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Analysis of Hydrogen Use in Gas Turbine Plants

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Abstract. Improvement of the efficiency of modern power systems requires the development of storage technologies, optimization of operation modes, and increased flexibility. Currently, various technical solutions are used for electricity storage. The results of a literary review with an analysis of existing energy storage systems are presented, their advantages and disadvantages are considered. One of the promising solutions is the use of hydrogen as an energy storage medium. The creation of corresponding energy complexes makes it possible to obtain hydrogen by electrolysis of water, and then use it to cover peak loads. Various schemes with hydrogen-fired gas turbines with a pressure up to 35 MPa and a temperature of 1500–1700 °C were considered. The new scheme of power plant with hydrogen-fired gas turbines was synthesized, which includes a power block, hydrogen generation blocks and hydrogen and oxygen preparation unit for burning. An atmospheric electrolyzer was considered as a hydrogen and oxygen generator. For the proposed scheme, parametric optimization was performed, where the storage efficiency factor has been used as a criterion. The influence of inlet temperature in the combustion chamber, the compression rate of hydrogen and oxygen, as well as the specific energy costs of the electrolyzer were analyzed. The results of the numerical experiment were approximated in the form of polynomial dependencies, and can be used in further research on the economic efficiency of proposed power plant.

Keywords: hydrogen, gas turbine plants, energy storage, power generation, energy efficiency

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Возможность использования водорода в газотурбинных установках

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Реферат. Повышение эффективности энергетических систем требует развития их аккумулирующих способностей, оптимизации управления режимами работы и улучшения маневренности генерирующего оборудования. В настоящее время применяются различные

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технические решения для аккумулирования электрической энергии. Представлены результаты литературного обзора с анализом различных способов аккумулирования энергии, рассмотрены их преимущества и недостатки. Одним из перспективных направлений является использование возможностей водородной энергетики, а именно создание энергетических комплексов, позволяющих получать водород методом электролиза воды и далее применять его для покрытия пиковых нагрузок. Рассмотрены различные схемы энергетических блоков с сжиганием водорода и использованием паровых и газовых турбин с давлением водяного пара до 35 МПа и температурой 1500–1700 °С. Для проведения исследований синтезирована схема энергетической установки по варианту электроэнергия – водород – электроэнергия, включающая силовой блок, блоки генерации водорода и подготовки водорода и кислорода к сжиганию. Функцию генератора водорода и кислорода выполнял электролизер атмосферного типа. Для предложенной схемы выполнена параметрическая оптимизация, где в качестве критерия применялся коэффициент эффективности процесса аккумулирования, а в качестве управляемых переменных – температура пара за камерой сгорания, степень сжатия в компрессоре водорода и кислорода, а также удельные затраты электроэнергии на привод электролизера. Полученные результаты численного эксперимента аппроксимированы в виде полиномиальных зависимостей и могут быть использованы в дальнейших исследованиях экономической эффективности рассмотренной энергетической установки.

Ключевые слова: водород, газотурбинные установки, системы аккумулирования энергии, производство электроэнергии, энергоэффективность

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Introduction

Improvement of the efficiency of modern power systems requires the development of storage technologies, optimization of operation modes, and increased flexibility to reduce the imbalance between the demand and supply of electricity through the wide introduction of variable renewable energy sources [1–5]. Various studies [6–8] show that the rapidly increasing of renewable installed capacities force the studies to improve the flexibility of power systems.

Figure 1 shows electricity production by all sources during the last decades. The growth of renewables is clearly seen during the last 5–10 years.

For power systems with a high share of combined heat and power plants and nuclear power plants the problem of power system flexibility planning is also acute.

O. Babatunde et al. showed that both large and small-scale energy storage systems attract interest in researching and further implementation [7].

Power plants that can quickly be started up when a power imbalance arises usually provide flexible generation. It is evident that increasing the share of renewable energy sources on the grid is fast transforming the power system sector and operational complexities of the power system network.

