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Thermodynamics of GT-MHR-250 modular nuclear plant with helium reactor and gas turbine based on the complex Brayton cycle

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ABSTRACT

Although most of the discussed Gas Turbine Modular Helium Reactor power plants are based on the Rankine cycle, the use of the complex Brayton cycle can be an advantage. However, scientific papers published in recent years do not evaluate this combination in more detail. This paper provides a thermodynamic analysis of the modular nuclear plant with thermal power of 250 MW, consisting of a helium-cooled nuclear reactor and the energy conversion unit, using the vertical gas turbine operating according to the complex Brayton cycle. Two modes of nuclear plant operation were considered, mainly electricity generation and combined electricity and heat production. The energy conversions unit parameters, such as the electrical efficiency, electrical power, and thermal power of heat regenerator and heat exchangers were obtained and analyzed. The results have confirmed that high cycle efficiency in the electricity production mode can be obtained if the best parameters of all in-plant elements currently achieved in the modern gas turbine and power engineering industries are used in the design. As found, the temperature coefficient of helium intercooling demonstrates a great impact on the nuclear plant's electrical efficiency and electrical power. The sensitive analysis was carried out to assess the reduction of GT-MHR-250 performance due to deterioration of the in-plant elements (turbine, compressor, heat exchangers) during operation. In this case decrease in the plant's electrical efficiency and electrical power is more noticeable in the combined mode rather than in the electricity generation.

1. Introduction

Currently, approximately 80 % of the world's energy demand comes from fossil fuels, while only about 30 % of the energy is used to produce electricity. Climate warming and environmental issues are accompanied with fossil energy generation. There are many approaches have developed and continue to develop to decrease the environmental load from fossil fuels combustion that focused research interests on the mixing biofuels, syngas, and hydrocarbon fuels [1,2]; application of combustible and non-combustible additives to fossil fuels, for example, water (coal-water fuel) [3] or glycerol [4]; on the specific treatment of the fuel composition before or during the combustion [5], and on the organizing of the combustion in some more efficient way [6–8]. Much research was also devoted to the utilization of coal and oil waste [9], ammonia combustion for power engineering purposes [10], and hydrogen energy utilization [11,12]. However, none of them do implement on the industrial level, up to date the main part of electricity and heat generation is based on the combustion processes. On the other hand, the deep energy crisis that is developed in the world due to natural gas market price manipulation by Russia clearly shows that mankind needs another energy source, which would be sustainable and environmentally friendly.

Nuclear energy is now being employed for about 14 % of the world's electricity production, moreover, in some countries (France, and Belgium) nuclear power dominates by producing over 60 % of the electrical energy. Nuclear power could be the option for reducing carbon dioxide emissions; for example, nuclear power plants in Europe reduce annually up to 700 million tons of CO_2 discharged into the atmosphere. From this point of view, nuclear energy is considered "green energy".

As of the year 2021, more than 440 nuclear power reactors are in the operation throughout the world, over 100 of them are in the United States, while about 200 are in France, China, and Russia. In addition, more than 50 nuclear reactors are now under construction in different countries. Currently, the park of nuclear power stations is based on reactors from 1000 to 1600 MW of thermal power. However, they are difficult to operate and control, occupy a large area, and require many maintenance personnel (1 person per 1 MW of plant capacity). In recent

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Nomenclature:

C_p	specific heat at constant temperature (J/kg·K)
C_v	specific heat at constant volume (J/kg·K)
G	mass flow rate (kg/s)
N_e	electrical power (W)
N_t	thermal power (W)
P	static pressure (Pa)
Q_1	reactor thermal power (W)
Q_r	regeneration heat (W)
s	entropy (J/kg·K)
T	temperature (K)
t	temperature (°C)

Greek letters:

τ_k	temperature coefficient of intercooling
η_{tcuw}	cycle useful work
ξ	relative pressure losses
σ	heat recovery rate

Subscripts:

c	“cold” channel
e	electricity
h	“hot” channel
hpc	high-pressure compressor
inter	intercooling heat exchanger
lpc	low-pressure compressor
prel	preliminary heat exchanger
r	regenerator
t	turbine
GT	gas turbine
MHR	Modular Helium-Cooled Reactor
ORC	Organic Rankine Cycle
PEM	Proton Exchange Membrane (fuel cell)

years, the movement towards more flexible and low-power units of (200 – 600) MW occurred, operating independently or as a part of larger energy systems.

As of today, the basis of the world nuclear plants is the second generation of nuclear reactors, the third generation is just beginning to be commissioned, while the fourth generation is under development to be introduced into the practice for the next 10 – 20 years. The priority trend for the nuclear plants of the fourth generation is a high (first) level of safety for the population and environment, high resistance to equipment failures and personnel errors, and limited radiation consequences in case of severe accidents. Such reactors will be based on the important property of “internal safety”, i.e. the more its core heats up in case of an accident, the weaker nuclear reaction speed occurs leading to the reactor’s independent shutdown.

Currently, world-leading companies from the USA, Russia, France, Japan, China, Argentina, Brasil, Korea, and other countries were involved in the international “Generation IV Nuclear Reactors” (“Gen-IV”) program. They agreed to concentrate their scientific skills and financial recourses on six reactor designs, which include [13]: (i) gas-cooled fast reactors (GFR); (ii) very high-temperature reactors (VHTR); (iii) sodium-cooled fast reactors (SFR); (iv) lead-cooled fast reactors (LFR); (v) molten salt reactors (MSR); and (vi) super-critical water-cooled reactors (SCWR).

Among these directions, the VHTR trend, and in particular the GT-MHR concept (Gas Turbine – Modular Helium Cooled Reactor), based on the coupling of a helium-cooled nuclear reactor with a closed-cycle gas turbine (“nuclear gas turbine”) [14] seems to be the very attractive configuration, which can be realized soon, based on the existing and proven technologies. The GT-MHR concept offers several advantages, such as unique reactor safety, high nuclear plant efficiency, low environmental impact, high proliferation resistance, and competitive electricity cost.

The usage of helium as a working medium has many advantages. The helium is an inert gas; so this excludes the removal of radiation from the reactor core. Thermophysical properties of helium allow effective cooling of the reactor core. Besides, helium has very low molecular mass and very high individual gas constant; as known, the gas constant is equal to the work done by 1 mol of an ideal gas during isobaric expansion if the gas is heated by one degree (high gas performance). So, the high cooling effectiveness and high gas performance predetermined the application of helium in the plant design.

Since the helium temperature at the nuclear reactor exit is relatively low (810 – 1000) °C, the high cycle efficiency would be achieved through the complex Brayton cycle application [15,16].

The GT-MHR “nuclear gas turbine” idea was first discussed as early as in 1946 [17]. However, proven technologies were not available at that time, therefore the nuclear plants were based on the low-efficient Rankine cycle and steam turbine application for electricity production. Very comprehensive efforts were undertaken in the USA in the mid to late 1970 s and the conclusion was made that the current technology state is inadequate to initiate the “nuclear gas turbine” project [18]. In the early 1990s, some technological achievements made in the gas turbine engineering field led to the conclusion that no serious breakthroughs should be made in GT-MHR design, but a few research programs would be established to improve the helium turbine, magnetic bearings compact heat exchangers, and whole helium system [19–21]. Also, some important improvements can be made in the axial compressor design to elevate its stability via surface indentations application on the blade surface [22]. As concluded in [23], the first GT-MHR plant operating with an efficiency of 45 % and even over could be developed soon using these novel technologies.

Therefore in the 1990s, a few projects were developed in the USA and Russia related to nuclear helium-cooled reactors with thermal capacity from 200 MW to 600 MW coupled with steam and gas turbines for electricity and heat production. A few details of the Russian research program were presented in [24–28]. In 1995 Russia and USA initiated a joint project of a modular nuclear plant GT-MHR with a thermal capacity of 600 MW, based on the helium-cooled reactor and gas turbine. Later on, the Framatome (France-Germany) and Fuji Electric (Japan) joined this project. In 1997 Russia presented this project, in 1999 it passed an examination in Russia and USA, and then – an international examination of independent experts from the USA, Japan, Germany, France, and Russia. This design uses the helium reactor with an outlet temperature of 850 °C providing the predicted cycle efficiency of 48 % [29]. The life cycle assessments of a fourth-generation power plant were presented in [30]. The conclusion, based on the process chain analysis led to a conclusion that GT-MHR concept provides the safest design for a nuclear power plant. The work [31] confirmed the effectiveness of the 2-step HELLIOS/MASTER procedure in the analysis of GT-MHR physics. As reported in [32] the thermal efficiency of about 50 % can be obtained in the improved GT-MHR/ORC-PEM cycle for the nuclear plant of 308.4 MW thermal power. Application of the bottoming cycles to recover waste heat after the gas turbine was investigated in [33].

