ENERGETICS

ЕНЕРГЕТИКА

UDC 621.311.4

V. Dubkovskyi, DSc, Prof.,
V. Segeda
Odessa Polytechnic National University, 1 Shevchenko Ave., Odesa, Ukraine, 65044; e-mail: vadubkovsky54@gmail.com, segedavova155@gmail.com

THE USE OF HIGH-TEMPERATURE NUCLEAR REACTORS IN HYDROGEN PRODUCTION TECHNOLOGIES

В. Дубковський, В. Сегеда. **Використання високотемпературних ядерних реакторів в технологіях виробництва водню.** Розглянуто можливість використання високотемпературних газоохолоджувальних ядерних реакторів (ВТГР) для виробництва водню як альтернативі викопному органічному паливу. Проведено огляд сучасних технологій вироблення водню та його переваги як енергоносія. Наведена структура світового виробництва та споживання водню. Виняткові властивості водню як енергоносія та компонента різних технологічних процесів розкривають перспективу його застосування у різних галузях енергетики, на транспорті та в промисловості. Якщо раніше основними перевагами вважались енергоємність водню, здатність до зберігання та розподілу, то зараз і на перспективу ключовим фактором стає його екологічна чистота та можливість декарбонізувати транспорт, хімічну, нафтохімічну, металургійну промисловість та комунальний сектор. Зараз більшу частину водню і водневмісних продуктів виробляють за допомогою парової конверсії природного газу. При цьому 40...50 % природного газу витрачається на енергетичне забезпечення процесу конверсії. Щоб заощадити природний газ та знизити навантаження на навколишнє середовище, розроблені схеми парової конверсії метану з підведенням тепла від високотемпературного газоохолоджуваного реактора. Для конверсії потрібен рівень температур 1000...1200 К. Саме такий рівень температур може забезпечити ВТГР. Запропонована схема багатоцільової атомної енерготехнологічної установки (АЕТУ) з ВТГР по виробництву водню при паровій конверсії природного газу та генерації електроенергії та розраховані основні параметри АЕТУ с ВТГР тепловою потужністю 3000 МВт. Визначено зниження витрати природного газу у порівнянні з традиційною технологією парової конверсії.
Ключові слова: високотемпературний реактор, водень, атомна енерготехнологічна установка, конверсія

V. Dubkovskiy, V. Segeda. **The use of high-temperature nuclear reactors in hydrogen production technologies.** The possibility of using high-temperature gas-cooled nuclear reactors (HTGR) for hydrogen production as an alternative to organic fossil fuel is considered. An overview of modern technologies of hydrogen production and its advantages as an energy carrier was conducted. The structure of world production and consumption of hydrogen is given. The exceptional properties of hydrogen as an energy carrier and component of various technological processes reveal the prospect of its application in various fields of energy, transport and industry. If previously the main advantages of hydrogen were considered to be its energy intensity, ability to store and distribute, now and for the future the key factor is its environmental cleanliness and the ability to decarbonize transport, chemical, petrochemical, metallurgical industries and the utility sector. Currently, the majority of hydrogen and hydrogen-containing products are produced using steam conversion of natural gas. At the same time, 40...50% of natural gas is spent on the energy supply of the conversion process. In order to save natural gas and reduce the burden on the environment, methane steam conversion schemes with heat input from a high-temperature gas-cooled reactor have been developed. For conversion, a temperature level of 1000...1200 K is required. It is this temperature level that HTGR can provide. The proposed scheme of a multi-purpose nuclear power plant (MNPP) with a HTGR for the production of hydrogen during the steam conversion of natural gas and electricity generation and the main parameters of an MNPP with a HTGR with a thermal capacity of 3000 MW are calculated. A decrease in the consumption of natural gas was determined, comparable to the traditional technologies.
Keywords: high-temperature reactor, hydrogen, nuclear power plant, conversion

Introduction

The possibility of using high-temperature gas-cooled nuclear reactors (HTGR) for the production of not only electrical energy, but also for providing high-potential thermal energy for other (non-electric) technologies will allow to significantly expand the use of nuclear energy and reduce the consumption of organic fuels and, accordingly, reduce the technogenic burden on the environment .

One of the promising directions for the introduction of HTGR in non-electrical technologies is the production of hydrogen as an alternative to fossil organic fuel. According to various forecasts, in 2050, hydrogen will provide the world's energy needs at the level of 18…24% [1, 2, 3].

