acknowledgments

The given research was funded by RFBR according to the research project № 18-38-00881.

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