Various electricity storage systems can contribute achieving the following goals [9–12]: to balance the energy production and consumption; to reduce the total installed capacity of the power system; to increase the efficiency of energy use.

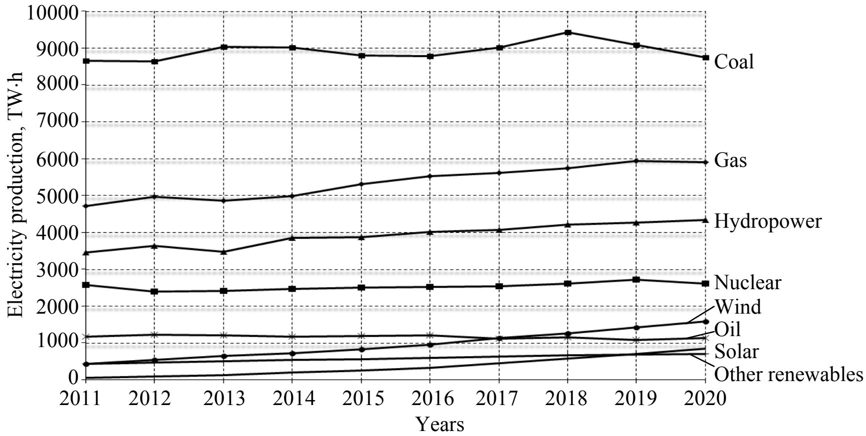

Fig. 1. Electricity production in world by source [9]

Today different types of storage systems are used. Figure 2 shows compares different storage technologies in terms of charge/discharge period and storage capacity [1].

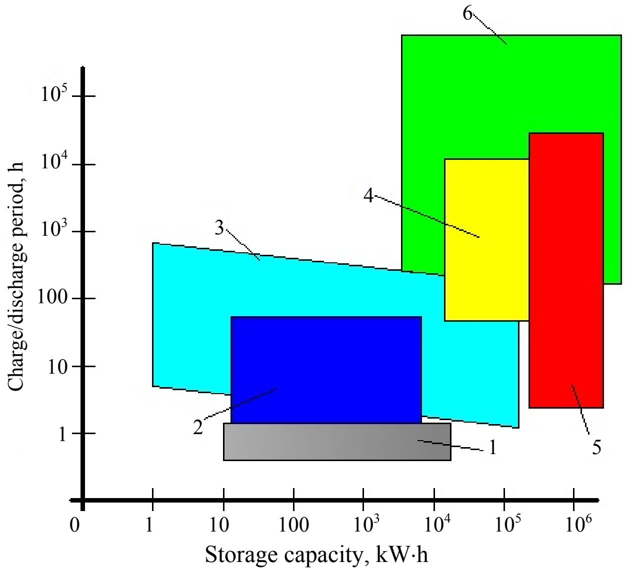

Fig. 2. Charge/discharge period and storage capacity of different electricity storage systems:
1 – fly wheels; 2 – batteries; 3 – compressed air energy storage; 4 – pumped hydro storage;
5 – hydrogen system; 6 – synthetic natural gas

Stationary Battery Energy Storage facility consists of a battery, a Power Conversion System to convert alternating current to direct current, when necessary, and the "balance of plant", which is used to support and operate the system. The existing storage systems based on batteries consist of cells that are integrated into battery modules, which are installed in standard racks in a specialized container to create an integrated battery system.

Behabtu et al. showed that the total installed electrochemical energy storage capacity is about 9.6 GW, and predominantly consists of Li-ion batteries (installed capacity of 8.5 GW) [13]. Very fast response rates (a fraction of a second) make Li-ion batteries good candidates for grid balancing services [14].

As described in [15], commercial application of Li-ion batteries electricity is growing rapidly. Also, there is a tendency for the cost reduction. According to the reviews of research storage systems based on Li-ion batteries are still limited in capacity and cycle charging.