Currently, there are no serious technical obstacles to the construction of the real GT-MHR plant. Over the last twenty years significant efforts were undertaken in Russia to overcome technical problems toward the development of nuclear fuel, helium turbine, two-stage compressor, compact high-performance heat exchangers, electromagnetic bearings, and verification of physical codes with experimental substantiation. Unfortunately, these results were not published widely, but only limited data regarding the GT-MHR-215 nuclear power plant (thermal power is 215 MW) can be found in [28].

Currently, modular nuclear plants with thermal power of 250 MW (GT-MHR-250) represent the primary industrial interest, so they can be employed as the first step toward the pilot GT-MHR nuclear plant. Such a unit size is especially attractive for the energy sector of developing countries to replace their environment-unfriendly thermal power stations and construct larger energy systems. The high cycle efficiency of about 50 % based on modern gas turbine technologies is also a very attractive issue. However, to design such a plant, some additional investigations into the thermodynamics of the GT-MHR-250 modular nuclear plant are required, so far.

Among the publications analyzed, only [34] describes the research of the combination of GT-MHR with the Stirling engine, while others are based on different variations of the Rankine cycle. The research [35] describes the optimization of the thermal efficiency of the modified Kalina cycle and GT-MHR. But, until now there are no mentions in the scientific literature of the complex Brayton cycle use in combination with GT-MHR for power generation.

Currently, Russia, Ukraine, and other countries widely use basic thermal power stations of 200 and 300 MW, based on coal applications. To replace them (obsolete stations) the nuclear plants 250 MW are more suitable to work separately, as well as at the larger energy systems formation. Therefore, this paper provides a detailed thermodynamic analysis of the GT-MHR-250 nuclear plant, based on the helium nuclear reactor coupled with a vertical gas turbine of the complex Brayton cycle with heat recovery after gas turbine and helium intercooling between compressor cascades.

Two modes of nuclear plant operation were considered, namely the electricity generation mode and the combined mode of electricity and heat production. The basic parameters of the GT-MHR-250 plant were identified, and the sensitivity analysis was carried out to assess the GT-MHR-250 electrical efficiency and power deterioration due to performance degradation of in-plant components during operation.

2. GT-MHR nuclear plant

GT-MHR concept

First of all, it should be noted that any serial gas turbine can't be used in plant design. This is because the helium turbine has many specific features which distinguish it from the serial powerful energy gas turbine. This includes the vertical position, magnetic bearings, and the best parameters of all elements of the plant to achieve the highest performance.

The proposed GT-MHR nuclear power plant design consists of two separate blocks (Fig. 1) – the helium-cooled nuclear reactor (MHR) and the energy conversion block, based on the complex Brayton cycle turbine [14–16].

As there are no metallic elements in the MHR core design with a graphite moderator (active zone), this allows elevating the helium temperature to (850–950) °C at the reactor exit and ensures the high efficiency of the electricity production in the complex Brayton cycle. The helium reactor layout provides efficient use of nuclear fuel and the possibility to implement various fuel cycle options (uranium, plutonium, thorium), low radiation impact on the environment, and the exclusion of core melting in severe accidents. The design of a nuclear power plant is greatly simplified due to the absence of intermediate coolants with a phase change (liquid–vapor) and bulky heat exchangers. The studies carried out have shown the "burning out" of weapons-grade plutonium can be used in the GT-MHR nuclear plant with subsequent disposal of spent fuel without additional reprocessing. The total capital costs of the GT-MHR nuclear plant are estimated to be from 1.000 to 1.600 U.S. dollars per 1 kWe, the plant construction time is 3 – 4 years.

The ring-type reactor core contains hexagonal fuel blocks assembled into the fuel columns. The microspheres of plutonium or uranium oxide with a diameter of (0.2 – 0.6) mm covered with the multilayer shell of pyrolytic carbon and silicon carbide with a total thickness of (150 – 200) microns are used as a fuel in a helium reactor. Production technology of nuclear microspheres was developed and patented in Russia; however, details of it were not revealed, so far. As known, the multilayer shell of the microsphere is created in the high-temperature fluidized bed. This fuel provides a significant reduction in the yield of fission products from the micro-fuel and retains fission fragments both under normal conditions and in emergencies. In the event of an accident or explosion of the reactor, the microspheres are not destroyed and can be collected by a special robot. The nuclear reactor core is confined in a high-pressure steel vessel, which is connected to the energy conversion unit body. The entire reactor module locates underground in the protective structure [14–16].

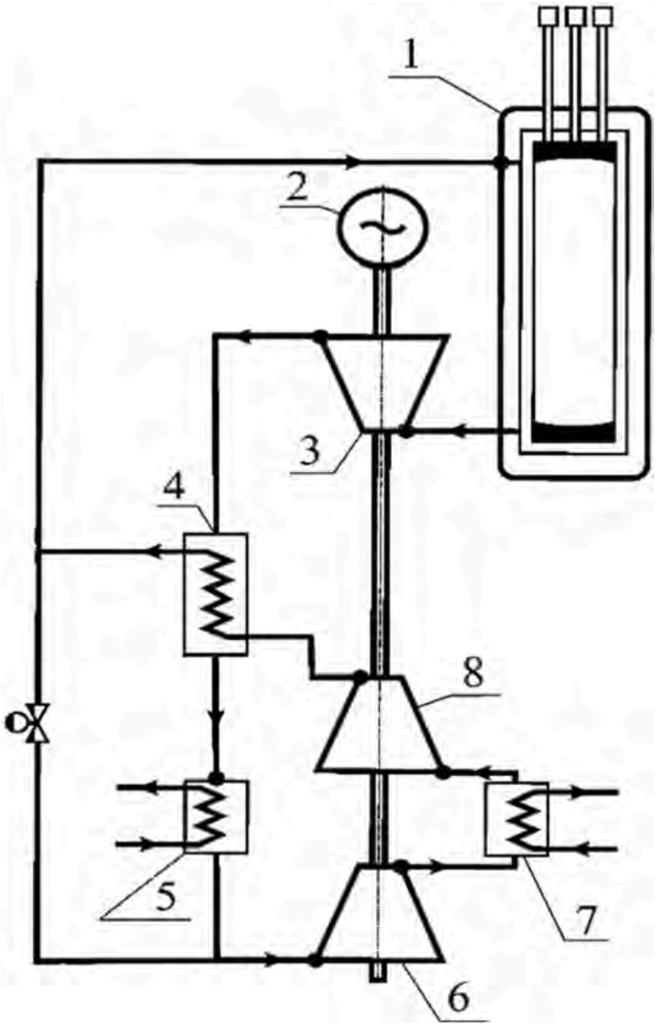

Fig. 1. Schematic of GT – MHR nuclear plant. 1 – nuclear reactor; 2 – electrical generator; 3 – turbine; 4 – heat regenerator; 5 – preliminary heat exchanger; 6 – low-pressure compressor; 7 – intercooling heat exchanger; 8 – high-pressure compressor.

The power plant operates in the mode of only electricity generation and in the combined mode of electricity and municipal heat production (the wastewater temperature is over 100 °C). When the plant operates in the combined mode, the heat to the consumer is transferred through heat exchangers 5 and 7 (Fig. 1). In the electricity production mode, the network circuit is shut down and heat to the environment is released through the cooling towers (not shown).

The power GT-MHR plant operates as follows: the heated helium from the nuclear reactor enters the turbine and after the expansion is sent to the heat regenerator 4 (Fig. 1) and then to the preliminary heat exchanger 5. After cooling down in the preliminary heat exchanger, the helium enters the low-pressure compressor 6. After compression, the helium is cooled in the intercooling heat exchanger 7, comes through the high-pressure compressor 8, and passes again through the heat regenerator, where after heating it returns to the nuclear reactor 1. As helium has a high value of the isobaric heat capacity and the highest gas exponent, its application as a working medium in the GT-MHR power plant provides a relatively small turbine size.

Energy conversion unit

To convert the thermal energy of the heated helium into electricity, the energy conversion unit is used, including the turbine 3, low 6 and high 8 pressure compressors, heat regenerator 4, preliminary 5, and intercooling 7 heat exchangers, electrical generator 2, connected to the gas turbine shaft. The turbine is installed vertically on the electromagnetic bearings and operates according to the complex Brayton cycle with a heat recovery after turbine and helium intercooling between compressor cascades. Application of the complex cycle is a solid requirement to achieve high cycle efficiency at a relatively low helium temperature (850 – 900) °C in front of the turbine.

Components of the energy conversion unit are the high-performance heat exchangers (Fig. 1; pos. 5 and 7) with enhanced heat transfer (indentations studied in [22] can be used), low-pressure losses (less than 5 MPa [25]), and a fairly long operating time at temperatures up to 600 °C [24]. Such conditions are beyond the operation conditions of traditional heat exchangers applied in power engineering, so a specific design of such a heat exchanger is required. As concluded in [27], the heat regenerator (Fig. 1; pos.4) should be able to provide a service life of at least 25 000 h, withstand a large number of thermal cycles during operation (10 000 – 15 000), and the high-pressure difference between the heat regenerator channels (up to 0.3 MPa). It should have low-pressure losses (from 3 % to 5 % of the pressure at the channel inlet), high compactness (1000 – 1700) m^2/m^3, and cost not exceeding $120 per 1 kW of electrical power, produced by the nuclear plant [25].

