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THE CONCEPT OF CREATING A MANEUVERABLE POWER PLANT BASED ON A SMALL MODULAR REACTOR

Purpose. To develop a maneuverable power plant (MPP) based on the NuScale small modular reactor (SMR) by selecting a thermal scheme structure for a steam turbine installation using minimal additional equipment and ensuring its operation in both nominal and peak modes with maximum efficiency. This also includes ensuring its maneuverability through the use of hydrogen technologies for generating, storing, and returning energy to the steam turbine cycle.

Methodology. The study employed the method of mathematical modeling of thermodynamic cycles of thermal schemes of steam turbine installations (STI) with concentrated parameters, which makes it possible to describe the dynamics of systems consisting of discrete elements that are thermodynamic systems.

Findings. Various structural options for the thermal scheme of the MPP based on the NuScale SMR for nominal operation were developed and mathematically modeled, followed by a comparative analysis of their energy efficiency. As a result, a scheme and operational parameters were selected with the highest electrical efficiency (net), which allows increasing the net efficiency of the NuScale SMR-based power plant from the developers’ announced 28 to 32.8 %. A thermal scheme for the MPP based on the SMR with an energy storage system was proposed. Applying this scheme allows increasing the net efficiency of a power plant based on NuScale SMR in peak mode to 34.8 %.

Originality. A concept for creation and schematic solution for a prospective MPP based on an SMR capable of accumulating electrical energy was proposed. The main innovative solution regarding the structure of the technological scheme of the MPP based on the SMR is the organization of its operation in nominal and peak modes, which fundamentally differ in the thermodynamic cycle. In the nominal mode, the steam turbine installation operates on a thermodynamic cycle with steam separation, and in the peak mode without it, by increasing the temperature of fresh steam as a result of burning hydrogen and oxygen. Hydrogen and oxygen are produced in an electrolyzer during the power plant’s operation in the nominal mode by using the generated electricity “excess”.

Practical value. Small modular reactors are currently mainly in the development stage. Additionally, the non-nuclear part of the SMR-based power plant, namely the STI, has not received sufficient attention, as evidenced by the literature. However, it plays a crucial role in the overall efficiency of the installation. The study focuses on the highly relevant issue of improving the efficiency of an SMR-based power plant by developing the structure of the STI thermal scheme involving hydrogen technologies. This will help reduce dependence on fossil hydrocarbons in the total volume of primary fuel and enable sustainable functioning of the Ukrainian energy system, as well as contribute to the preservation and improvement of the environmental state.

Keywords: *energy efficiency, thermal scheme, thermodynamic cycle, energy storage, hydrogen technologies, electrolyzer*

Introduction. Nuclear energy plays a crucial role in the energy systems of many countries worldwide. Current nuclear reactors generate over 10 % of the world’s electricity [1, 2]. These reactors generally have gigawatt capacities and are the largest source of carbon-neutral energy generation. According to the United Nations Economic Commission for Europe (UNECE), the share of nuclear energy in electricity production in UNECE member countries is as follows: Belgium – around 48 %, Bulgaria – nearly 39 %, the Czech Republic – approximately 35 %, Finland – 34 %, France – 70 %, Hungary – 48 %, Slovakia – 55 %, Slovenia – 37 %, Spain – 22 %, Sweden – 39 %, Ukraine – 54 %, and the USA – 18 % [1, 3].

Recently, there has been an increasing demand for the construction of new nuclear power plant (NPP) capacities worldwide. This is driven, on the one hand, by the growing need for energy amid declining hydrocarbon resources. On the other hand, NPP operation is not accompanied by CO_2 emissions, which contributes to achieving carbon neutrality [4, 5].

Currently, nuclear energy is evolving with the help of advanced technologies, including small modular reactors (SMRs). These reactors are expected to complement the existing fleet of high-power reactors and open new markets for nuclear energy. SMR-based power plants can supply electric-

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ity to small local grids, be used in remote areas, and increase the volumes of distributed generation in the United Energy System. The attractiveness of SMRs also lies in their ability to operate in a maneuverable mode of electricity generation, allowing for rapid compensation of electricity undersupply from unstable sources like solar and wind power plants [6].

Literature review. SMRs are defined as nuclear reactors with an electrical output ranging from 10 to 300 MW [7, 8]. It is noteworthy that the earliest nuclear power reactors had small capacities, and today, low-power reactors are operated on submarines and marine vessels. The distinction of modern SMRs lies in their design and manufacturing approach, which leverages their small size to integrate innovative passive safety systems, apply new manufacturing technologies (increased factory assembly and standardization), and explore new business models. Many SMRs are being developed with a focus on markets where gigawatt reactors would be too large due to insufficient electricity demand or specific grid characteristics.

SMRs can provide flexible electricity production for a wide range of consumers and applications, including the modernization of fossil fuel power plants by replacing the main equipment. They can also be used to create small electric power systems in even remote unelectrified areas. According to [8], at least 72 SMR concepts are in various stages of development, which is 40 % more than in 2018 [9]. Although the term SMR has been adopted worldwide to denote all small reactor designs, there are significant differences among the main types of SMRs. [10] presents a representative selection of SMRs by their power ranges being developed internationally, with about half of the design concepts based on light water reactor (LWR) technology, and the other half on Generation IV reactor concepts. LWR SMRs and heavy water SMRs from different manufacturers have power ranges from 30 to 450 MW and steam temperatures from 270 to 330 °C. It is worth noting that these steam parameters are some of the significant differences from large NPPs, as the existing nuclear power units and the high-power Generation IV reactors currently being investigated for commercial application have coolant temperatures at the steam turbine inlet exceeding 500 °C [8–10].

