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**V. Dubkovskyi,** DSc., Prof.,
**V. Segeda,**
**Y. Dobronos**
Odessa Polytechnic National University, Shevchenko Ave. 1, Odesa, Ukraine, 65044; e-mail: vadubkovsky54@gmail.com

# POSSIBILITIES OF USING MODULAR HIGH-TEMPERATURE REACTORS FOR THE CONVERSION OF ORGANIC FUELS

*В. Дубковський, В. Сегеда, Є. Добронос.* **Можливості застосування модульних високотемпературних реакторів для конверсії органічних палив.** Розглянуто можливість використання малих модульних високотемпературних газоохолоджувальних ядерних реакторів для конверсії паливних копалин. Використання високотемпературних газоохолоджуваних ядерних реакторів в якості джерела високопотенційної теплової енергії для перетворення органічних палив є новітніми технологіями, що дозволяють переробляти первинну органічну сировину (вугілля, природний газ, нафту, сланці) у вторинні енергоносії та вторинну сировину для хімічної, металургійної та інших видів промисловості: водень, конверторний газ, метанол, відновлювальний газ, сажа, кокс тощо. Важливе місце у розвитку високотемпературних реакторів займають модульні реактори малої потужності, теплова потужність яких знаходиться у межах 200...600 МВт. Наведені існуючи та проектовані модульні реактори та їх основні параметри. Обгрунтовано можливість застосування модульних високотемпературних реакторів для конверсії природного газу та газифікації вугілля. Наведено технологічні схеми енерготехнологічних установок з паровою конверсією природного газу та газифікацією вугілля, призначених як тільки для забезпечення процесів конверсії та газифікації, так і для вироблення електричної енергії. Викладена методика розрахунку енергетичної ефективності технологічної частини установок та установки в цілому. Розраховано кількісні показники енергетичної ефективності установок та їх частин, які лежить у межах 65...80 % залежно від технологічної схеми та виду технологічної сировини та істотно перевищують ефективність атомних газотурбінних установок при однаковій з розглянутими установками температурі гелію на виході з реактора.
*Ключові слова*: модульний високотемпературний реактор, енерготехнологічна установка, конверсія, газифікація, енергетична ефективність

*V. Dubkovskyi, V. Segeda, Y. Dobronos.* **Possibilities of using modular high-temperature reactors for the conversion of organic fuels.** The possibility of using small modular high-temperature gas-cooled nuclear reactors for the conversion of fuel fossils is considered. The use of high-temperature gas-cooled nuclear reactors as a source of high-potential thermal energy for the conversion of organic fuels is the latest technology that allows processing primary organic raw materials (coal, natural gas, oil, shale) into secondary energy carriers and secondary raw materials for the chemical, metallurgical and other types of industry: hydrogen, converter gas, methanol, reducing gas, carbon black, coke, etc. An important place in the development of high-temperature reactors is occupied by low-power modular reactors, the thermal power of which is in the range of 200...600 MW. Existing and planned modular reactors and their main parameters are given. The possibility of using modular high-temperature reactors for natural gas conversion and coal gasification is justified. Technological schemes of energy technology installations with steam conversion of natural gas and gasification of coal, intended only for ensuring the processes of conversion and gasification, as well as for the production of electrical energy, are given. The method of calculating the energy efficiency of the technological part of the installations and the installation as a whole is described. Quantitative indicators of the energy efficiency of the plants and their parts have been calculated, which lie within 65...80% depending on the technological scheme and the type of technological raw materials and significantly exceed the efficiency of nuclear gas turbine plants at the same temperature of helium at the reactor exit as the considered plants.
*Keywords*: modular high-temperature reactor, power plant, conversion, gasification, energy efficiency

## Introduction

The use of high-temperature gas cooled nuclear reactors (HTGR) as a source of high -potential thermal energy for the transformation of organic fuels are the latest technologies that allow to process primary organic raw materials (coal, natural gas, oil, slate) in secondary energy and raw material industry, namely hydrogen, converter gas, methanol, restorative gas, soot, coke and more.

An important place in the development of high-temperature reactors is occupied by modular reactors of low power whose thermal power is within – 200…600 MW [1, 2].

The advantages of high-temperature modular reactors are determined by their specific characteristics. They can be deployed incrementally to precisely match growing energy demand, resulting in lower costs for countries or regions with smaller grids [1]. High-temperature modular reactors make it possible to significantly reduce construction costs due to modularity and factory manufacturing. In the perspective of wider application, the design and dimensions of such reactors are better suited for partial or special use in non-electrical technologies, such as providing heat for industrial processes, hy-

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drogen production or seawater desalination. Replacing technological heat obtained by burning organic fuel with nuclear heat leads to significant savings in fossil fuels and reduces the burden on the environment. Some designs of high-temperature modular reactors can also serve niche markets, for example by building power plants with ultra-low power modular reactors – 20…50 MW to replace diesel generators in remote regions, islands, etc.