The *T*-s diagram of the GT-MHR nuclear plant cycle is shown in Fig. 2, the main cycle parameters are the electrical efficiency [36]:

$$\eta_e = \frac{N_e}{Q_1} \tag{1}$$

as well as the cycle of useful work:

$$\eta_{cuw} = \frac{N_e}{G \cdot l_T} \tag{2}$$

Here: Q_1 is the nuclear reactor thermal power, N_e is the generator electrical power, l_T is the specific turbine power.

As mentioned above, to increase the turbine efficiency in the complex Brayton cycle, the helium intercooling between compressor cascades (Fig. 2; line 2–3), as well as the helium heating in the regenerator is used (Fig. 2; line 4–5). The helium is cooling in the preliminary heat exchanger up to the temperature T_1, and then in the intercooling heat exchanger up to the temperature T_3 reduces the compression work and increases the specific cycle work. In this case, the lower the temperature T_3 and the deeper the intercooling rate, the greater increase in the cycle-specific work that can be obtained.

The helium intercooling between the low and high-pressure compressors allows the helium compression to be closer to the ideal isothermal process. The efficiency of helium intercooling is estimated by the temperature coefficient of intercooling [36]:

$$\tau_k = T_3/T_2 \tag{3}$$

However, helium intercooling does not always improve turbine efficiency. For example, for the GT-MGR-215 unit [28], the limited magnitude of the total pressure ratio in the compressor is 2.387 (the product of the compression ratio in the low and high-pressure compressors). This means that at constant nuclear reactor power, an increase in the total compression ratio above 2.387 decreases the cycle efficiency. The equations for the optimal distribution of compression ratio between compressor stages are given in [36] along with the overall compression ratio providing the maximum value of turbine-specific work.

The amount of heat recovered in the heat regenerator 4 (Fig. 1) is determined by the heat recovery rate which is the ratio of heat received by the helium in the regenerator to the maximum heat amount obtained in the ideal regenerator with an infinitely large heat exchange area:

$$\sigma = (T_5 - - T_4) / (T_7 - - T_4), \tag{4}$$

Here T_5 is the helium temperature at the regenerator exit (actual conditions); temperature T_5 is always less than T_7 temperature (Fig. 2).

In the actual turbine, the heat recovery rate determines the specific cycle work through the pressure drop in the heat regenerator, the value

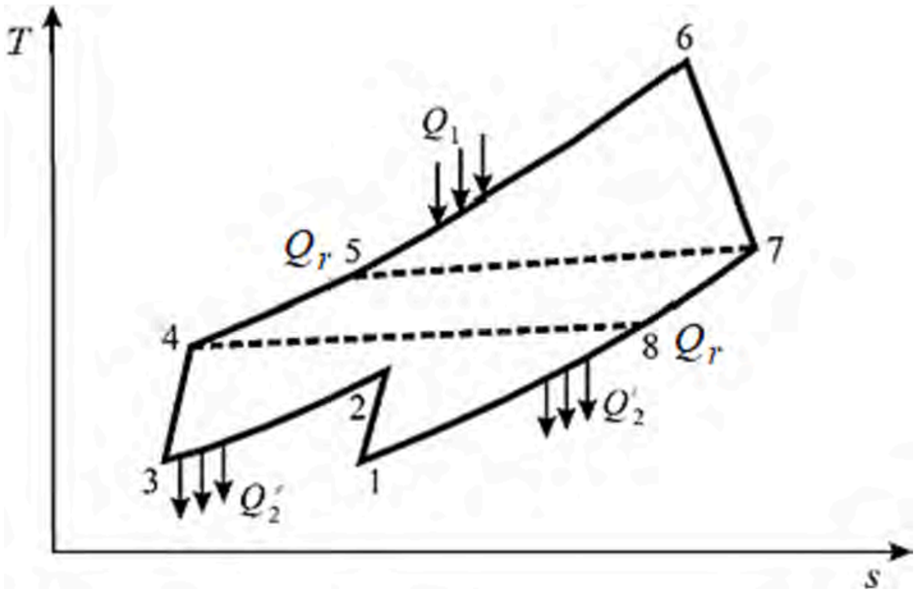

Fig. 2. *T*-s diagram of GT-MHR cycle. 1 – 2 – helium compression in the low-pressure compressor; 2 – 3 – heat removal in the intercooling heat exchanger; 3 – 4 – helium compression in the high-pressure compressor; 4 – 5 – heat supply in regenerator; 5 – 6 – heat supply in a nuclear reactor; 6 – 7 – helium expansion in turbine; 7 – 8 – heat exchange in regenerator; 8 – 1 – heat transfer in the preliminary heat exchanger.

of which grows rapidly at σ greater than 0.6. As a whole, the heat recovery reduces the required pressure ratio in the compressor, at which the maximum specific cycle work is achieved. The cycle recovery rate depends on the heat exchange area and regenerator size. For the actual conditions, the heat recovery rate ranges from 0.70 to 0.85, but at σ greater than 0.7 both the weight and heat exchange surface of the heat regenerator increase dramatically.

GT-MHR calculation procedure

The *T*-s diagram sketch of the GT-MHR nuclear plant, based on the complex Brayton cycle is given in Fig. 2, where the numbers 1–8 define characteristic points of the thermodynamic cycle. The heat source in the cycle is the helium nuclear reactor; the computer model includes basic equations from the gas turbine theory [36] and heat transfer foundations. It includes sub-models of turbines, compressors, heat regenerators, and heat exchangers. The basic designations used in the paper are as follows:

- nuclear reactor thermal power(Q_1);
- helium temperature at the reactor inlet and outlet (T_5, T_6);
- helium pressure at the reactor inlet (P_5);
- helium temperature at the turbine outlet (T_7);
- thermal efficiency of the low- and high-pressure compressor (η_{lpc}, η_{hpc});
- thermal efficiency of the regenerator, preliminary and intercooling heat exchangers (η_r, η_{prel}, η_{inter});
- relative pressure losses in the “hot” and “cold” lines of the heat regenerator (ξ_r^h and ξ_r^c);
- relative pressure losses in the “hot” lines of preliminary and intercooling heat exchangers (ξ_{prel}^h and ξ_{inter}^h).

Since the specific heat capacity of helium is independent of the temperature and pressure in a wide range of temperature $T = (0 - 1800)$ °C and pressure $P = (1 - 100)$ bar [37], then in calculations $C_p = 5195$ [J/(kg·K)]) $=$ *const* was taken. The helium adiabatic exponent γ is 1.6667, and its molar mass is 4.002602. The equation of state for an ideal gas was used as the equation of state.

The calculation procedure of the complex Brayton cycle for the mode of electricity production is based on the iterative process (Fig. 3). As a first step, an initial approximation of the compressor inlet temperature T_1 (minimal cycle temperature) and the heat recovery rate (σ_{given}) were established. As a result of this step, the σ_1 magnitude is defined, which is compared with the set value of σ_{given}. If the condition $\sigma_1 = \sigma_{given}$ is not satisfied, then the correction is made, and the next temperature value at the compressor inlet is set to $T_1{}^{(n+1)} = T_1{}^{(n)} - \Delta T$. The calculation procedure is repeated a few times until the condition $\sigma_n = \sigma_{given}$ is satisfied with a taken accuracy. After that, the cycle parameters are calculated.

The combined mode calculation procedure is actually the same as for the electricity production mode. In this case, the thermal power of heat exchangers is taken from the electricity production procedure taking into account the reduction in the thermal efficiency due to different helium flow rates. This allows for determining the minimal cycle temperature (at the compressor inlet) and heat recovery rate without any iterations.

Test case results

At the testing of the calculation procedure of the GT-MHR-215 plant, the results presented in [28] were used. To perform the calculations, the best (maximal) parameters of the in-plant components (gas turbine, compressor, heat exchangers), which are currently achieved in the gas turbine and power engineering fields were used in this procedure (Table 1). The obtained *P-v* diagram in the electricity production mode and combined mode is shown in Fig. 4.