Overall, SMR concepts based on LWR technology have the highest degree of readiness with the highest TRL and LRL indicators and are likely to be available for commercial deployment sooner than others.

On January 19, 2023, the U.S. Nuclear Regulatory Commission certified the design of the NuScale Power Module SMR [11]. This is the first certified SMR design, developed by NuScale Power Corporation (USA). The NuScale Power Module is a water-cooled, pressurized light water reactor with natural coolant circulation and a power output of 50 MW and a thermal power output of 160 MW (Table 1).

Table 1

Main characteristics of NuScale [12]

Parameter	Quantity
Electric power (net), MW	45
Electric power (gross), MW	50
Thermal capacity, MW	160
Term of operation, year	80
Refueling cycle, month	24–48
Pressure in the first circuit, MPa	8.72
Pressure of hot steam in the second circuit, MPa	3.1
Hot steam temperature, °C	255
Feed water temperature, °C	149
Efficiency (net), %	28

NuScale consists of a reactor core, a pressurizer, and two steam generators, all housed within a common vessel encased in a compact steel containment cylinder and submerged in a cooling pool. The NuScale Power Module offers promising nuclear energy applications for electricity generation, district heating, desalination, industrial hydrogen production, and other uses of process heat.

In Ukraine, the possibility of constructing energy plants based on the NuScale modular reactor is being considered. The module is fully assembled at the factory and can be delivered to the designated site by rail, road, river, or sea, enhancing its economic attractiveness and deployment flexibility. The nuclear reactor vessel, approximately 19.2 meters in length and 2.8 meters in diameter, is enclosed in a 25-meter-long and 4.6-meter-diameter steel casing [12].

Currently, increasing the net efficiency of SMR-based power plants by improving the efficiency of the steam-water cycle's thermal scheme is a pertinent issue. This topic is addressed in works [12, 13]. The primary goal of article [13] is to study the energy quality and cost of energy flow at SMR-based power plants. The results show that SMR technology makes nuclear power plants safer due to lower reactor temperatures, reduced fuel amounts, and lower flow mass rates. At the same time, the cost of electricity, total exergy, and energy efficiency are comparable to conventional nuclear power plants. In work [14], a scheme with small modular reactors and wind turbines for electricity, hydrogen, and hot water production is examined. The results show that the overall system can achieve an energy efficiency of about 57.5 % and an exergy efficiency of about 38.1 %.

High-efficiency SMR-based power plants should be developed using modern applied thermodynamics methods, particularly through thermodynamic and exergy analyses [15, 16]. For example, exergy analysis [17, 18] is currently being used to study energy transformations occurring in the reactor core. These works consider a pressurized light water reactor [19, 20].

The literature review also examines proposed schematic solutions for improving the efficiency of both large and small nuclear power plants [21, 22]. In work [23], simultaneous electricity production using heat released from nuclear fuel fission and hydrocarbon fuel combustion is proposed. In the authors' proposed scheme, heat from the combustion products of hydrocarbon fuel is used in a superheater to increase the parameters of steam generated in the nuclear reactor. As a result, superheated steam with higher temperature, similar to that in thermal power plants (TPPs), enters the high-pressure turbine rather than saturated or slightly superheated steam typical of traditional NPPs. After partial expansion in the turbine, the steam enters an intermediate superheater where it also receives heat from hydrocarbon fuel combustion products. The downside of this proposal is the use of hydrocarbon fuel, significantly increasing the negative environmental impact. In work [24], combining NPP units with an autonomous hydrogen complex featuring a gas turbine (GT) and a small-capacity steam turbine is proposed. This autonomous hydrogen complex enhances the energy and maneuvering capabilities of the NPP unit and ensures the supply of its own needs for over 72 hours (according to IAEA requirements) using residual heat energy in case of a complete power outage. However, this scheme can be used as an additional complex at a large NPP to improve operational reliability, not as a standalone small-capacity SMR-based power plant. Additionally, during off-peak nighttime hours when unused electricity is accumulated as hydrogen and oxygen, two turbines (GT and additional steam turbine) are stopped. Therefore, this scheme requires a lot of additional equipment that remains idle during off-peak hours. Nonetheless, the scheme presented in work [24] is quite promising and has high efficiency. However, there are currently difficulties with its implementation because GTs operating on a hydrogen-oxygen mixture are still under development. Modern GTs require fuel in the form of gas with hydrogen addition, necessitating the installation of an additional waste-heat boiler for the combined cycle operation.