**Analysis of literary data and statement of the problem**

Modern industry requires significant volumes of heat supply at high temperatures, and the lack of competitive low-carbon technologies currently makes it difficult to solve the problem of reducing $CO_2$ emissions. The high-temperature gas-cooled reactor, which is one of the nuclear technologies of the fourth generation, produces high-potential thermal energy that can be used for industrial applications on a large scale, and therefore the technical capabilities of the HTGR are based on more than half a century of development and experience in the operation of experimental and industrial high-temperature nuclear reactors [3, 4].

HTGRs can provide a number of advantages in energy supply for industrial sectors with the following characteristics:

– oxide-free energy source. Nuclear energy is one of the lowest greenhouse gas emissions of the existing technologies. Thus, the use of high-temperature reactors can contribute to reducing the use of fossil fuels and related carbon emissions not only due to the production of electricity, but also due to technological heat supply;

– high-temperature heat supply. HTGRs can supply heat for industrial processes in the high temperature range. Typical HTGR concepts currently proposed for early deployment offer approximately 550 °C to 850 °C of process heat. There is no low-carbon technology for such high-temperature heat supply that could be widely deployed for industrial processes on a significant scale;

– reliability and security of energy supply. The guaranteed service life of nuclear reactors of the fourth generation is 60 years. Natural resources for the production of nuclear fuel significantly exceed the resources of organic fossil fuels. Today, oil reserves amount to about 1.700 billion barrels, which at an average oil density of 885 kg/m$^3$ is 252 billion tons, and in energy terms – $10.8 \cdot 10^9$ GJ. Proved world reserves of natural gas amount to 192 trillion m$^3$, which in terms of energy is $6.44 \cdot 10^{12}$ GJ. World coal reserves amount to about 890 billion tons, and in terms of energy – $24.0 \cdot 10^{12}$ GJ.

At the same time, explored uranium reserves amount to about 17 million tons, without taking into account the content of uranium in phosphorites. If we estimate the amount of energy that can be obtained only from the use of the isotope $U^{235}$, which is the raw isotope for modern nuclear reactors on thermal neutrons, then the amount of energy is $8.62 \cdot 10^{12}$ GJ. If we take into account the use of the $U^{238}$ isotope in the application of fast neutron reactors, the value of the possible obtained nuclear energy increases by two orders of magnitude.

Low-power modular high-temperature reactors can be used for electricity production as part of a nuclear gas turbine plant (NGTP) and with a steam turbine plant [1 – 4]. But in accordance with the concept of using high-power HTGR in non-electrical technologies, pilot plants with modular high-temperature reactors have been developed for the production of technological heat, which will ensure endothermic chemical-technological processes in various industries. Table 1 shows the existing and project installations with low-power modular high-temperature reactors.

Thus, based on the data presented in Table 1, it can be stated that the application of modular high-temperature reactors in non-electrical technologies – heat generation to ensure technological processes is given considerable attention.

One of such technologies of using high-potential heat of modular high-temperature reactors is the conversion of organic fossil fuels, primarily natural gas and coal [1, 2, 5, 6].

When determining the possibility of using modular rectors for the production of technological products as part of a nuclear power plant, considerable attention is paid directly to the nuclear reactor, issues of nuclear fuel technology in such reactors, designs of heat-emitting elements, hydrodynamics and heat exchange in the active zone, accumulation of operational experience. The issues of heat transfer from the reactor to the technological circuit, alternative possibilities of using the heat of HTR in various technologies, the choice of raw technological raw materials, analysis of the structure and technological principles of production are considered [2 – 4, 7]. At the same time, various schematic solutions are proposed, which allow to more or less successfully combine the temperature potential of the HTR coolant with the parameters of technological processes. At the same time, the creation of new, specific technologies, including both energy conversion processes (energy processes) and transformation of technological raw materials (technological processes), requires the development of new technological schemes, cycles and a rational combination of energy and technological processes in energy technological installations with high-temperature modular reactors.