The results obtained (Table 2) demonstrate acceptable agreement

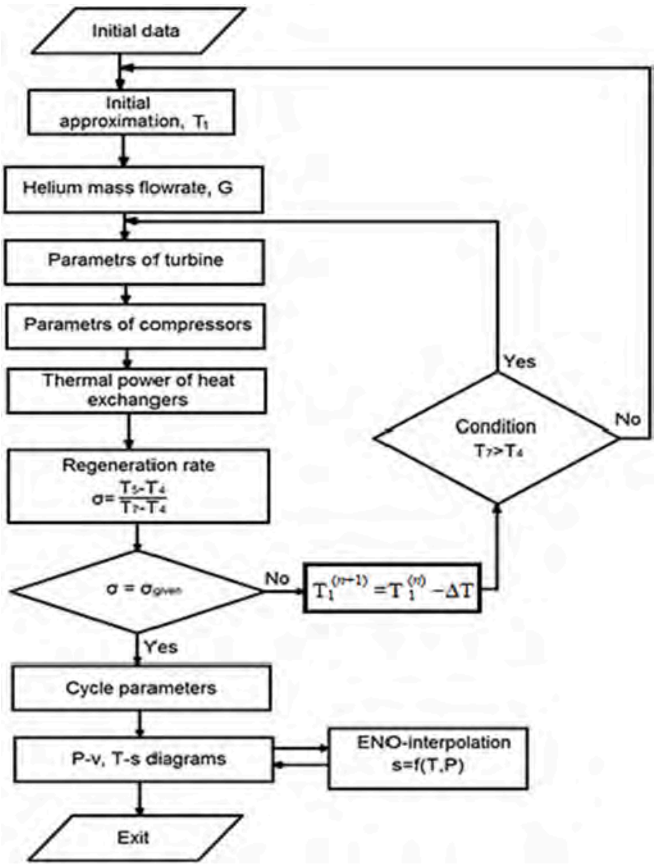

Fig. 3. Schematic of GT-MHR nuclear plant calculation procedure. Electricity generation mode.

Table 1
Initial data (GT-MHR-215) [28].

Parameter	Electricity generation mode	Combined mode
Nuclear reactor thermal power, MW	215	215
Helium temperature at the reactor inlet, °C	558	490
Helium temperature at the reactor outlet, °C	850	795
Helium pressure at the reactor inlet, MPa	4.91	4.93
Helium temperature at the turbine outlet, °C	583	595
Low-pressure compressor efficiency	0.87	0.87
High-pressure compressor efficiency	0.85	0.85
Turbine efficiency	0.93	0.93
Regenerator thermal efficiency	0.95	0.80
Thermal efficiency of preliminary heat exchanger	0.85	0.815
Thermal efficiency of intercooling heat exchanger	0.85	0.815
Electrical generator efficiency	0.987	0.987
Relative pressure losses in the heat regenerator “hot” line, %	3.0	3.0
Relative pressure losses in the heat regenerator “cold” line, %	3.0	1.5
Relative pressure losses in the “hot” line of preliminary heat exchanger, %	3.0	3.0
Relative pressure loss in the “hot” line of intercooling heat exchanger, %	3.0	3.0
Intercooling temperature coefficient	1.0	1.038
Cycle regeneration rate	0.86	0.458

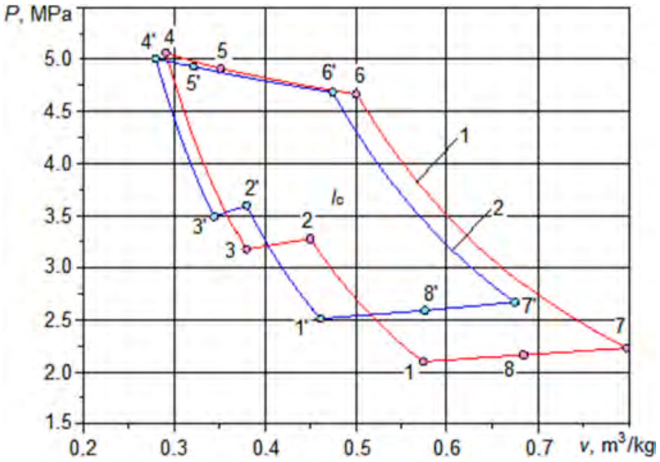

Fig. 4. P-v diagram of GT-MHR-215. 1 – electricity generation mode, 2 – combined mode.

Table 2
Results of GT-MHR-215 testing.

Parameter	Electricity generation mode		Combined mode	
	[28]	Calculations	[28]	Calculations
Reactor thermal power, MW	215	215	215	215
Electrical efficiency, %	46.1	46.5	25.4	26.7
Helium temperature at the reactor inlet/outlet, °C	558/ 850	558/850	490/ 795	490/795
Helium temperature at the regenerator inlet, °C	583	583	595	595
Helium consumption, kg / s	139.1	141.7	134	135.7
Helium pressure at the reactor inlet, MPa	4.91	4.91	4.93	4.93
Helium expansion ratio in turbine	2.09	2.09	1.77	1.76
Unit electrical power, MW	100	99.94	57	57.35
Unit thermal power, MW	—	—	154	154.05

with the data presented in [28]. In the electricity production mode, the electrical efficiency error is 0.6 %; while in the combined mode the error in the electrical and thermal power is 0.2 % and 0.1 %. The helium flow rate error is 2 % and 1 %. These confirm the best parameters of GT-MHR components used in the paper [28].

Thus, to achieve the highest electrical and thermal efficiency of the GT-MHR plant the highest (best) parameters of all in-unit components should be used in a real GT-MHR design.

The results obtained demonstrate the high electrical efficiency of the GT-MHR-215 plant, which is 46.5 % was obtained in the electricity production mode (thermal efficiency is 47.1 %), while the electrical power was 99.94 MW. In the combined mode, the electrical power was 57.35 MW and the thermal power was 154.05 MW.

Table 3
Initial data (GT-MHR-250).

Parameter	Electricity generation mode	Combined mode
Thermal power of the nuclear reactor, MW	250	250
Helium temperature at the reactor inlet, °C	560	500
Helium temperature at the reactor outlet, °C	850	800
Helium pressure at the reactor inlet, MPa	5.0	5.0
Helium temperature at the turbine outlet, °C	585	595
Turbine efficiency	0.93	0.93
Low-pressure compressor efficiency	0.875	0.875
High-pressure compressor efficiency	0.85	0.85
Regenerator efficiency factor	0.85	0.80
Preliminary heat exchanger efficiency factor	0.85	0.815
Intercooling heat exchanger efficiency factor	0.85	0.815
Relative pressure loss in regenerator “hot” line, %	3.0	3.0
Relative pressure loss in regenerator “cold” line, %	3.0	1.5
Relative pressure loss in the “hot” line of preliminary heat exchanger, %	3.0	3.0
Relative pressure loss in the “hot” line of intercooling heat exchanger, %	3.0	3.0
Relative pressure loss in reactor loop,%	5.0	5.0
Compressor intercooling temperature coefficient	1.0	1.038
The efficiency of the electrical generator	0.987	0.987
Cycle regeneration rate	0.83	0.493

Table 4
Results of calculation (GT-MHR-250).

Parameter	Electricity generation mode	Combined mode
Helium mass flow rate, kg/s	165.94	160.41
Total pressure ratio in compressor	2.397	2.018
The pressure ratio of the low-pressure compressor	1.557	1.465
The pressure ratio of the high-pressure compressor	1.539	1.427
Turbine pressure ratio	2.078	1.78
Regenerator thermal power, MW	123.74	123.74
Thermal power of preliminary heat exchanger, MW	132.74	132.74
Thermal power of intercooling heat exchanger, MW	111.18	65.99
Electrical power, MW	115.73	69.66
Thermal power, MW	–	182.13
Cycle (plant) thermal efficiency, %	46.9	28.2
Cycle (plant) electrical efficiency, %	46.3	27.7
Cycle useful work, %	50.7	40.78
Exergetic cycle efficiency, %	69.7	51.98

3. Results and discussion

Results of calculation

When studying the GT-MHR nuclear plant with thermal power of 250 MW, the highest (best) parameters of gas turbine, compressor, heat regenerator, and heat exchangers were used currently achieved in gas turbine and power engineering fields [36] (Table 3). The results of calculations for two modes of nuclear plant operation are presented in Table 4, while the P-v and *T*-s diagrams are given in Figs. 5, 6. The results given in Table 4 correspond to the maximal electrical efficiency and electrical power, which currently can be achieved on the available technology level. As follows, in the electricity production mode the electrical power is 115.73 MW, the thermal efficiency is 46.9 %, the electrical efficiency is 46.3 %, and the cycle useful work is 50.7 % Fig. 7.