Hydrogen is actively used in various branches of the chemical and petrochemical industry. It is used in the synthesis of ammonia; as a component of the reducing gas in the metallurgical industry; hydrogenation of fats and hydrogenation of coal, oils and hydrocarbons. In addition, hydrogen is needed for the production of liquid fuel by hydrogenation of coal and fuel oil. In its pure form, hydro-

DOI: 10.15276/opu.2.68.2023.02

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

gen is practically not found in nature, so solving the problems of obtaining it, concentrating it and cleaning it from impurities is of great importance.

Analysis of literature data and statement of the problem

The main ways of obtaining pure hydrogen in industry are the electrolysis of water and the conversion of coke or methane. In addition, hydrogen is obtained by extraction and concentration from various gas mixtures of petrochemical processes [4, 5].

Currently, hydrogen extraction is most often performed in two ways:

– hydrogen concentration using membrane units. This method of separation of gaseous mixtures makes it possible to isolate hydrogen from gas streams with minimal losses. The main advantages of membrane installations that allow concentrating hydrogen include low maintenance costs, simple hardware design, and a long service life of the membranes. It should be noted separately that membrane installations are characterized by high flexibility, which is realized during the creation of modular systems that allow you to quickly change the scale of hydrogen production. Another important advantage of this method of obtaining hydrogen is the affordable cost of the equipment, due to a number of features of the production and installation of membrane units;

– extraction of hydrogen using adsorption units. This method of obtaining pure hydrogen is based on the technology of short-cycle or ultra-short-cycle adsorption under variable pressure. This technology uses the principle of absorption of impurities of hydrogen-containing gas on the surface of specially developed adsorbent materials. The number of impurities retained by the adsorbent depends on the pressure, therefore, these hydrogen production installations allow the process of adsorption of impurities and regeneration of the adsorbent by changing the pressure. In this way, a very clean product is obtained hydrogen, with minimal pressure loss. The only disadvantage of this method of obtaining hydrogen is its rather high cost [6].

Currently, the majority of hydrogen and hydrogen-containing products are produced using steam conversion of natural gas. Water vapor at a temperature of 950…1200 K is mixed with methane under pressure in the presence of a catalyst. At the same time, 40…50% of natural gas is spent on the energy supply of the conversion process. In order to save natural gas and reduce the burden on the environment, methane steam conversion schemes with heat supply from a high-temperature gas-cooled reactor have been developed [6].

Over the years, extraction and concentration technologies have been improved, allowing to obtain hydrogen from various sources of raw materials. As a result, it was possible to create equipment that can extract hydrogen from gas mixtures. Thanks to this, hydrogen can be returned to the production cycle, significantly reducing losses. In addition, the extraction of hydrogen from the gas mixture has a positive effect on the ecology of the environment. Obtaining hydrogen from fuel, residual and waste gases can significantly increase the economic efficiency of production.

The exceptional properties of hydrogen as an energy carrier and component of various technological processes reveal the prospect of its application in various fields of energy, transport and industry. If earlier energy consumers were mainly attracted by hydrogen's energy density, ability to store and distribute it, now and for the future the key factor is its environmental cleanliness and the ability to decarbonize transport, the chemical, petrochemical, metallurgical industry and the utility sector. Today, hydrogen is considered by various states and companies as a key energy carrier of the future, a promising commodity. Today, hydrogen consumption in the world is about 70...75 million tons/year. The largest consumers (up to 90% of the total volume) are the chemical and oil refining industries. But this is mainly “self-made” hydrogen, which is produced with emissions of CO_2 into the atmosphere. In the coming decades, a sharp increase in hydrogen consumption is expected in connection with the transition of basic industries to new carbon-free technologies and the development of environmentally friendly transport, taking into account the requirements for reducing carbon pollution of the atmosphere. The largest contribution to the growth of global demand for hydrogen should be expected from transport and distributed energy supply systems when using hydrogen fuel cells. With large-scale development of production, transportation and storage technologies, hydrogen can also be used to solve energy problems: distribution of energy by sectors, regions and as a buffer-accumulator. For example, this is energy storage in power systems with an uneven load schedule, especially for nuclear power plants, a buffer-storage energy in combination with renewable energy sources (RES), energy supply to local consumers and district heating. The exceptional properties of hydrogen as an energy carrier and a component of various technological processes reveal the prospect of its application in various fields of energy, in transport, in industry, in the energy supply of local consumers and long-distance heat supply.

The choice of the method of obtaining hydrogen depends on the composition of raw materials, the required purity of hydrogen, and even on the mode of operation, production capacity and other factors.