**Table 1**

Installations with low-power modular high-temperature reactors (HTR)

| Modul reactor | Heat capacity, MW | Helium temperature at the entrance/exit of the active zone, °C | Country | The level of readiness | Using |
|---|---|---|---|---|---|
| HTR-PM | 250 | 250/750 | China | In development | Production of electricity in a steam turbine cycle |
| GTHTR300 | ≤ 600 | 587…633 / 850…950 | Japan | Pre-licensing | Production of electricity in the gas turbine cycle |
| StarCore | 50 | 280/750 | Canada, United Kingdom USA | Licensing | Production of electricity in a steam turbine cycle |
| GT-MHR | 600 | 490/850 | Russia | Sketch design has been completed; Key technologies are demonstrated | Production of electricity in the gas turbine cycle |
| MHR-T | 600 | 578/950 | Russia | Conceptual design | Production of hydrogen by steam conversion of methane |
| MHR-100 | 215 | 490…553/795…950 | Russia | Conceptual design | Production of electric and thermal energy, production of hydrogen |
| PBMR-400 | 400 | 500/900 | SAR | Demonstration of the test rig | Production of electricity in the gas turbine cycle |
| A-HTR-100 | 100 | 406/1200 | SAR | A conceptual project has been completed | Combined gas turbine and steam turbine cycles or production of technological heat |
| HTMR-100 | 100 | 250/750 | SAR | A conceptual project has been completed | Production of electricity in a steam turbine cycle or process heat |
| Xe-100 | 200 | 260/750 | USA | Basic project | Production of technological heat, electricity, desalination |
| SC-HTGR | 625 | 325/750 | USA | Basic project | Production of hydrogen, industrial technological heat and electricity |
| HTR-10 | 10 | 250/700 | China | In operation | Production of electricity, heat supply and technological heat |
| HTTR-30 | 30 | 395/850 (950 max.) | Japan | In operation | Research |
| RDE | 10 | 250/750 | Indonesia | Approval of the project | Research |

**The purpose and objectives of the research**

The development of energy technology installations with HTR includes the solution of a number of scientific and technical problems, among which the development and improvement of technological schemes and the related problem of increasing the technological efficiency of installations, without

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solving which it is impossible to create competitive nuclear plants, can be highlighted. At this stage of research, it is necessary to develop the basic thermal (technological) schemes of energy technology installations, to determine the parameters – the temperature level at the nodal points of the schemes; pressure and temperature of organic raw material reforming processes; ratio of technological agents; distribution of coolant costs, etc.

The purpose of the research is to create and substantiate the technological schemes of energy technology installations with a low-power modular reactor, in which the thermal energy produced by the high-temperature reactor is used only to ensure only technological processes or to generate electrical energy, and the technological raw material is natural gas or coal.

**Technological schemes of energy technology installations with HTR for the conversion of organic fuels**

When using HTR for the conversion of organic fuels – natural gas or coal, the minimum necessary temperature level to ensure technological processes is 750…850 °C for catalytic steam-water or steam-carbonic acid conversion of natural gas [8, 9], and 800…900 °C for steam-water gasification of coal [5, 7, 10, 11].

**Technological schemes of energy technological installation designed for steam-water conversion of natural gas**

Figure 1 shows the technological scheme of a single-purpose enrgy installation with HTR, designd for the conversion of natural gas.