The thermal power of the heat regenerator, preliminary heat exchanger, and intercooling heat exchangers is 123.7 MW, 132.74 MW, and 111.18 MW. Thus, high electrical efficiency was obtained in the electricity production mode using the complex Brayton cycle at the relatively low helium temperature in front of the helium turbine (900 °C). In the combined mode the electrical power is only 69.66 MW, while the thermal power is 182.13 MW. The plant electrical efficiency is 27.7 %, and cycle useful work is 50.8 %, while the thermal power of the

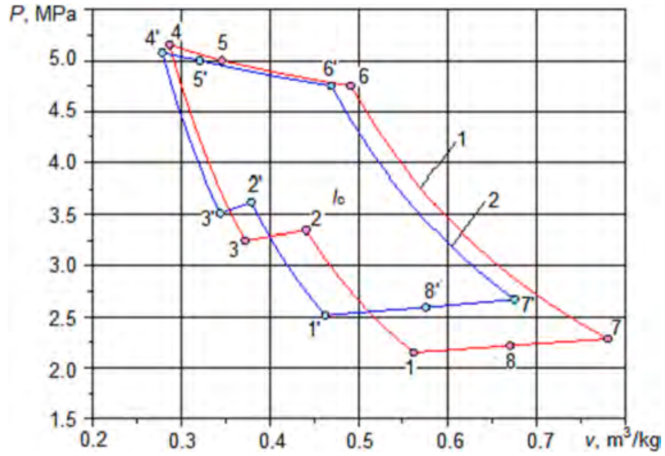

Fig. 5. P-v diagram of the GT-MHR-250 plant. 1 – electricity generation mode, 2 – combined mode.

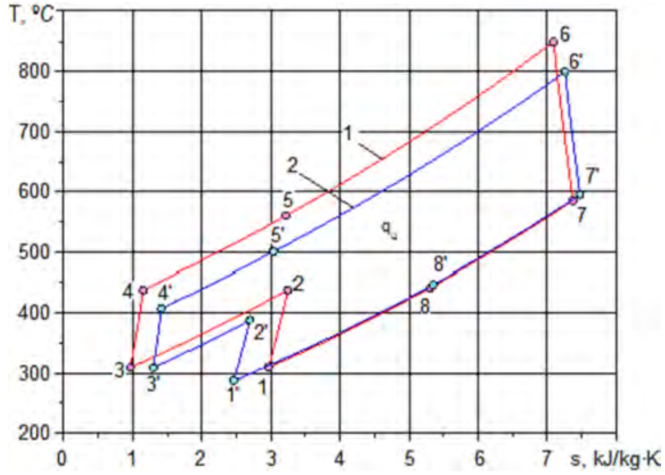

Fig. 6. *T*-*S* diagram of GT-MHR-250 plant.1 – electricity generation mode, 2 – combined mode.

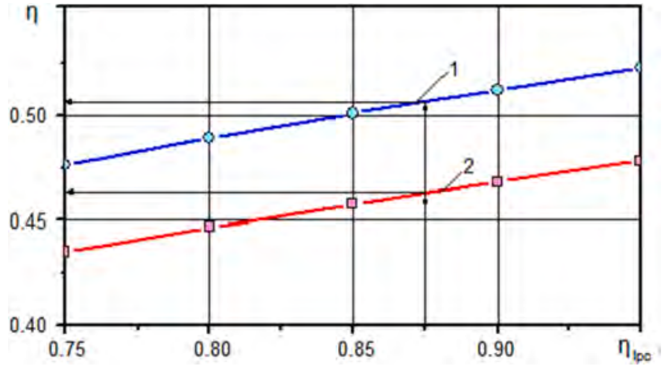

Fig. 7. The cycle useful work (1) and electrical efficiency (2) of GT-MHR-250 versus low-pressure compressor efficiency. Electricity generation mode.

heat regenerator, preliminary heat exchanger, and intercooling heat exchanger is 123.74 MW, 132.74 MW, and 65.99 MW, accordingly. The plant exergetic cycle efficiency is 69.7 % at the electricity generation and 51.98 % at the combined mode.

Sensitivity analysis. Electricity generation mode

Maintaining the highest electrical efficiency and electrical power of the GT-MHR nuclear plant (Table 4) during the entire operation time is quite difficult due to the gradual degradation of all in-plant components (turbine, compressors, heat regenerator, heat exchangers) during operation. Normally reduction of 3–5 % in the components' performance corresponds to two–three years of active operation when the main design problems may appear. Therefore, this reduction range was taken for the sensitivity analysis to assess the influence of deterioration. Below the sensitive analysis of the GT-MHR-250 scheme is provided to assess the reduction in the plant's electrical efficiency and electrical power due to the performance deterioration of in-plant components. This analysis was given for the case if only one parameter is changed while the other ones remain unchangeable (and maximal).

Low and high-pressure compressor

The maximum efficiency of the high-performance axial compressors is 0.875 for the high-pressure compressor and 0.85 – for the low-pressure compressor (Table 4). At the keeping of maximal performance of all in-plant elements, a decrease in the low-pressure compressor efficiency by 5 % (it is normal for two years of operation) leads to a reduction in the electrical unit efficiency by 2.2 %, and electrical power – by 2.3 %. A decrease in the high-pressure compressor efficiency by 5 % reduces the plant's electrical efficiency and electrical power by 1.7 % and 1.9 %, respectively. The simultaneous decrease in the efficiency of low-pressure and high-pressure compressors by 5 % each reduces the plant's electrical efficiency by 3.9 % and its electrical power by 4.2 %.

The helium intercooling between compressor cascades is usually used in the complex Brayton cycle. If the temperature coefficient of helium intercooling τ_k is 1.0 (Fig. 8) the electrical power is 115.73 MW; while the growth in this coefficient by 5 % (up to 1.05) reduces the plant electrical efficiency by 23.5 % and electrical power by 18.2 %. If τ_k parameter increases by 10 % (up to 1.1), the plant's electrical power decreases by 35 %, while the electrical efficiency – by 54.3 %. In contrast, a reduction in the temperature coefficient of helium intercooling increases the cycle's useful work and electrical efficiency. Thus, the precise design of the intercooling heat exchanger plays an important role in the development of a high-performance nuclear plant.

Gas turbine and heat regenerator

Fig. 9 demonstrates a correlation between the cycle useful work and electrical efficiency against the gas turbine efficiency. When the gas

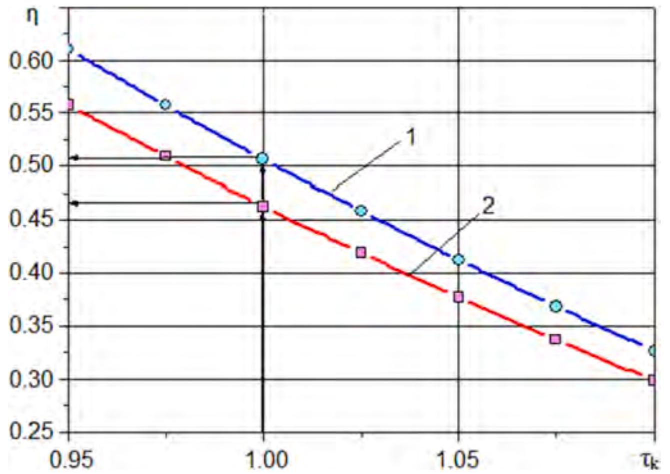

Fig. 8. The cycle useful work (1) and electrical efficiency (2) of GT-MHR-250 versus temperature coefficient of helium intercooling in the compressor. Electricity generation mode.

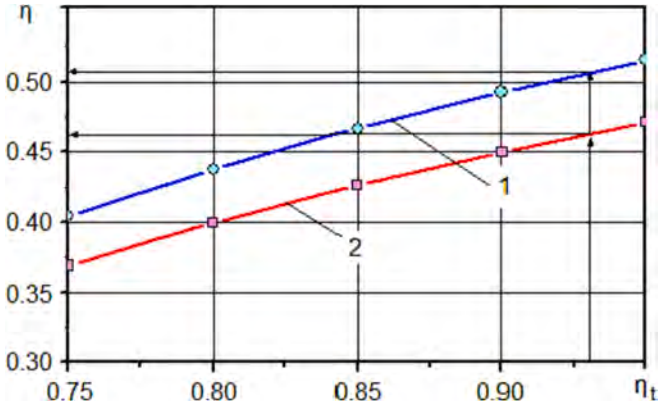

Fig. 9. The cycle useful work(1) and electrical efficiency (2) of GT-MHR-250 versus turbine thermal efficiency. Electricity generation mode.

turbine efficiency drops by 5 % from the maximal value of 0.93 to 0.88, both the plant's electrical efficiency and electrical power drop down by the same value of 5 %. Therefore, the linear correlation is observed, mainly – each percent reduction in the turbine efficiency decreases the plant's electrical power by around 1 %. In this case, the helium expansion ratio in the gas turbine passage grows from 2.078 to 2.19 (5.4 %) leading to a small increase in the pressure losses within the turbine stage.

Heat recovery after a gas turbine influences greatly the cycle's useful work and plant electrical efficiency. As seen (Fig. 10), the rapid growth in both parameters occurs when the heat recovery rate becomes over 0.7; however, this inevitably leads to the fast growth in the regenerator heat exchange surface and its weight. As known, the heat recovery rate of serial heat exchangers applied in power and chemical engineering is 0.75 – 0.79, so if the heat exchanger with σ = 0.79 is applied in the GT-MHR design (5 % less of 0.83) the electrical efficiency and electrical power drop down by 4.5 % and 3.6 %, respectively. Thus, to keep the high electrical efficiency of GT-MHR, the high-performance heat exchanger of a unique design with a heat recovery rate of around 0.83 should be used.