In article [12], an enhancement of the efficiency of a small nuclear power plant, whose thermal scheme includes the NuScale SMR, a steam turbine unit (STU), and a network energy storage classified as a Carnot battery (an electric heater that heats molten salts when there is an "excess" of electricity in the grid), is proposed. The essence of the method lies in increasing the temperature of the steam generated in the SMR using the heat accumulated in the Carnot battery. Due to the higher temperature at the turbine inlet, the efficiency of the combined generation-storage nuclear power plant is raised to the level of modern thermal power plants (TPPs). The drawback of this method is that the power plant operates on the same thermodynamic cycle both during energy storage in the Carnot battery during off-peak hours (charging process) and its discharge in peak hours. This method significantly increases the plant's efficiency and electrical power output. Still, it requires constant additional steam reheating in the superheater using the accumulated energy in the Carnot battery along with the SMR operation. This means that the Carnot battery charging process is conducted simultaneously with its discharging, reducing the efficiency of the energy storage process. Moreover, the maneuverability of such a plant is limited by the extraction of electrical energy during off-peak hours to heat the molten salts in the Carnot battery. The steam consumption in the steam-water circuit remains unchanged.

As a result of the analysis of literary sources, it can be said that for the development of a maneuverable power plant, one should choose the NuScale light-water SMR, which has passed certification and is the readiest for expansion into mass production, and develop structural and thermal schemes of a highly efficient maneuverable power plant based on this small modular reactor.

Concept of creating a maneuverable power plant based on an SMR. To improve the efficiency and maneuverability of an SMR-based power plant, the authors propose integrating an energy storage system (ESS) that uses hydrogen technologies. During times of surplus electricity in the energy system (usually at night), the power plant operates in a nominal mode, and the steam from the SMR goes directly to the STU. The "excess" electricity generated is stored as hydrogen and oxygen through water electrolysis. During peak electricity consumption hours, the stored gases are used in a hydrogen-oxygen steam generator, allowing an increase in both the temperature and flow rate of the steam before it enters the STU, thereby increasing the thermal and electrical power output of the power plant.

A schematic diagram of the maneuverable power plant based on the SMR with the ESS is shown in Fig.1.

The concept of the maneuverable power plant (MPP) based on a small modular reactor (SMR) with an energy storage system (ESS) involves its operation in two modes: nominal and peak. In the nominal mode, the electricity produced by the power system is partly delivered to the consumer through the grid and partly used for generating hydrogen and oxygen in an electrolyzer. In the peak mode, when there is a shortage of electricity in the power system, the stored "excess" energy in the form of hydrogen and oxygen is returned to the system by burning them in a hydrogen-oxygen combustion chamber. Using high-pressure electrolyzers, gases are produced at a pressure of around 15 MPa without additional energy costs for compression, ensuring their compact storage and additional potential energy of compression, which can also be utilized in peak mode.

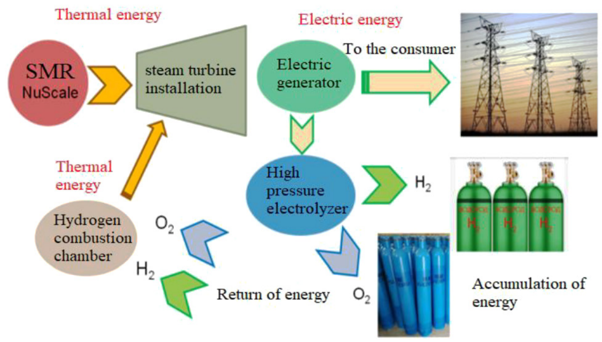

Fig. 1. Structural Diagram of the Maneuverable Power Plant Based on an SMR with ESS

Research objectives and tasks. The research aims to develop a maneuverable power plant based on the NuScale SMR by selecting the structure of the thermal scheme for a steam turbine unit (STU) using minimal additional equipment. The plant should operate efficiently in both nominal and peak modes and ensure maneuverability through hydrogen technologies for generating, storing, and returning energy to the STU cycle.

To achieve the stated objective, the following tasks must be completed:

- to develop various options for the structure of the thermal scheme for the steam turbine unit (STU) with the NuScale SMR, considering recommendations for organizing the thermal scheme of nuclear power plants (NPPs) operating on saturated steam for nominal mode operation;
- to develop a thermal scheme for the STU with the NuScale SMR for peak mode operation;
- to propose a general thermal scheme for the maneuverable power plant with the NuScale SMR.

Design features of NPP steam turbines. The main features of NPP steam turbines are related to their operation on saturated steam and, consequently, a relatively small temperature drop (large steam flow rate). Since the steam enters the turbine saturated, it quickly becomes wet as it expands in the turbine. The maximum allowable moisture content of the steam should generally not exceed 8–12 % to avoid intensive erosion wear of the blade apparatus by water droplets. When the maximum moisture content is reached, all the steam is diverted from the high-pressure section (HPS) and passed through a separator-reheater (SR), where it is dried and reheated. Some steam is extracted from the separator to remove moisture and then directed to the regenerative system. The efficiency of moisture removal increases with the amount of extraction, but this also leads to a reduction in electricity generation from the steam.

For intermediate reheating, superheated steam is usually used, and its drainage is collected in the deaerator.

The HPS of the turbine is single-flow, while the low-pressure section (LPS) of the turbine is usually double-flow. The negative impact of steam moisture on the thermal economy of the plant is significant – the internal relative efficiency of the turbine decreases when operating with wet steam.

It is roughly estimated that an increase in the average moisture content of the steam by 1 % leads to a decrease in the internal relative efficiency of the turbine by approximately 1 %.