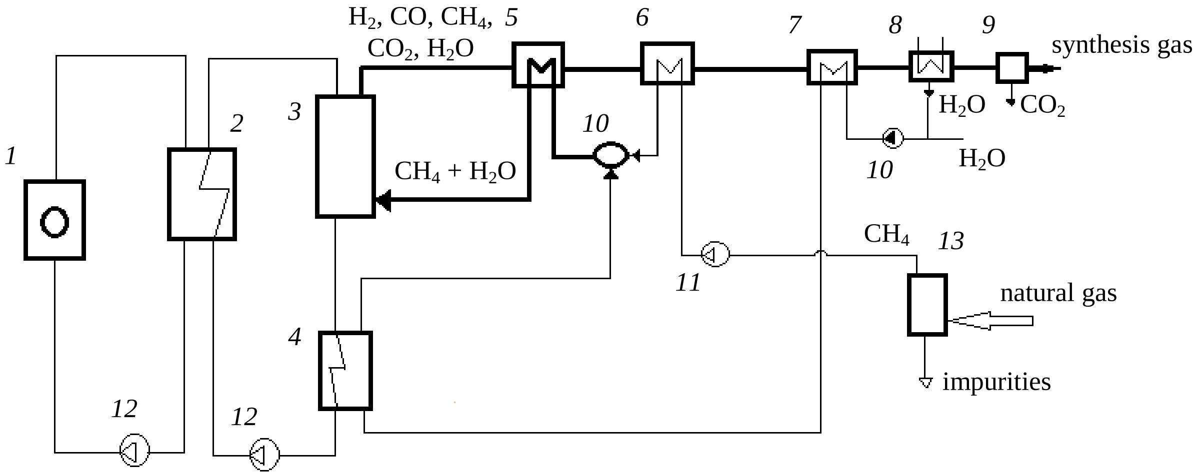


**Fig. 1.** Technological scheme of a single-purpose energy installation, designed for the conversion of natural gas: *1* – HTR; *2* – industrial circuit heat exchanger; *3* – methane converter; *4* – technological steam generator; *5* – regenerator; *6* – methane heater; *7* – process water heater; *8* – water vapor condenser; *9* – purification of converted gas from $CO_2$; *10* – water vapor and methane mixer; *10* – pump; *11* – compressor; *12* – helium gas blowers; *13* – removal of impurities from natural gas

Helium, after heating in the reactor, is sent to the heat exchanger of circuit *2*, where it heats the helium of the second circuit. Helium of the second circuit is sent to the methane converter, where it provides an endothermic reaction of steam-water conversion, after which it is sent to the technological steam generator, where steam is generated for methane conversion. The converted gas is cooled in the regenerator *5*, heating the steam-methane mixture, then it is sent to the methane heater *6* and the process water heater *7*. The cooled converted gas is cleaned of water vapor in the water vapor condenser *8*. The water vapor condensate is added to the process water. Natural gas, which on average consists of 98% methane, is cleaned of impurities. After heating, methane is mixed with water vapor in the mixer *10*, the steam-methane mixture is heated in the regenerator *5* and sent to the methane converter. $CO^2$ is removed from the converted gas in the converted gas purification system *9*. The amount of methane in the converted gas is a small percentage, therefore, the purification of synthesis gas from methane is carried out only in case of high requirements for its purity.

Figure 2 shows the technological scheme of a multi-purpose energy installation with HTGR, designed for the conversion of natural gas and electricity generation.

A multi-purpose energy technological installation consists of a technological and energy part. Unlike a single-purpose energy installations, process steam for the conversion process is obtained from a steam turbine plant. The type and parameters of the steam turbine installation must be such as to satisfy the needs of the technological part of the power plant in technological steam.

The energy distribution of the HTR coolant between the technological and energy parts is determined by the temperature of the helium at the exit from the methane converter.

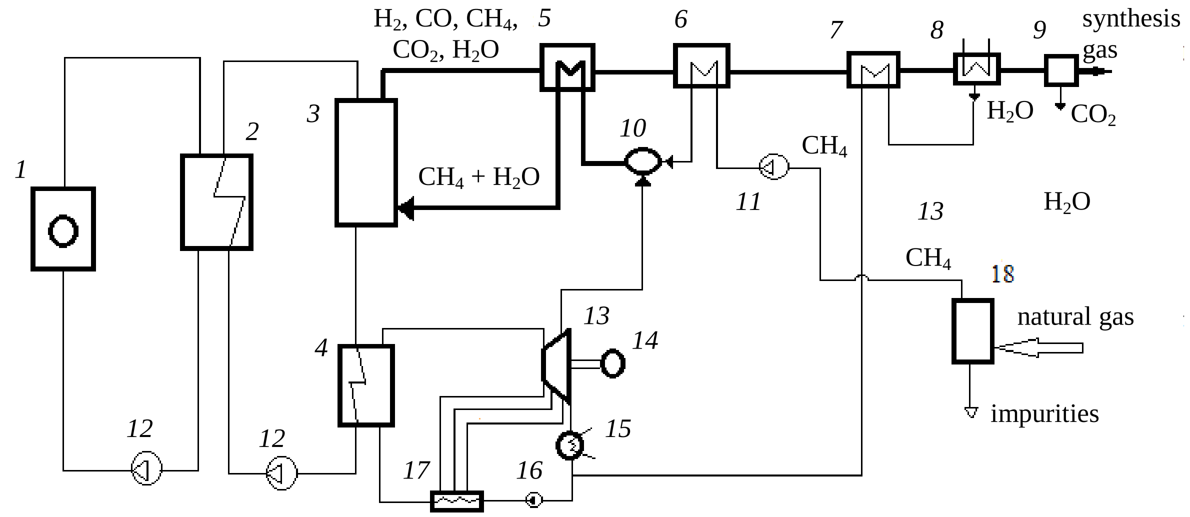


**Fig. 2.** Technological diagram of a multi-purpose energy installations designed for natural gas conversion and electricity generation: *1* – HTR; *2* – circuit heat exchanger; *3* – methane converter; *4* – steam generator; *5* – regenerator; 6- methane heater; *7* – process water heater; *8* – water vapor condenser; *9* – purification of converted gas from $CO_2$; *10* – water vapor and methane mixer; *11* – compressor; *12* – helium gas blowers; *13* – steam turbine; *14* – generator; *15* – turbine capacitor; *16* – condensate pump; *17* – regenerative system of steam turbine installation; *18* – removal of impurities from natural gas

**Technological schemes of energy technological installation with HTR intended for steam-hydrogenation of coal gasification**

Figure 3 shows a scheme of a single-purpose energy technological installation designed for steam-water gasification of coal.