Fig. 11 shows the nuclear plant electrical power versus relative pressure losses in the "hot" and "cold" lines of the heat regenerator. As seen, with the growth of pressure losses in the heat regenerator lines, the plant's electrical power drops down approximately linearly. The growth of pressure losses in the "cold" line from 3 % (Table 4) to 5 % at the relative pressure losses in the "hot" line at the level of 3 % leads to a reduction in the nuclear plant's electrical power by about 2 %. Actually, the same losses in the plant electrical power are observed in the case of pressure losses growth in the "hot" line from 3 % to 5 % and pressure loss keeping in the "cold" line at the 3 % level. The simultaneous growth in the relative pressure losses from 3 % to 5 % in both channels reduces the plant's electrical power by 4.3 %.

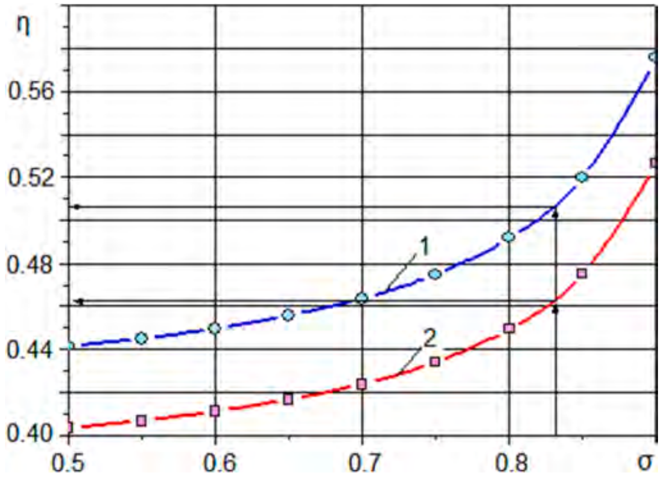

Fig. 10. The cycle useful work (1) and electrical efficiency (2) of GT-MHR-250 versus heat recovery rate in the heat regenerator. Electricity generation mode.

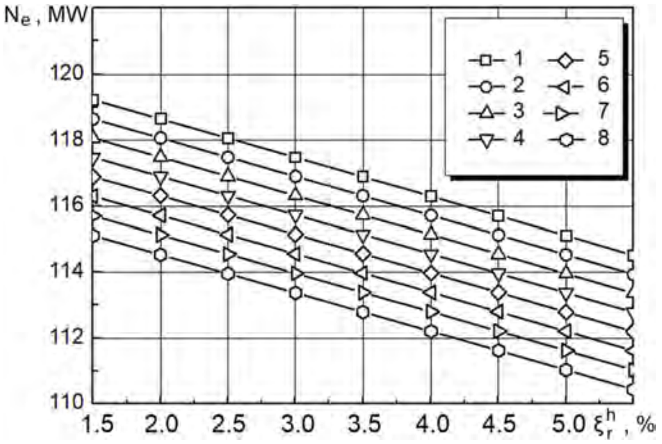

Fig. 11. The GT-MHR-250 electrical power versus relative pressure losses in the "hot" and "cold" lines of the heat regenerator. Electricity generation mode. 1 – ξ_r^c = 1.5%; 2 – = 2 %; 3 – = 2.5 %; 4 – = 3 %; 5 – = 3.5 %;6 – = 4 %;7 – = 4.5 %; 8 – = 5 %.

Pressure losses in heat exchangers

Fig. 12 provides correlations on the plant's electrical efficiency and electrical power versus relative pressure losses in the "hot" line of the preliminary heat exchanger and intercooling heat exchanger. The pressure loss growth in the "hot" line of both heat exchangers from 3 % to 5 % leads to a reduction of about 2 % in the plant's electrical efficiency and electrical power.

Results of sensitivity analysis

The results of the sensitivity analysis are presented in Table 5. As seen, the scheme of the GT-MHR-250 nuclear plant is quite stable. The approximately linear correlation is between the reduction of plant electrical efficiency, electrical power, and performance deterioration of plant components. Only the helium cooling between low-pressure and high-pressure compressors reduces greatly the plant's performance. The reduction of 5 % in the temperature coefficient of intercooling τ_k decreases the plant's electrical efficiency and electrical power by 23.5 %

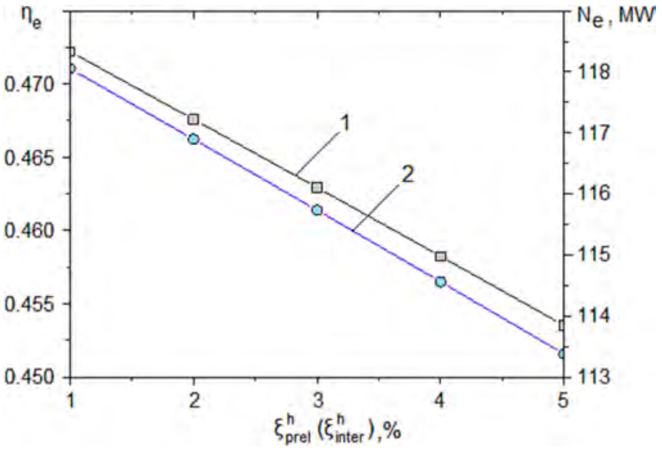

Fig. 12. The electrical efficiency (1) and electrical power (2) of GT-MHR-250 versus relative pressure loss in the "hot" line of preliminary and intercooling heat exchangers. Electricity generation mode.

Table 5
Results of sensitivity analysis.

Parameter	Action	Reduction in electrical efficiency	electrical power
The efficiency of the low-pressure compressor	Reduction, 5 %	2.2 %	2.3 %
The efficiency of the high-pressure compressor	Reduction, 5 %	1.7 %	1.9 %
Gas turbine efficiency	Reduction, 5 %	5.0 %	5.0 %
Heat recovery rate	Reduction, 5 %	4.5 %	3.6 %
Temperature coefficient of intercooling	Reduction, 5 %	23.5 %	18.2 %
Pressure loss in the "hot" line of the regenerator, preliminary and intercooling heat exchangers	Increase	3 %…5%	2 %

and 18.2 %, respectively.

Sensitivity analysis. Combined mode

In the combined mode the plant's electrical efficiency is quite low (27.7 %), electrical power is only 69.66 MW, but the thermal power is 182.13 MW (Table 4). The thermal power of the heat regenerator, preliminary, and intercooling heat exchanger is 123.74, 132.74, and 65.99 MW, accordingly.

Low and high-pressure compressor

The general behavior of the low-pressure compressor efficiency on the plant cycle work and electrical efficiency has actually the same character as in the electricity production mode (Fig. 9). Reduction from 0.875 to 0.83 (5 %) in the low-pressure compressor efficiency reduces the total plant efficiency by 3.3 %., electrical power – by 4.5 %, but increases the thermal power by 1 % (Fig. 13). Note, in the electricity generation mode reduction in the electrical efficiency was 2.2 %, and in the electrical power – 2.3 %. (Table 5). A decrease in the high-pressure compressor efficiency from 0.85 to 0.81 (5 %) reduces the plant's electrical efficiency and electrical power by 2.2 % (1.7 % and 1.9 % at the electricity generation mode). As far as the plant's thermal power is concerned, it grows by 1.3 % in this case.

Turbine and heat regenerator

Reduction in the helium gas turbine efficiency affects greatly the plant's electrical efficiency, and electrical and thermal power (Fig. 14).

The reduction in gas turbine efficiency from 0.93 to 0.88 (by 5 %) reduces the plant's electrical efficiency by 7.8 % and the electrical power – by 8.05 %. Thus, in the combined mode reduction in the plant's electrical efficiency and electrical power is more noticeable than in the electricity generation mode (Table 5). The heat recovery rate decreases by 3.6 % (4.5 % in the electricity generation), while the helium in turbine expansion ratio grows by 3.9 % – from 1.78 to 1.85 leading to lower turbine power.

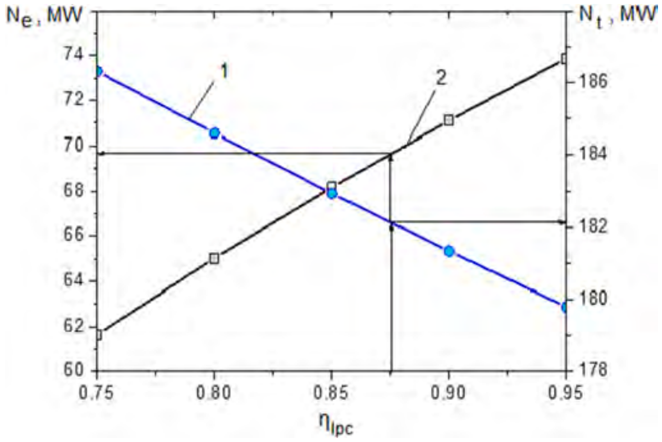

Fig. 13. The electrical (1) and thermal power (2) of GT-MHR-250 versus the low-pressure compressor efficiency. Combined mode.