Compressed air energy storage (CAES) systems use compressed air for power generation. CAES can operate with additional fuel consumption to enhance efficiency. Cost of electricity storage varies from 0.1 to 0.3 USD/(kW·h). It is worth mentioning that only two plants are under operation now with electricity to electricity efficiency of 42 and 54 %, respectively. According to [1, 15], there are limited places that are feasible for CAES to be built. The future competitiveness of CAES is based on the implementation of adiabatic systems with an efficiency of about 70 %.

Pumped hydro storage (PHS) is the most widespread power storage technology with an installed capacity of about 100 GW. The efficiency of PHS is in the range of 70 to 80 % and depends on the availability of height between two storage basins. There are also environmental restrictions that impede the introduction of new PHS. PHS is a well-known technology and new research is head to enhance the efficiency, to use underground storage like flooded mine shafts or other cavities [15].

Chemical energy storage. As defined in [13], the technologies for a long power discharge period are required. Chemical energy storage could be one of the promising solutions. In such systems, the excess of electricity is used to produce intermediate medium, store it and then produce the electricity via different technologies.

Hydrogen is one of these media and as clean fuel, it is a subject of interest for many research institutions [16]. Hydrogen would be produced from water by an electrolysis process powered by excess renewable or nuclear energy. The system layer for a chemical energy storage system encompasses hydrogen production, transmission and storage, and power production using hydrogen. As described in [17], hydrogen can be directly used as a fuel in gas turbines or converted to methane, synthesis gas, liquid fuels, or chemicals. During periods of undersupply, hydrogen could be drawn from storage and used as a fuel to produce power through either a gas turbine or a stationary fuel cell [18, 19].

There are several ways to use hydrogen as fuel for gas turbines. The existing natural gas-fired gas turbines can operate with a blend of hydrogen and natural gas. Turbine combustion systems are limited in the amount of hydrogen they can burn. The list of commercial initiatives of gas turbines manufactories to develop a new modern combustion system firing 100 % hydrogen is described in [20].

The second direction is to use stoichiometric combustion of hydrogen and oxygen mixture. Such combustion does not cause any NO_x or CO_2 emissions and could lead to 60 % efficiency achievement.

The possibility of using a hydrogen energy complex with nuclear steam turbines to produce hydrogen via electrolyze during nighttime periods was considered in [21]. In the daytime, the authors propose to burn hydrogen and use it directly in the existing or additionally installed steam turbine to produce peak power [22].

Theoretical evidence for the large-scale installations with a hydrogen-oxygen gas-turbine unit is well-known. Various cycles (Fig. 3) for the hydrogen combustion turbine system with high thermal efficiency were described in [23].

Figure 3a shows the cycle proposed by Toshiba Co in 1999, based on the Rankine cycle, and consists of four turbine parts and two combustors with H_2–O_2 combustion in a steam flow. The regeneration heat exchanger is placed before low-pressure part. Analysis of the Toshiba cycle shows the paired values of pressure and temperature (T_{max} = 1700 °C, p = 7.3 MPa, and p_{max} = = 34.3 MPa, T = 876 °C) allowing to obtain maximal overall thermal efficiency of 58.3 %.

Figure 3b shows the cycle proposed by Westinghouse Electric Co (1998). The concept is based on the Rankine cycle and consists of two H_2–O_2 combustors and three turbine parts. As compared with the Toshiba cycle, there is no high-pressure turbine part and the Westinghouse cycle can be as a new Rankine cycle with one reheating stage classified. Additional H_2–O_2 combustor provides the second reheat of steam. Analysis of this cycle also shows the paired values of pressure and temperature (T_{max} = 1700 °C, p = 25.0 MPa, and p_{max} = 27.7 MPa, T = 517 °C) allowing to obtain maximal overall thermal efficiency at 60.6 %.