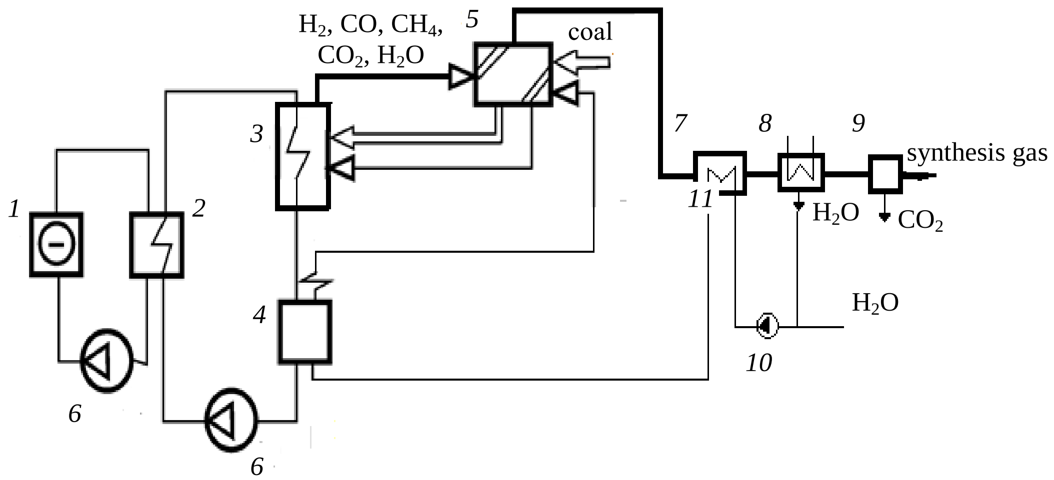


**Fig. 3.** Technological diagram of a single-purpose energy technological installation for coal gasification: *1* – HTR; *2* – industrial circuit heat exchanger; *3* – gasifier; *4* – steam generator of process steam; *5* – regenerator; *6* – helium gas blowers; *7* – process water heater; *8* – water vapor condenser; *9* – purification of gasification products from $CO^2$; 10 – pump

Helium, after heating in the reactor, is sent to the heat exchanger of the industrial circuit, where it heats the helium of the second circuit. Helium of the second circuit is sent to gasifier *3*, where final

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heating and steam-water gasification of coal is carried out. After the gasifier, helium is fed into the process steam generator *4*, where process steam is generated. Gaseous products of gasification are fed into the regenerative heat exchanger *5*, where coal and process steam are heated. After the regenerator, the gaseous products of gasification are sent sequentially to the process water heater *7* and the water vapor condenser *8*. The water vapor condensate is added to the process water. Gaseous products of gasification are cleaned of $CO^2$ in the cleaning system *9*.

The technological scheme of the multi-purpose energy technological installation for coal gasification and electricity generation is shown in Figure 4.

