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Thermodynamic modeling of high-temperature combined cycle for hydrogen and electricity co-production

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The high (HTGR) and very high (VHTR) temperature nuclear reactors are the most innovative designs and belong to the most advanced fourth generation gas-cooled reactor technology. These types of reactors are designed to have an outlet temperature between 800–1000°C for the HTGR and the VHTR respectively. Such systems are able to generate electrical energy and supply process heat in a broad spectrum of high-temperature and energy-intensive non-electric and thermal processes. In this paper, a numerical analysis of high temperature the HTGR/VHTR combined cycle with co-production of hydrogen and electricity is conducted. The presented cycle consists of three subsidiary circuits with gas turbine and two steam turbines for electric energy generation, and two heat exchangers for hydrogen production at high or medium temperature. The results show that such a combination allows a significant increase of thermal efficiency to about 50% at the reactor outlet temperature of 1273 K and a decrease in cost of hydrogen production.

Keywords: high temperature nuclear reactor, HTR, VHTR, hydrogen production, combined cycle.

1. Introduction

The growing demand for electricity and contemporary development of nuclear power technology, computer technology and materials science allows in today's design to implement new solutions for nuclear energy, energy security as well as an energy conversion system, to lower unit cost of energy conversion, and to explore new possibilities in energy and fuel production. New generation of nuclear reactors are the most innovative constructions that belong to the most advanced reactor technology. The HTGR/VHTR employs gas-cooled nuclear reactor technology, which allows to use high outlet temperature from 800°C to 1000°C for the HTGR and the VHTR respectively [2, 6]. Nowadays, new generation of power plants working in combined cycle represent the most advanced power generation system and allow to achieve thermal efficiencies up to 60 percent, in contrast to about 33% in conventional power generation which utilizes fossil fuels [2, 5, 6, 9, 10]. Much of the wasted energy in gas turbine cycles ends up as thermal energy appearing in the hot exhaust gases from the combustion process. To increase the overall efficiency of thermal power plants, different processes can be combined to recover and utilize the residual heat energy in hot exhaust gases. Such a cycle operation employs a heat recovery steam generator (HRSG) that uses the heat from high temperature gas turbine exhaust gases to produce steam, which is then supplied to a steam turbine to generate additional electric power [5, 9, 10]. The most common type of combined cycle power plant utilizing gas exhaust is called a gas turbine combined cycle (GTCC) power plant. Because gas turbines have low efficiency in the simple operation cycle, the output produced by the steam turbine accounts for about a half of the GTCC plant output [18, 19]. The current projects and configurations for GTCC depend on the exhausted gas characteristics and its temperature. The exhaust gases from a gas turbine can actually reach 600°C [9, 10]. The power plant working in GTCC may produce steam at different pressure to optimize energy recovery system, and it usually contains three sections of heat exchanger modules: one for high pressure (HP), one for intermediate pressure (IP), and one for low pressure (LP) steams. The main constraint in the operations of the GTCC power plant is the HRSG system, as it is located directly after the gas turbines, where changes in temperature and pressure of the exhaust gases may cause significant thermal and mechanical stresses [9, 10, 19]. Additionally, when such a plant is used in a load-following operation mode, which is typical and can lent to a large thermal stress in practical application that can eventually damage some components of the system. Operating conditions for the steam turbine are directly coupled with the gas turbine and heat recovery system [18, 19]. The above observations show that complex system requires specific conditions to work properly. The situation becomes even more complex if an additional heat exchanger is installed before or after the gas turbine in order to extract the heat for high-temperature thermochemical processes. Finding proper conditions for all elements, which would allow for efficient work of the cycle, becomes a very complex problem [5, 9, 10]. Coupling the high temperature nuclear reactor with combined cycle for electricity production and with co-production of hydrogen is a very promising, new way in energy generation [18, 19]. The first historical constructions of high-temperature nuclear reactors are shown in Table 1.

Table 1. Presentation of the first historical constructions of high temperature nuclear reactor.