One important task when developing SRs is choosing the pressure within them, known as the separation pressure. It has been established [25] that for turbines with unit capacities greater than 1,000 MW, a higher separation pressure should be chosen, while for capacities of 1,000 MW and below, a lower separation pressure should be selected.

In some cases, it is suggested to eliminate the intermediate reheater, replacing single-stage separation and intermediate reheating with two-stage separation. This proposal would allow the removal of the intermediate reheater, which has large dimensions and low reliability.

The structure of the steam turbine unit for the NuScale SMR is presented in [12], which includes a separator and intermediate steam reheating between the high-pressure and low-pressure sections of the turbine. However, this structure is not final, as the non-nuclear part of the power plant, namely the STU based on the SMR, is still in the design stage. Therefore, it is extremely necessary and timely to develop the structure of the thermal scheme for the STU with the highest efficiency.

Mathematical model of calculation of thermal schemes of power plant. To develop the thermal scheme structure for the STU, the method of mathematical modeling of thermodynamic cycles of thermal schemes for power plants with concentrated parameters was used.

The calculations were carried out using a software package developed at the A.M. Pidgorny Institute for Mechanical Engineering Problems of the National Academy of Sciences of Ukraine. The basic mathematical model and the software package are adapted for power plant calculations and verified based on studies of thermal schemes of large-scale combined heat and power plants (CHP). The verification object was the T-100/120-130 turbine of power units Nos. 1 and 2 at PJSC "Kharkiv CHP-5" [26].

The mathematical model allows describing the processes occurring in the elements of the power plant using the following equations: energy balance for each element of the scheme, flow balance for each energy carrier of each element of the scheme, hydraulic balance for each energy carrier for each element of the scheme, and enthalpy change for each energy carrier in the elements of the scheme [26].

The principal thermal scheme of the power plant is represented as separate elements connected by certain signals, as mentioned earlier. Energy flows are used as connecting signals. The calculation of the physical properties of the working fluid at specific points is performed through two-dimensional linear interpolation using previously calculated tables of working fluid properties at reference nodes.

Below are the main equations used during the calculation of the STU thermal scheme.

The adiabatic efficiency of the k^{th} stage of the turbine section is determined as

$$\eta_{Tk} = \frac{(h_{ent} - h_{out})_k}{(h_{ent} - h_{out(s)})_k},$$

where $h_{out(s)}$ is enthalpy of steam at the exit from the turbine, which is determined when the entropy is equal $s = s_{\text{ent}}$ at $P = P_{\text{out}}$.

Calculation of water enthalpy increase in the pump

$$(h_{out} - h_{ent})_k = \frac{v_{mid.ent}(P_{out} - P_{ent})_k}{\eta_{Hk}},$$

where $v_{mid.ent}$ is average specific volume of water in the pump; η_{Hk}– isentropic efficiency of the k^{th} pump.

The fraction of steam α_k, which condenses in the separator and is removed as condensate to the deaerator, is defined as

$$\alpha_k = (1 - x_k),$$

where x_k is the dryness fraction of the steam at the inlet of the separator.

The internal efficiency η_i is the ratio of the work done by the turbine, which is determined as the difference in enthalpies considering the reduction in steam flow for extractions, to the heat supplied to the water in the SMR.

Development of the thermal scheme for the steam turbine power plant with NuScale SMR (Nominal Operating Mode). Various structural options for the thermal scheme of the STU with the NuScale SMR are proposed (Table 1), as shown in Figs. 2–5. The exergy analysis of these schemes is presented in work [27]. In this work, we will focus on them from the perspective of creating an MPP. In the figures, the points of the thermodynamic cycle of the working fluid are labeled with numbers from 1 to 18, and the parameters of the cooling condenser water are labeled as points 19 and 20.

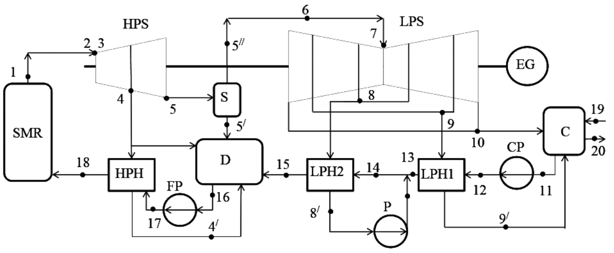

Fig. 2. Scheme 1 with steam separator:

D – deaerator; S – separator; EG – electric generator; C – condenser; CP – condensate pump; FP – feed pump; P – booster pump