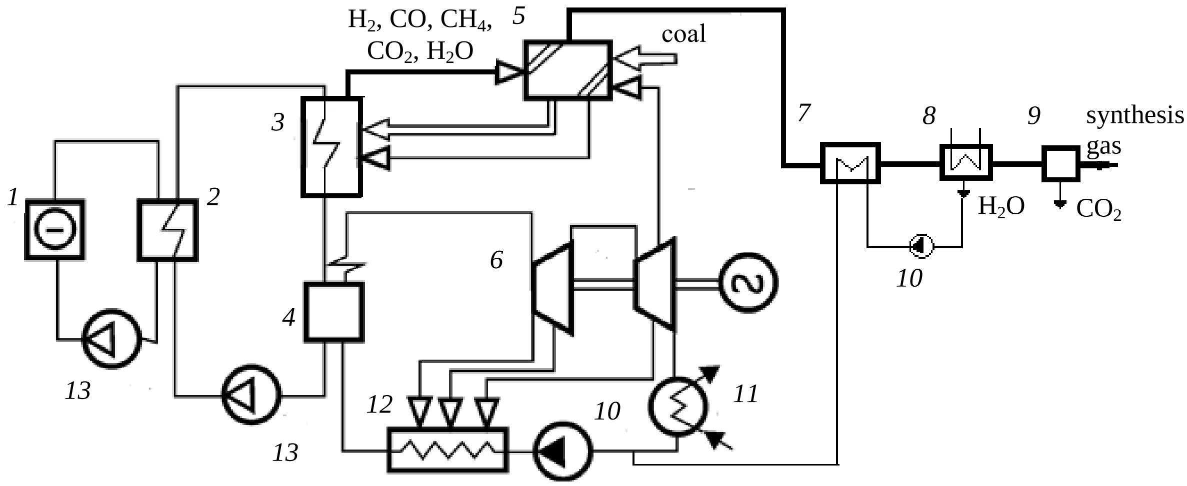


**Fig. 4.** Technological diagram of a multi-purpose energy technological installation for coal gasification and electricity generation: *1* – HTR; *2* – industrial circuit heat exchanger; *3* – gasifier; *4* – steam generator; *5* –regenerator; *6* – steam turbine with electric generator; *7* – condensate heater; *8* – water vapor condenser; *9* – purification of gasification products from $CO_2$; *10* – pump; *11* – turbine condenser; *12* – regenerative system of steam turbine installation; *13* – helium gas blowers

Also, as in the multi-purpose energy technological installation with natural gas conversion, water steam for the technological part of the installation is provided from the intakes of the steam turbine with adjustable intakes or from the exhaust of the turbine with back pressure.

**Determination of parameters and indicators of energy efficiency of energy technological installation**

The following input parameters were adopted to determine the number of produced products and indicators of energy efficiency of energy technological installation with HTR. The thermal capacity of the HTR is 600 MW, the temperature of helium at the reactor exit is 950 °C, the helium pressure at the reactor entrance is 5.0 MPa. The temperature of the helium before the reactor gas blower is 350 °C. The temperature of helium at the outlet of the heat exchanger of the intermediate circuit is 900 °C, the pressure of helium in the circuit is 5.5 MPa, the temperature of helium before the gas blower of the circuit is 300 °C.

An important parameter that determines for multi-purpose installations the distribution of reactor energy between the technological and energy parts is the temperature of helium at the exit from the converter (for the schemes shown in Figures 1 and 2) or at the exit from the gasifier (for the schemes shown in Figures 3 and 4). The value of this temperature depends on the temperature of the main technological process and the temperature of the input technological agents at the exit from the regenerator *5*. In the calculations, the temperature of helium at the exit from the converter (schemes 1 and 2) and the gasifier (schemes 3 and 4) was taken as 700 °C [1, 5].

For the adopted values of the helium circuit temperatures, the power of the HTR was $Q_p^t = 200$ MW for the converter and gasifier and $Q_p^{(pg)} = 400$ MW for the steam generators.

The amount of converted natural gas and gasified coal was determined as:

$$M_s = \frac{Q_p^t}{\Delta H_T + q_{pid}}, \qquad (1)$$

where $\Delta H_T$ – the thermal effect of a chemical reaction, which is defined as:

$$\Delta H_T = \Delta H^0 + \sum_{i=1}^{n} \Delta I_{pr_i} - \sum_{i=1}^{m} \Delta I_{vh_i} \ , \tag{2}$$

where $\Delta H^0$ – standard thermal effect of a chemical reaction;

$\Delta I_{pr_i}$ , $\Delta I_{vh_i}$ – enthalpy, respectively, of reaction products and input substances at the temperature of the chemical reaction;

$q_{pid}$ – is the amount of heat spent on heating the input substances to the reaction temperature.

The $q_{pid}$ value was calculated for the selected temperature pressure of 50 °C in regenerator *5* and was 5.4 MJ/kmol for schemes with natural gas conversion and 6.3 MJ/kmol for schemes with coal gasification.

For the energy part of the multi-purpose energy installation, the parameters of a standard turbo installation with an initial steam temperature of 560 °C and adjustable steam withdrawals were adopted. The parameters of the selected steam for the technological process are 350 °C and 2.0 MPa.

The amount of necessary process steam ($G_n$) and the amount of synthesis gas ($H_2$+CO) obtained were determined from the corresponding chemical reactions of steam conversion of natural gas and steam gasification of coal.

The electric power of multi-purpose energy installation schemes was calculated as:

$$N_e = \eta_T \left(Q_r^{pg} - Q_p\right), \tag{3}$$

where $\eta_T$ =0.42 – turbo installation efficiency;

$Q_p = G_p (i_p^{vid} - i_{gv})$ – process steam heat;

$i_p^{vid}$ , $i_{gv}$ – respectively, the enthalpy of the selection steam and the feed water.