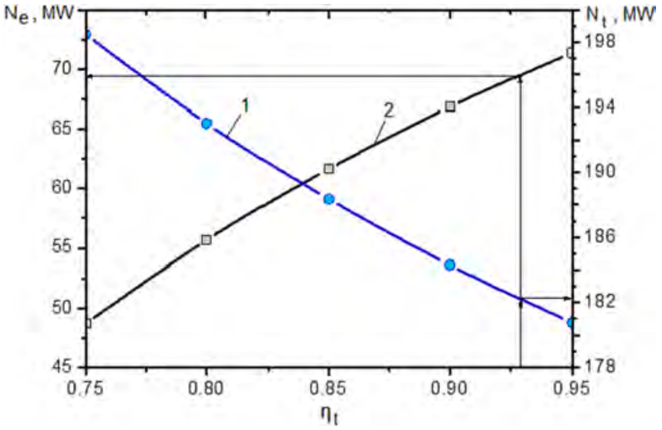

Fig. 14. The electrical (1) and thermal (2) power of GT-MHR-250 versus turbine thermal efficiency. Combined mode.

The growth in the relative pressure losses from 3 % to 5 % in the regenerator "hot" line (1.5 % is kept in the "cold" line) reduces the plant's electrical efficiency and electrical power by about 4 %, while the thermal power grows by 1 % (Fig. 15). An increase in the pressure loss in the heat regenerator "cold" line from 1.5 % to 3 % (3 % is kept in the "hot" line) decreases the electrical efficiency by 2.6 % and electrical power by 3 %. These results are higher than those available for electricity generation (2 %). In both cases, the thermal power grows by 1 % (Fig. 15). The simultaneous increase of relative pressure loss from 3 % to 5 % in the "hot" line and from 1.5 % to 3 % in the "cold" line of heat regenerator decreases the plant's electrical efficiency and electrical power by 7.3 % and 7 %, accordingly, but increases the thermal power of plant by 2 %.

Pressure losses in heat exchangers

At the relative pressure loss growth from 3 % to 5 % in the "hot" line of preliminary and intercooling heat exchangers, both the electrical efficiency and electrical power dropped down by 4.2 %. At the same time, the plant's thermal power was grown by 1 % (Fig. 16). These results are almost two times greater than pressure losses in the preliminary and intercooling heat exchangers for electricity generation (Table 5).

As a whole, reduction in the plant performance due to deterioration

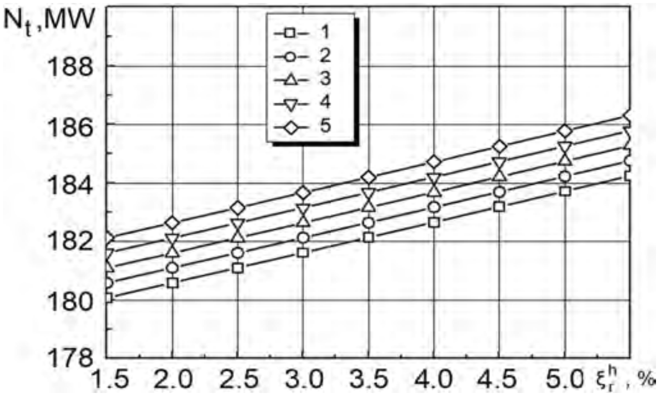

Fig. 15. The thermal power of GT-MHR-250 versus relative pressure losses in the "hot" and "cold" lines of the heat regenerator. Combined mode. ξ_r^c = 1.0%; 2 – = 1.5 %; 3 – = 2.0 %; 4 – = 2.5 %; 5 – = 3.0 %.

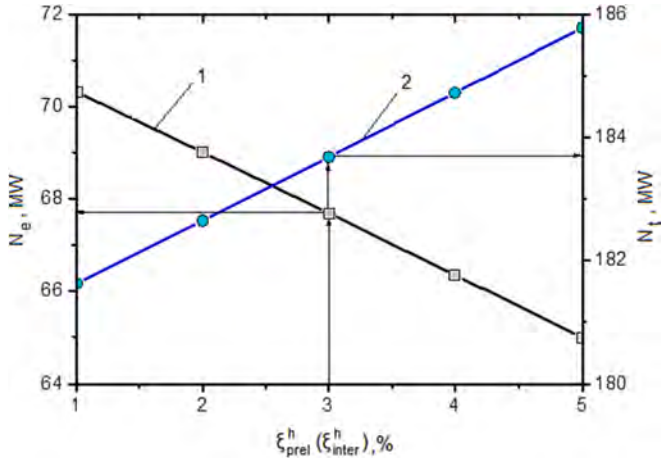

Fig. 16. The electrical (1) and thermal (2) power of GT-MHR-250 versus relative pressure loss in the “hot” line of preliminary and intercooling heat exchangers. Combined mode.

of in-plant components during operation (gas turbine, compressors, regenerator, heat exchangers) is much more noticeable in the combined mode than in the electricity generation. As far as the plant thermal power is concerned, in the combined mode it grows slightly in case of performance reduction of in-plant components.

4. Conclusions

The thermodynamic parameters of the GT-MHR modular nuclear plant of 250 MW thermal power with helium reactor and vertical gas turbine, operating according to the complex Brayton cycle were obtained and discussed in this paper. Two operating modes of the nuclear plant, namely the electricity generation mode and the combined mode with electricity and heat production were considered. The analysis was carried out to define the GT-MHR-250 plant sensitivity concern in performance deterioration of the in-plant elements during their operation. Based on the results obtained, the following main conclusions are drawn as follows:

- In the electricity production mode, quite a high electrical efficiency of the plant was achieved (46.3 %) if the best parameters of in-plant elements currently achieved in the gas turbine and power engineering industries are used.
- In the combined mode the plant’s thermal power is 182.13 MW, while the electrical power is only 69.66 MW with an electrical efficiency of 27.9 %.
- The scheme of the GT-MHR-250 nuclear plant is low sensitive concerning performance deterioration of in-plant elements however reduction in the helium intercooling between compressor stages affects greatly the plant’s electrical efficiency and electrical power.
- A decrease in the plant’s electrical efficiency and electrical power due to performance deterioration of in-plant elements is more noticeable in the combined mode rather than in the electricity production mode.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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References

[1] B.N. Agrawal, S. Sinha, A.V. Kuzmin, V.A. Pinchuk, Effect of vegetable oil share on combustion characteristics and thermal efficiency of diesel engine fueled with different blends, Therm. Sci. Eng. Prog. 14 (2019), 100404, https://doi.org/10.1016/j.tsep.2019.100404.

[2] A.I. Guryanov, O.A. Evdokimov, V.A. Burtsev, V.I. Koshkin, S.V. Veretennikov, O. V. Komova, An experimental study of syngas combustion in a bidirectional swirling flow, Int. J. Hydrogen Energy 48 (2023) 4503–4515, https://doi.org/10.1016/j.ijhydene.2022.11.004.

[3] V.A. Pinchuk, T.A. Sharabura, A.V. Kuzmin, S.A. Pinchuk, Engineering equations for determining coal-water fuel combustion stages, J. Energy Inst. 93 (2020) 1924–1933, https://doi.org/10.1016/j.joei.2020.04.007.

[4] V.A. Pinchuk, M. Moumane, K.V. Kremneva, A.V. Kuzmin, S.A. Pinchuk, Specific features of the ignition behavior of coal-water fuel with the addition of glycerol, Combust. Sci. Technol. (2021) 1–22, https://doi.org/10.1080/00102202.2021.1983550.

[5] V.A. Pinchuk, T.A. Sharabura, Physical and chemical transformations under the thermal action on coal-water fuel made of low-grade coal, Metall. Min. Ind. 7 (2015) 623–628.

[6] O.A. Evdokimov, The structure of coaxial buoyant jets with swirling and combustion, Int. J. Energy Clean Environ. 20 (2019) 339–350, https://doi.org/10.1615/InterJEnerCleanEnv.2019033297.

[7] A.I. Guryanov, O.A. Evdokimov, S.V. Veretennikov, D.A. Prokhorov, A development and numerical study of a high-pressure gas turbine combustion chamber based on mesoscale coaxial swirling jets, Int. J. Energy Clean Environ. 23 (2022) 55–76, https://doi.org/10.1615/InterJEnerCleanEnv.2022041397.

[8] O.A. Evdokimov, A.I. Guryanov, D.A. Prokhorov, An experimental study on combustion in mesoscale coaxial swirling burner arrays, Combust. Sci. Technol. (2022), https://doi.org/10.1080/00102202.2022.2111213.

[9] A. Rai, H. Singh, V. Singh, A. Bhardwaj, A. Nandi, R. Sahoo, B. Nayak, Waste transformer oil to biodiesel: effect of injection timing on engine performance and emission characteristics, Int. J. Energy Clean Environ. 23 (2022) 53–63, https://doi.org/10.1615/InterJEnerCleanEnv.2022039748.