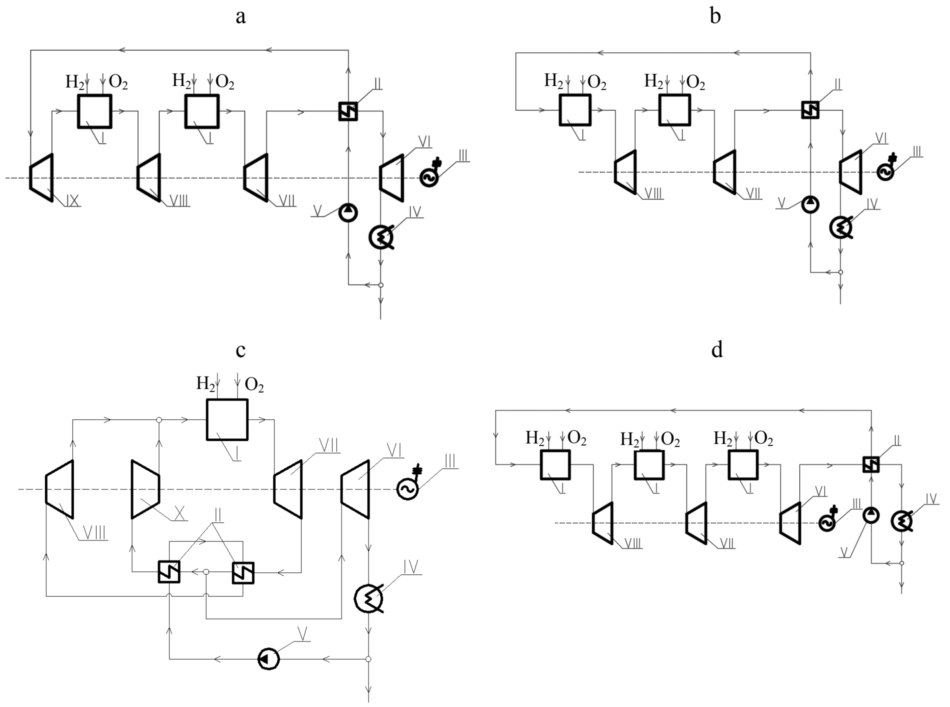

Fig. 3. Cycle diagrams of hydrogen turbines: a – Toshiba; b – Westinghouse; c – Graz; d – modified Rankine cycle; I – combustion chamber; II – heat exchanger; III – generator set; IV – condenser; V – pump; VI – high pressure turbine (HPT); VII – intermediate pressure turbine (IPT); VIII – second stage HPT; IX – first stage HPT; X – compressor

Figure 3c shows the Graz cycle originally proposed by prof. Hebert Jericha, which combines Brayton and Rankine systems and consists of one combustor, three turbine parts, heat recovery steam generator, condensing part, and compressor [23]. The top cycle is the Brayton cycle with high parameters and the bottom cycle is the Rankine cycle with low parameters. An increase in efficiency for this cycle is achieved due to a significant decrease in compression work. Analysis of the Graz cycle shows the paired values of pressure and temperature (T_{max} = 1700 °C, p = 5.0 MPa, and p_{max} = 35 MPa, T = 650 °C) allowing to obtain maximal overall thermal efficiency of 58.0 %.

Figure 3d shows the modified Rankine cycle. Contrary to other cycles, H_2–O_2 combustor is located above the first stage of HPT. Heat recovery steam generator is located between the last turbine part and condenser. Analysis of this cycle shows the paired values of pressure and temperature (T_{max} = 1700 °C, p = 25.0 MPa, and p_{max} = 27.7 MPa, T = 463 °C) allowing to obtain the maximal overall thermal efficiency of 64.7 %. It is worth mentioning that all these cycles were proposed to increase the steam temperature at the turbine inlet up to 1700 °C with corresponding pressure of 35 MPa which is technically unattainable at present.

The studies also did not consider the units for the hydrogen and oxygen production and preparation for combustion.

Materials and methods

This paper considers a part of the chemical energy storage system including hydrogen production by electrolysis and power production using hydrogen. The hydrogen and oxygen are produced through an atmospheric-type electrolyzer. The power plant scheme is shown in Fig. 4 with two-stage hydrogen-fired gas turbine.