The energy efficiency of the considered technological schemes of energy installation was determined by the expression:

$$\eta = \frac{\sum M_i \, \Delta H_T^i + N_e}{Q_r + M_S \Delta H_T^S} \ , \tag{4}$$

where $M_i$ and $\Delta H_T^i$ – accordingly, the amount and standard heat of combustion of synthesis gas components;

$\Delta H_T^S$ – standard heat of combustion of technological raw materials.

The energy efficiency of the technological part of the schemes was determined by the expression:

$$\eta = \frac{\sum M_i \, \Delta H_T^i}{Q_R^T + Q_P + M_s \Delta H_T^S}. \tag{5}$$

Table 2 shows the results of calculations of technological schemes of energy installation.

**Table 2**

Calculation results of technological schemes of energy technological installation

| Parameter | Conversion of natural gas | | Gasification of coal | |
|---|---|---|---|---|
| | Single-purpose | Multipurpose | Single-purpose | Multipurpose |
| The temperature of the technological process, °C | 750 | 750 | 800 | 800 |
| Consumption of technological raw materials, kmol/s | 0.9695 | 0.9452 | 1.4503 | 1.4503 |
| Process steam heat, MW | 52.94 | 51.61 | 91.22 | 91.22 |
| The amount of synthesis gas produced, kmol/s | 3.878 | 3.7808 | 2.9006 | 2.9006 |
| Electric power, MW | – | 146.33 | – | 129.7 |
| Efficiency of the technological part | 0.9478 | 0.9440 | 0.8834 | 0.8834 |
| Efficiency of energy installations | 0.7097 | 0.8097 | 0.6504 | 0.7612 |

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Relatively lower efficiency for single-purpose installations is explained by the fact that the amount of steam produced in steam generators significantly exceeds the amount of steam required for the technological process. The excess amount of steam for a single-purpose plant with natural gas conversion is 114.9 kg/s or in energy terms 336.5 MW. For a single-purpose installation with coal gasification, it is 110.4 kg/s and 323.5 MW, respectively. The use of single-purpose installations is advisable if there is a need for industrial or household heat supply.

The conducted studies allow us to assert that the use of HTR for the conversion of organic fuels increases the efficiency of using energy in a nuclear reactor in comparison with the use of HTR only for the production of electrical energy as part of a nuclear gas turbine installation, the efficiency of which does not exceed 50…52% at the same temperature of helium as the considered installations exits from the reactor [1, 2].

**Conclusions**

1. The possibilities and advantages of low-power modular high-temperature gas-cooled reactors in their application for the conversion of organic fuels are determined.
2. Technological schemes of energy technological installations with HTR for steam conversion of natural gas and gasification of coal, intended only for technological process support (single-purpose) and for the production of electrical energy (multi-purpose) are given.
3. The energy efficiency of the use of technological installations with HTR for the conversion of organic fuels is determined. The efficiency of the installations is equal to 65…80% depending on the technological scheme and the type of technological raw materials and significantly exceeds the efficiency of nuclear gas turbine installations with HTR.
4. Multi-purpose technological installations have a higher efficiency compared to single-purpose ones due to the presence of the energy part, which makes it possible to fully use the heat of the HTR.
5. The use of single-purpose technological installations with HTR becomes expedient if there is an additional need for industrial or household heat supply.