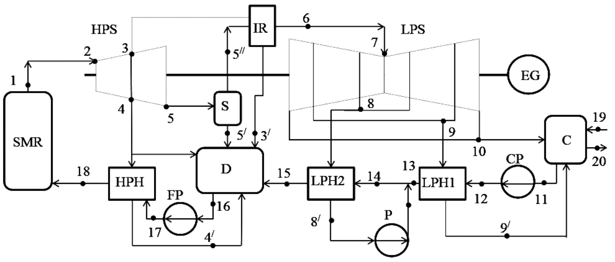

Fig. 3. Scheme 2 with steam heater (IR) at $P_3 = P_4$ and S

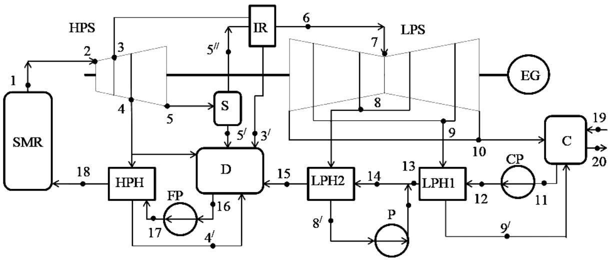

Fig. 4. Scheme 3 with IR at $P_3 > P_4$ and S

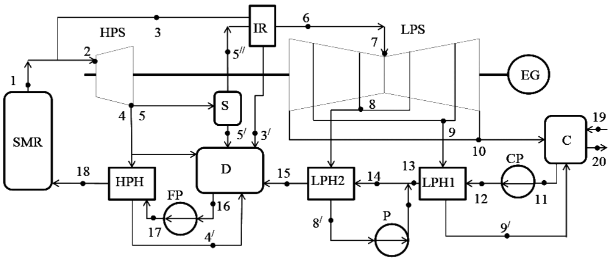

Fig. 5. Scheme 4 with Separator (S) and IR operating on fresh steam at $P_1 = P_3$

When calculating the thermodynamic parameters of the cycles, assumptions recommended for the calculation of NPP thermodynamic cycles were adopted. Considering the throttling of steam in the control organs of the high-pressure section of the STU, pressure losses were assumed to be 5 %. Thus, the pressure at the inlet of the high-pressure section (HPS) of the STU is $P_2 = 2.945$ MPa. At this pressure and steam enthalpy $i_1 = i_2$ its temperature is $T_2 = 252.5$ °C.

The pressure losses during the intermediate reheating of steam before the low-pressure section (LPS) of the STU were assumed to be 10 %. The pressure losses due to throttling of steam at the LPS inlet were also considered to be 5 %. The steam pressure at the inlet of the high-pressure heater (HPH) and low-pressure heater (LPH) was assumed to be equal to the steam pressure at the extraction points, with no pressure losses considered. The temperature of the intermediate reheating of steam was taken as 5 °C below the temperature of the saturated steam at the steam extraction pressure going to the intermediate heater (IR).

In *Scheme 1* (Fig. 2), after the high-pressure section (HPS), a separator is installed. The condensate from the separator goes to the atmospheric deaerator. In this scheme, there is no steam extraction for intermediate reheating, and the steam parameters at point 2 are equal to their parameters at point 3.

In *Scheme 2*, the steam pressure $P_3 = P_4$, meaning that a portion of the steam from this extraction goes to the deaerator (D) and the high-pressure heater (HPH), while another portion is directed to the intermediate reheater (IR) (Fig. 3).

In contrast to *Scheme 2*, in *Scheme 3* P_3 is greater than P_4. Thus, a separate steam extraction is organized for the IR (Fig. 4).

In *Scheme 4*, the pressure and temperature of the steam supplied to the IR are equal to $P_3 = P_1$, $T_3 = T_1$ and the pressure and temperature of the steam from the extraction are $P_4 = P_5$, $T_4 = T_5$ (Fig. 5). Therefore, Scheme 4 requires the use of a high-pressure deaerator (HPD), unlike *Schemes 1–3*. Since the temperature of the feedwater after the HPD is approximately 149 °C at $P_{16} = 0.46$ MPa, the HPH is not present.

When calculating the thermodynamic parameters of the thermal schemes, the fixed parameters were selected as follows: steam parameters at the outlet of the SMR (3.1 MPa, 255 °C); feedwater temperature at the inlet to the SMR: (149 °C); the difference between the saturation line steam temperature and the feedwater temperature at the inlet to the SMR (at the outlet of the HPH or HPD) is $\Delta T_{fwh} = 3$ °C, parameters of the second extraction to the HPH or HPD $P_4 = 0.5018$ MPa, $T_4 = 152$ °C; The difference between the saturation line steam temperature and the feedwater temperature at the outlet of the low-pressure heaters (LPH1 and LPH2) is $\Delta T_{\text{lph}} = 5$ °C; moisture content at the outlet of the low-pressure section LPS (12 %); steam parameters at the condenser inlet (4 kPa); steam flow rate through the SMR ($G = 71.2$ kg/s); pump efficiencies (0.75); adiabatic efficiencies of HPS – 0.92 (from point 3 to point 4) and 0.9 (from point 4 to point 5), adiabatic efficiencies of LPS – 0.89 (from point 7 to point 8), 0.87 (from point 8 to point 9) and 0.85 (from point 9 to point 10) (Figs. 2–5).

The variable parameters were chosen as follows: parameters of the first extraction to the IR; exhaust parameters of the HPS; and extraction parameters for the low-pressure heaters LPHs.

The steam parameters in the deaerator were calculated using the heat balance equation to ensure that the moisture content at the outlet of the LPS for all scheme options was equal to 12 %.

The selection of the LPS structure was carried out by varying the steam pressure in the LPS extractions while keeping the HPS steam parameters fixed for all schemes. During the calculation of thermodynamic parameters, dependencies were obtained showing that the highest values of relative internal efficiency of the actual cycle approximately correspond to the condition $\delta\delta T = (T_8/T_9 - T_9/T_{10}) = 0$, where T is measured in Kelvin. The most efficient mode was found to be achieved at a first extraction pressure of $P_8 = 0.09$ MPa and a second extraction pressure of $P_9 = 0.02$ MPa.