Water under atmospheric pressure 21 is delivered to electrolyser I where split into oxygen and hydrogen with the help of electricity 24. The produced hydrogen 1 and oxygen 2 are compressed II, III and taken 3, 4 to the combustion chamber IV. For lowering temperature after combustor to 1500 °C the preliminary heated water 20 is injected in the combustion chamber.

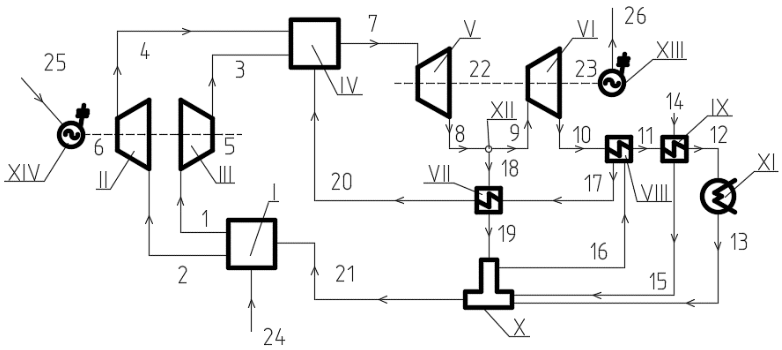

Fig. 4. Basic P&I diagram of plant cycle: I – electrolyser; II – oxygen compressor; III – hydrogen compressor; IV – combustion chamber; V – HPT; VI – IPT; VII, VIII, IX – heat-exchangers; X – atmospheric deaerator; XI – condenser; XII – flow separation point; XIII – generators; XIV – electric drive

Steam flow 7 is expanded in the HPT V, then 18 parted 9 to the IPT 22 and regeneration heat exchangers 18. The steam leaving the turbine 10 has high temperature and goes through heat recovery heat exchangers VIII, IX before exhausted 12 to a condenser XI. The condensate 13 from the condenser is fed to atmospheric deaerator X for closing the cycle. Heat recovery heat exchangers VIII, IX is used for heating make-up water 14, 15 and water after deaerator 16, 17 that used for injection in the combustion chamber 20.

In the proposed cycle hydrogen combustion with surplus oxygen was assumed. Water injection in combustion chamber helps to maintain stable hydrogen burning [24]. Thermodynamic model for proposed cycle has been created to analyse the efficiency. For this purpose, the authors used Visual Basic Application for Microsoft Excel. Further shortcut balance equations set for proposed cycle are shown. Thermodynamically properties according to [25] are considered.

The following balance equations are used:

$$\begin{cases} G_{21}h_{16} + N_{24}\eta_{\mathrm{I}} = G_1h_1 + G_2h_2; \\ G_{21} = G_1 + G_2; \\ G_2h_2 + N_6\eta_{\mathrm{II}} = G_2h_4; \\ G_1h_1 + N_5\eta_{\mathrm{III}} = G_1h_4; \\ G_{16}h_{20} + G_2h_4\eta_{\mathrm{IV}} + G_1h_3 = G_7h_7; \\ G_{16} + G_2 + G_1 = G_7; \\ G_7h_7\eta_{\mathrm{V}} = N_{22} + G_7h_8; \\ G_9h_8\eta_{\mathrm{VI}} = N_{23} + G_9h_{10}; \\ G_{18}h_8\eta_{\mathrm{VII}} - G_{18}h_{19} = G_{16}h_{20} - G_{16}h_{17}; \\ G_9h_{10}\eta_{\mathrm{VIII}} - G_9h_{11} = G_{16}h_{17} - G_{16}h_{16}; \\ G_9h_{11}\eta_{\mathrm{IX}} - G_9h_{12} = G_{14}h_{15} - G_{14}h_{14}; \\ G_{18}h_{19}\eta_{\mathrm{X}} + G_{13}h_{13} + G_{14}h_{15} = G_{16}h_{16} - G_{21}h_{16}; \\ G_{13} = G_9 - G_{14}; \\ G_{12}h_{12} - Q = G_{13}h_{13}; \\ G_8h_8 = G_{18}h_8 + G_9h_8; \\ \left(N_{22} + N_{23}\right)\eta_{\mathrm{XIII}} = N_t; \\ \dfrac{\left(N_5 + N_6\right)}{\eta_{\mathrm{XIV}}} = N_k, \end{cases}$$