**Література**


1. Advances In Small Modular Reactor Technology Developments. 2020, Edition. 343 p. URL: https://aris.iaea.org/Publications/SMR_Book_2020.pdf.
2. High-temperature Gas-cooled Reactors and Industrial Heat Applications. OECD/NEA. Nuclear Technology Development and Economics. 2022. URL: https://www.oecd-nea.org/jcms/pl_70442/high-temperature-gas-cooled-reactors-and-industrial-heat-applications.
3. Beck L.M., Pincock L.F. High Temperature Gas-Cooled Reactors: Lessons Learned Applicable to the Next Generation Nuclear Plant. Idaho National Laboratory. Next Generation Nuclear Plant Project, INL/EXT-10-19329. 2011. URL: https://inldigitallibrary.inl.gov/sites/sti/sti/5026001.pdf.
4. Hittner D. High Temperature Industrial Nuclear Cogeneration. NEA Nuclear Innovation 2050 R&D Cooperative Programme Proposal. 2017. URL: www.oecd-nea.org/upload/docs/application/pdf/2020-07/09hittnerni2050 heatandcogeneration.pdf.
5. Дубковский В.А. Рациональные процессы, циклы и схемы энергоустановок. Одесса : Наука и техника, 2003. 224 с.
6. Шрайбер О.А., Дубровський В.В., Тесленко О.І. Сучасний стан і перспективи розвитку водневої енергетики у світі. *Вчені записки НТУ ім. .І.В. Вернадського. Серія:Технічні науки*. Том 32(71), №5. С. 199–209. DOI: https://doi.org/10.32838/2663-5941/2021.5/30.
7. Gary J. Stiegel, Massood Ramezan, Hydrogen from coal gasification: An economical pathway to a sustainable energy future. *International Journal of Coal Geology*. 2006. Volume 65, Issues 3–4. P. 173–190. DOI: https://doi.org/10.1016/j.coal.2005.05.002.
8. Jianguo Xu, Gilbert F. Froment. Methane steam reforming, methanation and water-gas shift: I. Intrinsic kinetics. *AlChE Journal*. 1989. Vol. 35, Is. 1. P. 88–96.
9. Industrial Applications of Nuclear Energy. 2017. IAEA. URL: https://www-pub.iaea.org/MTCD/Publications/PDF/P1772_web.pdf.
10. Verfondern K. Nuclear coal gasification. Nuclear Hydrogen Production Handbook / Yan X.L., Hino, R. Eds., CRC Press, Boca Raton, FL. 2011, p. 547–554.
11. Jäger W., Weisbrodt I., Hörning H. Nuclear process heat applications for the modular HTR. *Nucl. Eng. Design*. 1984. 78. P. 137–145.

**References**

1. Advances In Small Modular Reactor Technology Developments. (2020). 2020 Edition, 343 p. Retrieved from: https://aris.iaea.org/Publications/SMR_Book_2020.pdf.
2. Nuclear Technology Development and Economics. OECD/NEA. (2022). *High-temperature Gas-cooled Reactors and Industrial Heat Applications*. Retrieved from: https://www.oecd-nea.org/jcms/pl_70442/high-temperature-gas-cooled-reactors-and-industrial-heat-applications.
3. Beck, L.M., & Pincock L.F. (2011). *High Temperature Gas-Cooled Reactors: Lessons Learned Applicable to the Next Generation Nuclear Plant*. Idaho National Laboratory, Next Generation Nuclear Plant Project, INL/EXT-10-19329. Retrieved from: https://inldigitallibrary.inl.gov/sites/sti/sti/5026001.pdf.
4. Hittner, D. (2017). *High Temperature Industrial Nuclear Cogeneration*. NEA Nuclear Innovation 2050 R&D Cooperative Programme Proposal. Retrieved from www.oecd-nea.org/upload/docs/application/pdf/2020-07/09hittnerni2050 heatandcogeneration.pdf.
5. Dubkovskiy, V.A. (2003*). Rational processes, cycles and diagrams of power plants.* Monograph. Odessa: Science and Technology.
6. Shraiber, O.A., Dubrovskyi, V.V., & Teslenko, O.I. (2021). Current state and prospects of hydrogen energy development in the world. *Scientific notes of NTU named after .I.V. Vernadskyi. Series: Technical sciences, 32*(71), 5, 199–209. DOI: https://doi.org/10.32838/2663-5941/2021.5/30.
7. Gary J. Stiegel, & Massood Ramezan, (2006). Hydrogen from coal gasification: An economical pathway to a sustainable energy future. *International Journal of Coal Geology, 65*, 3–4, 173–190. DOI: https://doi.org/10.1016/j.coal.2005.05.002.
8. Jianguo Xu, & Gilbert F. Froment. (1989). Methane steam reforming, methanation and water-gas shift: I. Intrinsic kinetics. *AlChE Journal, 35,* 1, 88–96.
9. IAEA. (2017). *Industrial Applications of Nuclear Energy*. Retrieved from: https://www-pub.iaea.org/MTCD/Publications/PDF/P1772_web.pdf.
10. Verfondern, K. (2011). Nuclear coal gasification. Yan, X.L., & Hino, R., (Eds.) *Nuclear Hydrogen Production Handbook* (pp. 547–554). CRC Press, Boca Raton, FL.
11. Jäger, W., Weisbrodt, I., & Hörning, H. (1984). Nuclear process heat applications for the modular HTR. *Nucl. Eng. Design, 78*, 137–145.

**Дубковський В'ячеслав Олександрович**;Viacheslav Dubkovskiy, ORCID:https://orcid.org/0000-0002-4955-7104
**Сегеда Володимир Олегович;** Volodymyr Segeda, ORCID: https://orcid.org/0009-0009-8364-6344
**Добронос Євген Олександрович**; Yevhen Dobronos, ORCID: https://orcid.org/0009-0002-4524-4722

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