Table 2 shows the maximum internal relative efficiencies $\eta_i^{\max}$ for each scheme obtained in the calculation study by varying cycle parameters, as well as the corresponding steam parameters.

In Table 2, G_3, G_4, G_5 denote the steam flow rates from the respective extractions, and $(1 - x_5)$ indicates the steam moisture content at the inlet to the separator (*S*).

Table 2

Parameters of a pair of thermal schemes 1–4

No. schemes	P_3, MPa	T_3, °C	P_4, MPa	T_4, °C	P_5, MPa	TT_5, °C	$(1-x_5)$, %	$\eta_i^{\max}$, %
1	–	–	0.502	152	0.140	109.3	14.02	34.29
2	0.502	152.0	0.502	152	0.220	123.3	12.41	34.20
3	0.84	172.5	0.502	152	0.270	130	11.66	33.99
4	2.945	252.5	–	–	0.502	152	8.98	33.82

Variants of all schemes with one low-pressure heater (LPH) were also considered. However, it was found that compared to schemes with two LPHs (Figs. 2–5 and Table 2), the maximum internal efficiencies η_i for each such scheme are approximately 1.5 % lower.

From Table 2, it can be seen that Scheme 1 demonstrates the highest gross efficiency η_i with the lowest pressure at the outlet of the high-pressure section (HPS) (34.29 %). This corresponds to a net efficiency of 32.77 %, calculated as

$$\eta_e^{STI} = \eta_{SMR}\eta_i\eta_M\eta_{EG},$$

where η_{SMR} is efficiency accounting for losses in the *SMR* (0.98); η_i – internal efficiency; η_M – mechanical efficiency, accounting for losses in bearings and the oil pump drive of the turbine unit (0.995); η_{EG} – efficiency of the electric generator (0.98).

Thus, the most rational thermal scheme chosen is *Scheme 1*, which does not include the intermediate reheater (IR).

Development of the thermal scheme for the STU of the maneuverable power plant based on SMR with ESS in peak mode. In this study, unlike the scheme presented in [12], a thermal scheme for a maneuverable power plant based on SMR is proposed, operating in two modes (nominal (Fig. 2) and peak (Fig. 6)), which fundamentally differ in their thermodynamic cycles (Fig. 7).

Calculations showed that with steam pressure at the inlet to the combustion chamber (CC) $P_1 = 3.1$ MPa, its temperature can be increased to 450 °C while maintaining the steam parameters at the inlet to the low-pressure section (LPS) (Fig. 6). This is clearly shown in Fig. 7 when comparing the thermodynamic cycles of the HPS and LPS in the two modes.

The thermal scheme for the STU with SMR for peak mode operation differs from *Scheme 1* (Fig. 2) in that the STU receives superheated steam at a higher temperature from the hydrogen combustion chamber (CC) located after the SMR. Therefore, in this mode, the separator is turned off, and the steam from the HPS goes directly to the LPS. The excess steam generated by burning the hydrogen-oxygen mixture in the CC is condensed and directed to the feedwater tank (FWT) for subsequent electrolysis during nominal mode operation.

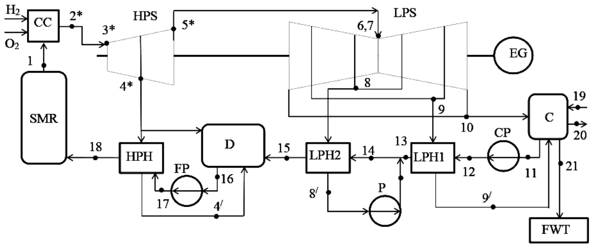

Fig. 6. Thermal scheme for STU with SMR for peak mode operation. FWT – feedwater tank

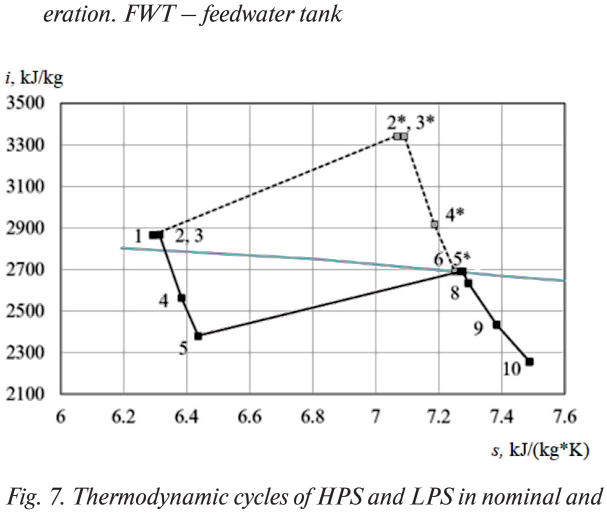

Fig. 7. Thermodynamic cycles of HPS and LPS in nominal and peak modes:

——— – nominal mode; - - - - - – peak mode

General scheme of the maneuverable power plant based on SMR with ESS. The general scheme of the maneuverable power plant (MPP) based on a small modular reactor (SMR) with an energy storage system (ESS), operating in both nominal and peak modes, is shown in Fig. 8 [28]. Fig. 8 also illustrates the cycle points of the working fluid corresponding to Fig. 7.