where G_1, G_2 are hydrogen, oxygen flow rates; G_7, G_8, G_9, G_{12}, G_{18} are steam flow rates; G_{13}, G_{14}, G_{16}, G_{21} are water flow rates; h_1, h_2, h_3, h_4 are hydrogen, oxygen enthalpies; h_7, h_8, h_{10}, h_{11}, h_{12}, h_{16}, h_{17}, h_{19}, h_{20} are steam enthalpies; h_{13}, h_{14}, h_{15} are water enthalpies; N_5, N_6 are adiabatic power consumption of hydrogen and oxygen compressors; N_{22}, N_{23} are adiabatic gas turbines power output; N_{24} is electrolysis power consumption; N_t is net gas turbine power output; N_k is net power consumption of compressors; η is loss index.

Based on the developed mathematical model, a numerical experiment was carried out for the parametric optimization of the proposed cycle.

The storage efficiency factor (SEF) was chosen for cycle optimization and can be defined as

$$SEF = \frac{N_{el}}{N_i} 100\ \%, \tag{1}$$

where N_{el} is power consumption for electrolysis process; N_i is power of gas turbine.

Results

Through simulation studies in cycle parameters variations the change of storage efficiency factor has been observed. Parametric optimization was carried out while turbine inlet temperature varied from 1000 to 1500 °C, pressure ratio R_p of oxygen and hydrogen compressors varied from 5 to 30, specific power consumption for electrolysis process varied from 3.6 to 4,1 kW·h/m^3.

Figures 5, 6 show SEF as a function of the turbine inlet temperature and compression ratio. These results indicate that SEF vary from 35 to 45 %.

The obtained data of the numerical calculation were approximated by the second order polynomials regressions. The dependence of the SEF on the turbine inlet temperature has almost a linear form (Fig. 5), which is determined by the degree of the coefficient at x^2. The coefficient of determination for the approximating polynomial approaches (1), which indicates almost complete coincidence of the dependence and the approximating equation.

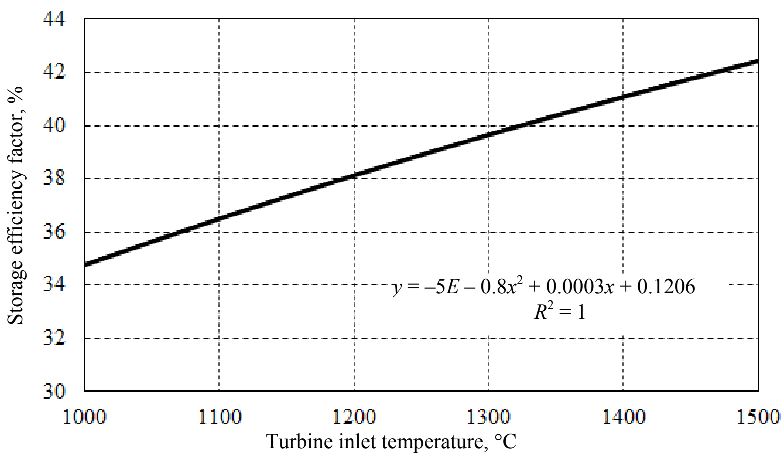

Fig. 5. Storage efficiency factor as a function of the turbine inlet temperature

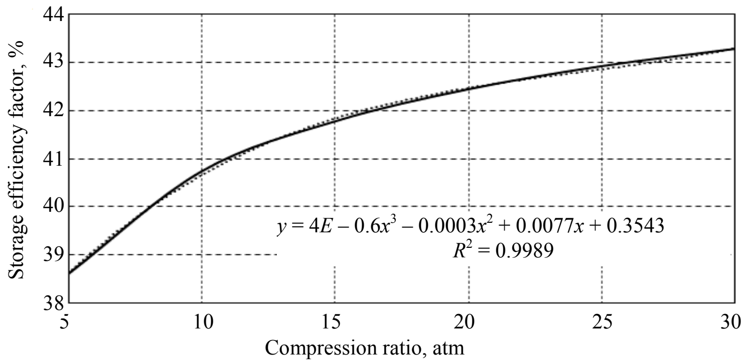

Fig. 6. The relationship between the storage efficiency factor and the compression ratio