Thus, hydrogen generation is possible using the following technologies [6, 7, 8, 9]:

– from organic fossil fuels – steam conversion of natural gas or light oil fractions or gasification of coal;

– electrolysis;

– biotechnological or renewable sources;

– using nuclear energy sources (nuclear-hydrogen energy).

Table 1 shows the structure of world production and consumption of hydrogen.

Table 1

Shows the structure of world production and consumption of hydrogen

Production		Consumption	
Steam conversion of natural gas	~85%	Ammonia production	50%
Conversion of light oil fractions	7%	Oil refining industry	37%
Coal gasification	4%	Methanol production	8%
Electrolysis	4%	Space industry	4%
Others	<1%	Others	4%

Purpose and objectives of the research

When producing hydrogen using technologies that use natural resources as raw materials, such as natural gas, oil, or coal, 30…50% of the raw materials are used as fuel to ensure the technological process. At the same time, a temperature level of ~950 K is required for conversion, and ~1100 K for gasification. It is this level of temperatures that HTGR can provide.

In principle, the production of hydrogen using nuclear energy is possible either with the use of light water reactors (LWR) by electrolysis of water or HTGR using thermochemical processes of natural gas conversion or coal gasification [7]. Both closed and open fuel cycles using uranium, plutonium and thorium can be used in HTGR. The overall efficiency for the implementation of such a technology can reach 58…59% [7], while the efficiency of the technology with electrolysis due to the electricity produced by light water reactors does not exceed 24…25%.

Such an advantage in the efficiency of hydrogen production when using the high-potential thermal energy of HTGR in thermochemical processes of natural gas conversion or coal gasification is determined purely by thermodynamic factors, because in the case of using electrolysis for hydrogen production, electricity is needed, which is produced by light water reactors with an efficiency that does not exceed 33%.

Determination of optimal parameters – temperatures at nodal points of the scheme; pressure and temperature of the natural gas conversion process; ratio of water vapor and natural gas in the technological part of the installation; distribution of heat carrier costs are the tasks of research of MNPP with HTGR.

The paper proposes a thermal scheme of a multi-purpose nuclear energy technological installation with VTGR, and a consolidated calculation of the technological and energy indicators of such an installation is carried out.

Such an advantage in the efficiency of hydrogen production when using the high-potential thermal energy of HTGR in thermochemical processes of natural gas conversion or coal gasification is determined purely by thermodynamic factors, because in the case of using electrolysis for hydrogen production, electricity is needed, which is produced by light water reactors with an efficiency that does not exceed 33%.

Research of the parameters of thermal (technological) schemes of MNPP with HTGR

Figure 1 shows the proposed thermal (technological) scheme of a multi-purpose MNPP with HTGR for hydrogen production and electricity generation.

MNPP consists of three parts: nuclear, technological and energy. The helium heated in the active zone of the HTGR is fed through the heat exchanger of the industrial circuit *2* to the high-temperature

 ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

heat exchanger of the technological part *5*, where it heats a mixture of water vapor from the selection of the steam turbine *12* and natural gas (which consists of 98% methane), which is fed to the tubular contact apparatus of the first stage of conversion of methane 7.8, where ~70% of methane is converted [10], and then through recuperative heat exchangers *11* – to the second stage of conversion – mine methane converter *9*, where air is also introduced to carry out the exothermic reaction of the final conversion of methane. The converted gas is cooled in recuperative heat exchangers *11* and cooler *10*. The cooled converted gas is fed to the carbon monoxide converter, where the autothermal conversion reaction is carried out, then to the carbon dioxide purification system and to the hydrogen release system.