[10] Y. Huo, R. Zhang, S. Zhu, J. Gao, S.R. Holden, M. Zhu, Z. Zhang, D. Zhang, A preliminary experimental investigation into ammonia oxidation in a fixed-bed, Int. J. Energy Clean Environ. 23 (2022) 23–37, https://doi.org/10.1615/INTERJENERCLEANENV.2022039811.

[11] A.I. Guryanov, O.A. Evdokimov, S.V. Veretennikov, D. Prokhorov, Specifics of Stoichiometric Hydrogen-Oxygen Mixtures Combustion in a Bidirectional Swirling Flow, Int. J. Energy Clean Environ. 24 (2023) 165–178, https://doi.org/10.1615/InterJEnerCleanEnv.2022040614.

[12] A.V. Kuzmin, V.A. Pinchuk, Environmental engineering, innovations, and management, Editorial Review, Int. J. Energy Clean Environ. 24 (2023) v–ix, https://doi.org/10.1615/InterJEnerCleanEnv.2022045186.

[13] I.L. Pioro, ed., Handbook of generation IV nuclear reactors, 2nd ed., Elsevier; Woodhead Publishing, Amsterdam, 2022. https://www.elsevier.com/books/handbook-of-generation-iv-nuclear-reactors/pioro/978-0-12-820588-4.

[14] A.V. Vasyaev, N.G. Kodochigov, N.G. Kuzavkov, L. Kuznetsov, International project GT-MHR - new generation of nuclear reactors, in: Proc. Int. Conf. Bulg. Nucl. Soc. 2001, Bulgarian Nuclear Society, Varna, Bulgaria, 2001: p. 22. https://inis.iaea.org/collection/NCLCollectionStore/_Public/32/057/32057831.pdf.

[15] M.P. LaBar, The gas turbine-modular helium reactor: a promising option for near term deployment, in: Proc. ICAPP02 2002 Int. Congr. Adv. Nucl. Power Plants, American Nuclear Society - ANS, La Grange Park (United States), Hollywood, FL, US, 2002: p. 8. https://www.osti.gov/biblio/21167941 (accessed April 13, 2022).

[16] Y.A. Hassan, R.A. Chaplin (Eds.), Nuclear Energy Materials And Reactors, UNESCO-EOLSS Publications, 2010.

[17] C. Keller, The Escher Wyss-A.K. closed cycle gas turbine. Its development and future projects, Trans. ASME. 68 (1946) 791–882.

[18] C.F. McDonald, C.O. Peinado, The Nuclear Gas Turbine: A Perspective on a Long-Term Advanced Technology HTGR Plant Option, in: Vol. 3 Coal Biomass Altern. Fuels Combust. Fuels Oil Gas Appl. Cycle Innov., American Society of Mechanical Engineers, London, England, 1982: p. V003T08A013. 10.1115/82-GT-289.

[19] W.A. Simon, A.J. Neylan, F.A. Silady, Design Features of the Gas Turbine Modular Helium Reactor (GT-MHR), General Atomics, San Diego, CA, USA, 1993.

[20] A.J. Neylan, A. Shenoy, F.A. Silady, T.D. Dunn, GT-MHR design, performance, and safety, in: Proc. IAEA Tech. Comm. Meet. Dev. Status Modul. High Temp. React. Their Future Role, General Atomics, San Diego, CA (United States), Petten, Netherlands, 1994: p. 15. https://www.osti.gov/biblio/10103412-gt-mhr-design-performance-safety (accessed April 13, 2022).

[21] R.C. Potter, A. Chenoy, Gas turbine – modular helium reactor (GT-MHR), Conceptual design description report, General Atomics, San Diego, California, US, 1996 https://www.nrc.gov/docs/ML0224/ML022470282.pdf.

[22] A. Khalatov, E. Shi-Ju, D. Wang, I. Borisov, Film cooling evaluation of a single array of triangular craters, Int. J. Heat Mass Transf. 159 (2020), 120055, https://doi.org/10.1016/j.ijheatmasstransfer.2020.120055.

[23] C.F. McDonald, Enabling Technologies for Nuclear Gas Turbine (GT-MHR) Power Conversion System, in: Vol. 3 Coal Biomass Altern. Fuels Combust. Fuels Oil Gas Appl. Cycle Innov., American Society of Mechanical Engineers, The Hague, Netherlands, 1994: p. V003T08A005. 10.1115/94-GT-415.

[24] J.B. Zgliczynski, F.A. Silady, A.J. Neylan, The gas turbine-modular helium reactor (GT-MHR), high efficiency, cost competitive, nuclear energy for the next century, in: General Atomics, San Diego, CA (United States), Pittsburgh, PA, US, 1994: p. 13. https://www.osti.gov/biblio/10161171-gas-turbine-modular-helium-reactor-gt-mhr-high-efficiency-cost-competitive-nuclear-energy-next-century (accessed April 13, 2022).

[25] O.A. Bikh, V.F. Golovko, I.V. Dmitrieva, B.M. Kamashev, A.E. Krasilschikov, Design and experimental investigations of compact recuperators for reactor plants with gas-turbine cycle, in: Proc. 2nd Int. Top. Meet, High Temp. React. Technol, Beijing, China, 2004, p. 6.

[26] O.A. Bikh, V.F. Golovko, I.V. Dmitrieva, N.G. Kuzavkov, L.K. Nikanorov, Design and experimental investigations of high-temperature high-performance recuperator, in: Proc. 2nd Int. Top. Meet, High Temp. React. Technol, Beijing, China, 2004, p. 6.

[27] S.A. Wright, M.E. Vernon, P.S. Pickard, Concept design for a high temperature helium Brayton cycle with interstage heating and cooling, Sandia National Lab. (SNL-NM), Albuquerque, NM (United States), New Mexico and Livermore, California, US, 2013. 10.2172/1323907.

[28] A.Y. Stolyarevsky, N.G. Kodochigov, A.V. Vasyaev, V.F. Golovko, M.E. Ganin, Application of high-temperature module helium reactors for heat supply of energy-intensive industries, Nov. Tepl. 2 (2011) 13.

[29] C.B. Baxi, A. Shenoy, V.I. Kostin, N.G. Kodochigov, A.V. Vasyaev, S.E. Belov, V. F. Golovko, Evaluation of alternate power conversion unit designs for the GT-MHR, Nucl. Eng. Des. 238 (2008) 2995–3001, https://doi.org/10.1016/j.nucengdes.2007.12.021.

[30] P. Koltun, A. Tsykalo, V. Novozhilov, Life Cycle Assessment of the New Generation GT-MHR Nuclear Power Plant, Energies. 11 (2018) 3452, https://doi.org/10.3390/en11123452.

[31] K.H. Lee, K.S. Kim, J.M. Noh, J.S. Song, S.Q. Zee, Benchmark calculation for GT-MHR using HELIOS/MASTER code package and MCNP, in: Proc. KNS Autumn Meet. CD-ROM Pages, KNS, Taejon (Korea, Republic of), Korean Nuclear Society, Taejon (Korea, Republic of), 2005: p. 2. https://www.osti.gov/etdeweb/biblio/20765328.

[32] A.E. Alali, Z.B. Abulawi, A.Y.M. Obeidat, Assessment of thermal performance improvement of GT-MHR by waste heat utilization in power generation and hydrogen production, Int. J. Hydrog. Energy. 46 (2021) 22719–22734, https://doi.org/10.1016/j.ijhydene.2021.04.116.

[33] A. Habibzadeh, M.M. Rashidi, Thermodynamic analysis of different working fluids used in organic rankine cycle for recovering waste heat from GT-MHR, J. Eng. Sci. Technol. 11 (2016) 121–135.

[34] A.E. Alali, A.A. Tubeshat, K.A. Khasawneh, Performance analysis of stirling engine double-effect absorption chiller hybrid system for waste heat utilization from gas turbine modular helium reactor, Energy Convers. Manag. 251 (2022), 114976, https://doi.org/10.1016/j.enconman.2021.114976.

[35] T. Parikhani, J. Jannatkhah, A. Shokri, H. Ghaebi, Thermodynamic analysis and optimization of a novel power generation system based on modified Kalina and GT-MHR cycles, Energy Convers. Manag. 196 (2019) 418–429, https://doi.org/10.1016/j.enconman.2019.06.018.

[36] M.P. Boyce, Gas turbine engineering handbook, 4th ed,, Elsevier/Butterworth-Heinemann, Amsterdam; Boston, 2012.

[37] H. Petersen, Properties of helium: density, specific heats, viscosity, and thermal conductivity at pressures from 1 to 100 bar and from room temperature to about 1800 K, Danish Atomic Energy Commission, Risoe, Research Establishment, Engineering Department, Section of Experimental Technology, Copenhagen, Denmark, 1970 https://www.osti.gov/biblio/4084930.