It is possible to increase the SEF value using high-pressure electrolysers, as well as electrolysers using a vapor medium as a source for oxygen and hydrogen. The influence of the SEF from the power consumption on the electrolyzer drive is shown in Fig. 7. The approximating dependence also has an almost linear form, which is determined by the small value of the coefficient at x^2.

Figure 8 shows SEF as a function of turbine inlet temperature and compression ratio R_p.

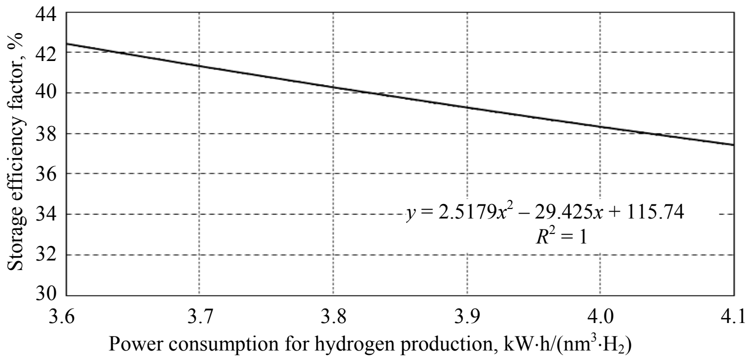

Fig. 7. The relationship between the storage efficiency factor and the power consumption

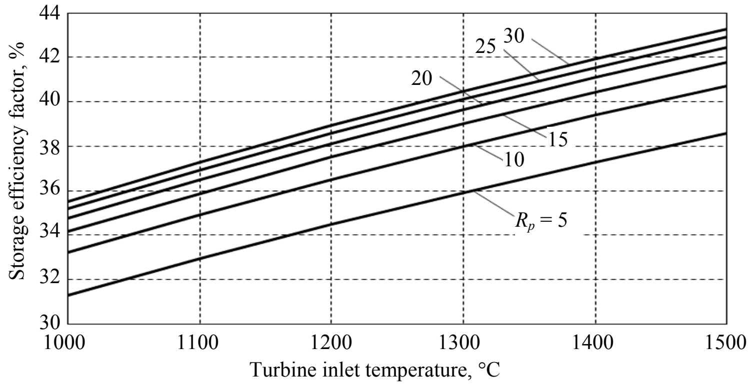

Fig. 8. The storage efficiency factor as a function
of turbine inlet temperature and compression ratio

Obviously, with an increase of compressors pressure ratio, SEF will increase, while the effect will be decaying. In the case of gas turbine operation on hydrogen, an increase in the SEF is also seen, but the extremum was reached at 30 atm, and a further increase in pressure was not considered.

Increase of turbine inlet temperature also leads to SEF increase. The extremum of the function in this case will correspond to the maximum temperature.

CONCLUSIONS

1. Currently, a lot of research efforts are focused on energy storage solutions development, including both large- and small-scale systems. In this paper, a part of the chemical energy storage system including hydrogen production by electrolysis and power production using hydrogen was investigated.
2. Through simulation studies in cycle parameters variations, the change of storage efficiency factor was observed. Parametric optimization was carried out while turbine inlet temperature varies from 1000 to 1500 °C, the pressure ratio of oxygen and hydrogen compressors varies from 5 to 30, specific power consumption for electrolysis process varies from 3.6 to 4.1 kW·h/m^3. The storage efficiency factor was chosen for cycle optimization. These results indicate that storage efficiency factor varies from 35 to 45 %.
3. The obtained results of the numerical experiment were approximated in the form of polynomial regressions and can be used in further research of hydrogen gas turbine cycles.

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