The MPP based on the SMR with ESS (Fig. 8) includes an energy storage system and consists of a small modular reactor, a power block that includes primary and peak condensation turbines with a shared condenser and heat regeneration system, and primary and peak electric generators. In nominal mode, the electricity from the primary electric generator is partially supplied to the grid and partially used for hydrogen and oxygen generation. The peak electric generator operates in parallel with the primary one only in the peak mode, with all generated electricity supplied to the grid. The transition from nominal to peak operation modes is carried out using valves.

The implementation of the ESS as a hydrogen complex allows for the storage of energy from environmentally friendly substances, hydrogen, and oxygen, during off-peak hours when the primary turbine operates on saturated steam in the primary mode. These substances are then burned during peak electricity consumption hours in the peak steam generator without CO_2 emissions. This enables both the primary and peak turbines to operate on superheated steam in peak mode.

Including the peak condensation turbine in the power block allows the primary condensation turbine to work on superheated steam in peak mode with higher efficiency and power without changing its dimensions, thanks to a balanced redistribution of steam flow between the peak and primary turbines from the peak steam generator.

Discussion of research results. To develop the thermal scheme for the MPP based on the SMR with ESS, the following initial data for the NuScale SMR were accepted: temperature and pressure of the superheated steam at the turbine inlet: 255 °C, 3.1 MPa, feedwater temperature: 149 °C, thermal/electrical power – 160 MW/45 MW. Four variants of the STU thermal scheme were analyzed, differing in the presence/absence of an intermediate reheater before the low-pressure section and the locations of steam extractions supplied to the reheater. For each scheme, the highest efficiencies were determined through thermodynamic analysis at optimal values of the first extraction parameters for the IR, HPS exhaust, and extractions for the low-pressure heaters.

From the examined schemes, the rational choice was the one with steam separation and without an intermediate reheater. The application of this scheme allows for increasing the net efficiency of the NuScale SMR-based power plant from the developers' announced 28 to 32.8 % when the STU operates in nominal mode. It should be noted that the obtained efficiency value of 32.8 % is not the limit, as it is calculated for the case of a typical turbine efficiency. The proposed concept involves creating a maneuverable power plant (MPP) based on a small modular reactor (SMR) with an energy storage system (ESS), which operates in two modes (nominal and peak) that fundamentally differ in their thermodynamic cycles. Specifically, in the nominal mode, only the primary turbine is engaged, operating on the typical nuclear power plant (NPP) thermodynamic cycle with steam separation. In the peak mode, both the primary and peak turbines operate on the typical thermal power plant (TPP) cycle. Residual electrical energy produced in nominal mode during off-peak hours is used to generate oxygen and hydrogen in the electrolyzer. All the electricity produced during peak load times is supplied to the grid, and the generated hydrogen and oxygen are burned in the combustion chamber. It has been established that switching the plant from nominal to peak mode increases its efficiency by 2 %, reaching 34.8 %. Such an increase in efficiency is primarily due to the fact that in the peak mode, burning the hydrogen-oxygen mixture significantly raises the temperature of the steam supplied to the steam turbine section of the plant.

It should be noted that this research was conducted within the framework of the program II-25-23 "Improvement and development of the main equipment of turbine units for NPP units, including the use of small modular reactor technologies and energy storage, to ensure energy security and sustainable development of Ukraine's economy during war and post-war periods", this program comprehensively investigates the issues of improving turbine efficiency using modern methods for calculating three-dimensional compressible viscous flows and spatial profiling of blade machines [29]. It also analyzes daily load graphs in the Unified Energy System (UES) of Ukraine to determine the necessary amount of hydrogen to ensure the operation of the MPP based on SMR with ESS during this time and develops the design of the hydrogen-steam-oxygen combustion chamber. It was found that the minimum oxygen concentration in the mixture with water vapor, to be used as an oxidizer for burning hydrogen, is 25 %. The calculated adiabatic temperature for the stoichiometric $H_2/O_2/H_2O$ mixture is 2,454 K.

Recommendations were developed for burning hydrogen in the combustion chamber in a mixture of water vapor and

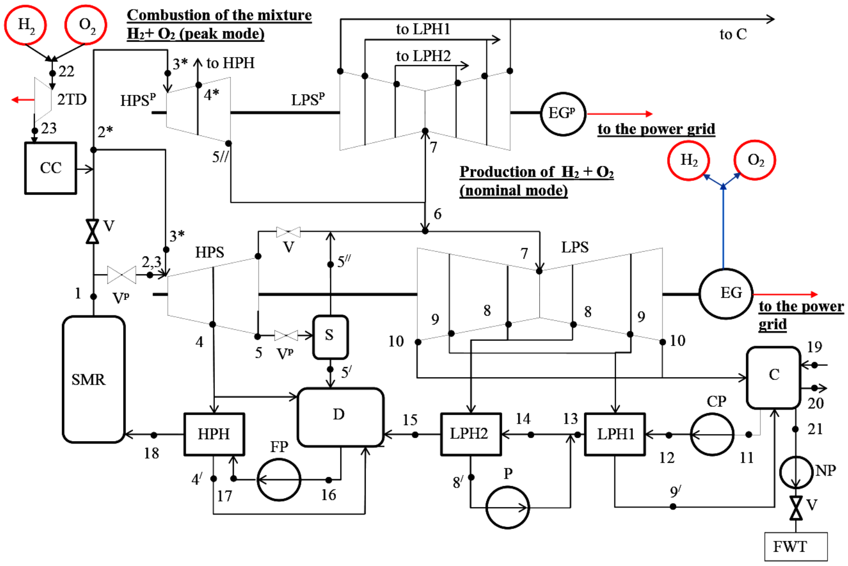

Fig. 8. General thermal scheme of the MPP based on SMR with ESS:
2TD – two turbo-expanders; V – valves closed in nominal mode; V^p – valves closed in peak mode