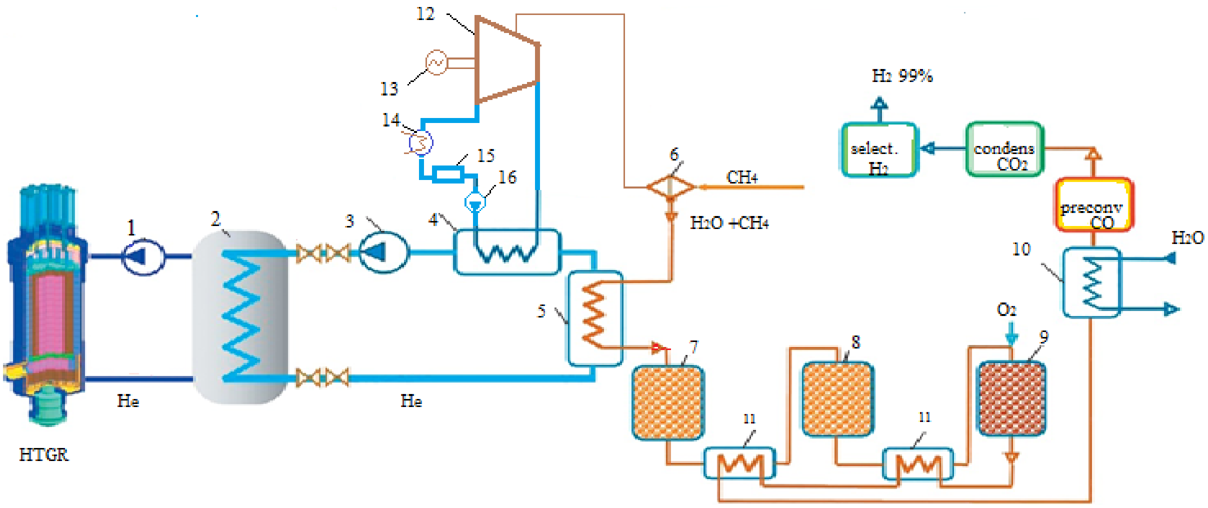

Fig. 1. Scheme of a MNPP with HTGR for hydrogen production and electricity generation: *1*, *3* – gas blowers; *2* – industrial circuit heat exchanger; *4* – steam generator; *5* – high-temperature heat exchanger of the technological part; *6* – water vapor and methane mixer; *7*, *8* – tubular contact devices of the first stage of methane conversion; *9* – mine methane converter; *10* – cooler of convertible gas; *11* – recuperative heat exchangers; *12* – steam turbine; *13* – electric generator; *14* – turbine condenser; *15* – regenerative system; *16* – feed pump

The energy part consists of a standard steam power plant, which includes a steam generator 4, into which helium is supplied after the high-temperature heat exchanger of the technological part.

Thermodynamic and techno-economic analyzes are the method of research of energy technological installations. At the first stage, a thermodynamic analysis is carried out, there is a determination of the most favorable operating parameters of the installation, the ratio of the produced products and an assessment of thermodynamic (energy) perfection.

Results of consolidated energy calculation of MNPP with HTGR

Table 2 shows the results of the calculation of the main parameters of the MNPP with a HTGR with a thermal capacity of 3000 MW.

Thus, the use of HTGR in the technology of steam conversion of natural gas leads to a decrease in the total consumption of the latter by 18...19% due to the provision of high-potential heat energy for the exothermic reaction at the first stage of conversion.

If we consider the amount of reduction in the consumption of natural gas as a fuel to ensure the exothermic conversion reaction, the share of HTGR is about 77%.

The study of the possibilities of using HTGR as part of MNPP includes several important directions, one of which is the determination of the optimal ratio of the production of a technological product – hydrogen, renewable gas in metallurgy, chemical fertilizers, oil refining, etc. and electric energy; evaluation of thermodynamic perfection of both technological and energy parts of the installation and the entire MNPP [7, 11]; selection of optimal installation parameters, etc.

Table 2

The main parameters of MNPP with HTGR thermal capacity of 3000 MW

INCOMING DATA	Value	PARAMETER	Value
Thermal capacity of HTGR, MW	3000	Thermal capacity of HTGR, transferred to the technological part, MW	1754
Helium temperature at the reactor exit, K	1273	Thermal capacity of the HTGR, transferred to the power unit, MW	1246
Helium temperature at the entrance to the reactor, K	623	Consumption of natural gas, kmol/s, including:	11.710
		– as raw materials in the first stage of conversion, kmol/s	8.505
		– as raw materials in the second stage of conversion, kmol/s	2.550
		– as fuel to ensure the second stage of conversion, kmol/s	0.655
Helium temperature at the entrance to the high-temperature heat exchanger of the technological part, K	1223	Hydrogen production, kmol/s Including using the heat of HTGR, kmol/s	33.15 22.50
Helium temperature at the entrance to the industrial circuit heat exchanger, K	573	Electric power, MW	520
Helium temperature at the inlet to the steam generator, K	843	Natural gas economy, kmol/s	2.184

Conclusions

1. The introduction of HTGR into non-electrical technologies, including for the production of hydrogen as an alternative to fossil organic fuel, is a promising direction for the development of nuclear energy.

2. The use of HTGR will reduce the ecological burden on the environment due to oxide-free processes of providing energy for the steam conversion of natural gas during hydrogen production.

3. At MNPP for hydrogen production, the reduction of natural gas consumption is 18-19% compared to traditional steam conversion technology.

4. An important task of the development and creation of MNPP is to determine the optimal ratio of production of technological product and electrical energy; evaluation of the thermodynamic perfection of both technological and energy parts of the installation and the entire MNPP; selection of optimal operating parameters of the installation.