oxygen, ensuring uniform saturation of the primary (oxidizer) steam with oxygen.

Further studies will conduct detailed calculations of the condenser for operation in two modes and the turbo-expanders (Fig. 8).

Conclusions.

1. Various structural options for the thermal scheme of the MPP based on the NuScale SMR for nominal mode operation were developed and compared in terms of net efficiency. As a result, the scheme with the highest net efficiency, operating on the typical NPP thermodynamic cycle with steam separation after the HPS without further reheating, was chosen. The application of this scheme increases the net efficiency of the NuScale SMR-based power plant from the developers' announced 28 to 32.8 %.

2. Based on the rational variant of the thermal scheme for a nominal mode operation, a thermal scheme for the MPP with SMR and a hydrogen-oxygen combustion chamber (CC) for a peak mode operation was proposed, operating on the typical TPP cycle without steam separation after the HPS. In the peak mode, the net efficiency is 34.8 %, an additional 2 % increase compared to the proposed scheme for the nominal mode operation. The CC creates an additional steam flow of 3.8 % of the steam flow $G = 71.2$ kg/s from the SMR.

3. A thermal scheme for the MPP based on the SMR with ESS, operating in two modes (nominal and peak), was proposed. In the nominal mode, the net electrical power $N_{net} = 52.17$ MW, while in the peak mode – $N_{net} = 70.31$ MW. The use of a maneuverable power plant based on a small modular reactor with an energy storage system improves the efficiency and maneuverability of the small-scale NPP's operation.

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Концепція створення маневреної енергетичної установки на базі малого модульного реактору

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Мета. Розроблення маневреної енергетичної установки (МЕУ) на базі малого модульного реактора (ММР) NuScale шляхом вибору структури теплової схеми паротурбінної установки за умови використання мінімальної кількості додаткового обладнання й можливості її роботи в номінальному та піковому режимах із максимальною ефективністю, а також забезпечення її маневреності за рахунок використання водневих технологій для генерації, накопичення й повернення енергії до циклу паротурбінних установок (ПТУ).

Методика. У роботі було використано метод математичного моделювання термодинамічних циклів теплових схем ПТУ із зосередженими параметрами, які дозволяють описувати динаміку систем, що складаються з дискретних елементів, саме якими є термодинамічні системи.

Результати. Розроблені різні варіанти структури теплової схеми МЕУ на базі ММР NuScale для роботи в номінальному режимі та проведене їх математичне моделювання, а також порівняльний аналіз за енергетичною ефективністю. У результаті обрана схема й параметри режиму роботи з найбільшим електричним ККД (нетто), застосування якої дозволяє підвищити ККД (нетто) енергоустановки на базі ММР NuScale з анонсованого розробниками 28 до 32,8 %. Запропонована теплова схема МЕУ на базі ММР із системою накопичення енергії. Застосування цієї схеми дозволяє підвищити ККД (нетто) енергоустановки на базі ММР NuScale при роботі у піковому режимі до 34,8 %.

Наукова новизна. Запропоновані концепція створення та схемне рішення перспективної МЕУ на базі ММР, що здатна акумулювати електричну енергію. Основним новітнім рішенням щодо структури технологічної схеми МЕУ на базі ММР є організація її роботи в номінальному й піковому режимах, що принципово відрізняються за термодинамічним циклом. У номінальному режимі паротурбінна установка працює за термодинамічним циклом із сепарацією пари, а у піковому — без неї, завдяки підвищенню температури свіжої пари в результаті спалювання водню й кисню. Водень і кисень виробляються в електролізері під час роботи енергоустановки в номінальному режимі за рахунок використання «надлишків» згенерованої електроенергії.

Практична значимість. Малі модульні реактори наразі в основному знаходяться на стадії розроблення. Крім того, неядерній частині енергоустановки на базі ММР, а саме ПТУ, не приділяється достатньо уваги, про що свідчать літературні джерела. Але вона відіграє не останню роль в ефективності всієї установки. У роботі приділена увага вкрай актуальному питанню підвищення ефективності енергетичної установки на базі ММР шляхом розроблення структури теплової схеми ПТУ із залученням водневих технологій, що допоможе зменшити залежність від використання викопних вуглеводнів у загальному обсязі первинного палива та уможливить стале функціонування української енергетичної системи, а також сприятиме збереженню й поліпшенню стану довкілля.

Ключові слова: *енергетична ефективність, теплова схема, термодинамічний цикл, накопичення енергії, водневі технології, електролізер*

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