Література

1. 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.* 2021. Том 32(71), №5, С. 199–209. DOI: https://doi.org/10.32838/2663-5941/2021.5/30.
2. Hydrogen production using nuclear energy. Vienna: IAEA, 2013. 400 p. URL: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1577_web.pdf. (дата звернення: 18.08.2023).
3. Шевченко В.Г., Ляшенко В.І., Осадча Н.В. Світові тенденції розвитку водневої енергетики. *Вісник економічної науки України*. 2021. №2(41). С. 17–26. DOI: hths://doi.org/10.37405/1729-7206.2021.2(41).17-26.
4. Shulten R. and Kuaeler K. High temperature reactor and application to nuclear procesis heat. *Annals of Nuclear Energy*. 1976. V. 3. P. 95–111.
5. Hydrogen Basics. *AFDS.* URL: https://afdc.energy.gov/fuels/hydrogen_basics.html.
6. Водень в альтернативній енергетиці та новітніх технологіях / за ред. В.В. Скорохода, Ю.М. Соломіна. Київ : КІМ, 2015. 294 с.
7. Дубковский В.А. Рациональные процессы, циклы и схемы энергоустановок. Монография. Одесса : Наука и техника, 2003. 224 с.
8. Stern A.G. A new sustaina-ble hydrogen clean energy paradigm. *International Journal of Hydrogen Energy*. 2018. Vol. 43, Issue 9. P. 4244–4255. DOI: https://doi.org/10.1016/j.ijhydene.2017.12.180.
9. Burhan M., Shahzad M.W., Choon N.K. Hydrogen at the Rooftop: compact CPV-hydrogen system to convert sunlight to hydrogen. *Applied Thermal Engineering*. 2018. Vol. 132. P. 154–164. DOI: https://doi.org/10.1016/j.applthermaleng.2017.12.094.

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

10. Яцков В.М., Корчик Н.М., Пророк О.А. Основні технологічні схеми базових неорганічних виробництв: навч. посібник. Рівне : НУВГП, 2020. 212 с.
11. Дубковський В.О., Лапшов В.М. Деякі загальні властивості термодинамічних процесів. Монографія. Київ : ІСДО, 1995. 84 с.

References

1. 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.
2. *Hydrogen production using nuclear energy.* (2013).Vienna: IAEA, 400 p. Retrieved from: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1577_web.pdf. (Last access 18.08.2023).
3. Shevchenko, V.G., Lyashenko, V.I., & Osadcha, N.V. (2021). World trends in the development of hydrogen energy. *Herald of economic science of Ukraine, 2*(41), 17–26. DOI: htths://doi.org/10.37405/1729-7206.2021.2(41).17-26.
4. Shulten, R. & Kuaeler, K. (1976). High temperature reactor and application to nuclear procesis heat. *Annals of Nuclear Energy, 3*, 95–111.
5. Hydrogen Basics. *AFDS.* Retrieved from: https://afdc.energy.gov/fuels/hydrogen_basics.html.
6. Skorokhoda, V.V., & Solomina, Yu.M. Eds. (2015). *Hydrogen in alternative energy and the latest technologies.* Kyiv: KIM.
7. Dubkovskiy, V.A. (2003). *Rational processes, cycles and diagrams of power plants.* Monograph. Odessa: Science and Technology.
8. Stern, A.G. (2018). A new sustaina-ble hydrogen clean energy paradigm. *International Journal of Hydrogen Energy, 43*, 9, 4244–4255. DOI: https://doi.org/10.1016/j.ijhydene.2017.12.180.
9. Burhan, M., Shahzad, M.W., & Choon, N.K. (2018). Hydrogen at the Rooftop: compact CPV-hydrogen system to convert sunlight to hydrogen. *Applied Thermal Engineering, 132*, 154–164. DOI: https://doi.org/10.1016/j.applthermaleng.2017.12.094.
10. Yatskov, V.M., Korchyk, N.M., & Prorok, O.A. (2020). *Basic technological schemes of basic inorganic productions*: training. manual. Rivne: NUVHP.
11. Dubkovskiy, V.O., & Lapshov, V.M. (1995). *Some general properties of thermodynamic processes.* Monograph. Kyiv: ISDO.

Дубковський В'ячеслав Олександрович; Viacheslav Dubkovskiy, ORCID: 0000-0002-4955-7104
Сегеда Володимир Олегович; Volodymyr Segeda, ORCID: 0009-0009-8364-6344

Received September 04, 2023

Accepted October 26, 2023