	Dragon	Peach Bottom	AVR	Fort St. Vrain	THTR	HTTR	HTR-10
Localization	UK	US	Germany	US	Germany	Japan	China
Power [MWth/MWe]	20	115/40	46/15	842/330	750/300	30	10
Construction	Cylindrical	Cylindrical	Spherical	Hexagonal	Spherical	Hexagonal	Spherical
Helium Temperature [Inlet/Outlet]°C	350/750	377/750	270/950	400/775	270/750	395/950	300/900
Helium Pressure [Bar]	20	22.5	11	48	40	40	20
Power Density [MW/m^3]	14	8.3	2.3	6.3	6	2.5	2
Fuel forms	TRISO	BISO	BISO	TRISO	BISO	TRISO	TRISO
Degree of enrichment	LEU/HEU <20% U^{235}	HEU >20% U^{235}	HEU >20% U^{235}	HEU >20% U^{235}	HEU >20% U^{235}	LEU <20% U^{235}	LEU <20% U^{235}
Exploitation Period	1965–1976	1967–1974	1968–1988	1979–1989	1985–1989	1998–	1998–

The advantage of the last two types of HTTR in Japan and HTR-10 in China, operated on TRISO fuel is a protection against radioactive leakage, which is in contrast to the traditional solutions where contamination is restricted to the reactor's pressure vessel [2, 6]. The first industrial installation of high-temperature reactor HTGR-PM with a capacity of 210 MW was built in Shandong, China. Actually, numerous studies have been conducted on the implementation of high-technology nuclear reactors in the United States, Russia, Japan, and France [6]. Table 2 includes basic parameters of high-temperature gas turbine plant concepts [7].

Table 2. HTGR plant world projects.

Parameter	HTR Gas Turbine Plant Concepts			
	GTMHR	GTHTR300	ANTARES	VHTR NGTCC
Power [MWth]	600	600	600	350
Thermodynamic cycle	Inter-Cooled Recuperated Brayton Cycle	Recuperated Brayton Cycle	Combined Cycle	Combined Cycle
Power conversion working fluid	He	He	He/N_2	He
Reactor inlet/outlet temperature [°C]	491/850	587/850	355/850	400/950
Turbine inlet temperature [°C]	850	850	800	950
Reactor gas pressure [Bar]	71	70	55	71
Compression ratio	2.86	2	2	1.94
Plant Net Power [MWe]	286	274	280 (80 GT, 200 ST)	180 (50 GT, 130 ST)
Thermal efficiency [%]	47.6	45.6	47.0	51.5
Number of compressor stages	9	6	4	6
Turbine blade cooling	Uncooled	Uncooled	Uncooled	First two stages cooled

2. High-temperature combined cycle – description of system

High-temperature combined cycle presented in Fig. 1 works in three independent cycles consisting of three subsidiary circuits (helium, nitrogen/helium and steam circuits). The system is equipped with a gas turbine working in Brayton's cycle [1], two steam turbines (low and high – pressure turbine) working in Rankine's cycle, and, in addition, the system is equipped with two heat exchangers able to delivery process heat for hydrogen production, at high or medium temperature. Primary loop uses pure helium as a working fluid and helium directly flows through the reactor, then the moderator and heats the gas up to a temperature of 1273 K. Hot helium exchanges the high temperature in the heat exchanger and heats a working fluid up in the secondary cycle (mixture of gases: 50% of nitrogen and 50% of helium). The second loop, presented in this cycle, completes a complex Brayton cycle in the gas turbine with the simultaneous production of hydrogen in the high-temperature iodine-sulphur (I-S) cycle and medium-temperature thermochemical copper-chlorine (Cu-Cl) cycle [11, 13]. The third loop, presented in this cycle, contains two independent Rankine's cycles where steam is produced.

Both considered thermochemical cycles are very promising for large-scale, continuous and efficient hydrogen production without CO_2 emissions [11, 12]. The efficiency of high-temperature I-S cycle is about 52%, while the medium-temperature Cu-Cl cycle efficiency is about 47%. The high-temperature combined cycle analyzed in this paper may reach the maximum efficiency of around 60%, and with a significant decrease of hydrogen production costs as well as energy generation. To perform the high-temperature thermochemical I-S cycle, it is necessary to have the working fluid temperature of at least 850°C in order to enable the thermochemical decomposition of H_2SO_4 according to the reaction (1). The entire process of thermochemical I-S cycle is carried out according to the reactions (1–3) and the scheme shown in Fig. 2.

1. **Oxygen production:**

$$2H_2SO_4 \rightarrow 2SO_2 + 2H_2O + O_2 \qquad [850^\circ C]. \tag{1}$$

2. **Hydrogen production:**

$$2HI \rightarrow I_2 + H_2 \qquad [450°C]. \qquad (2)$$

3. **HI and H_2SO_4 production:**

$$I_2SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \qquad [120°C]. \qquad (3)$$

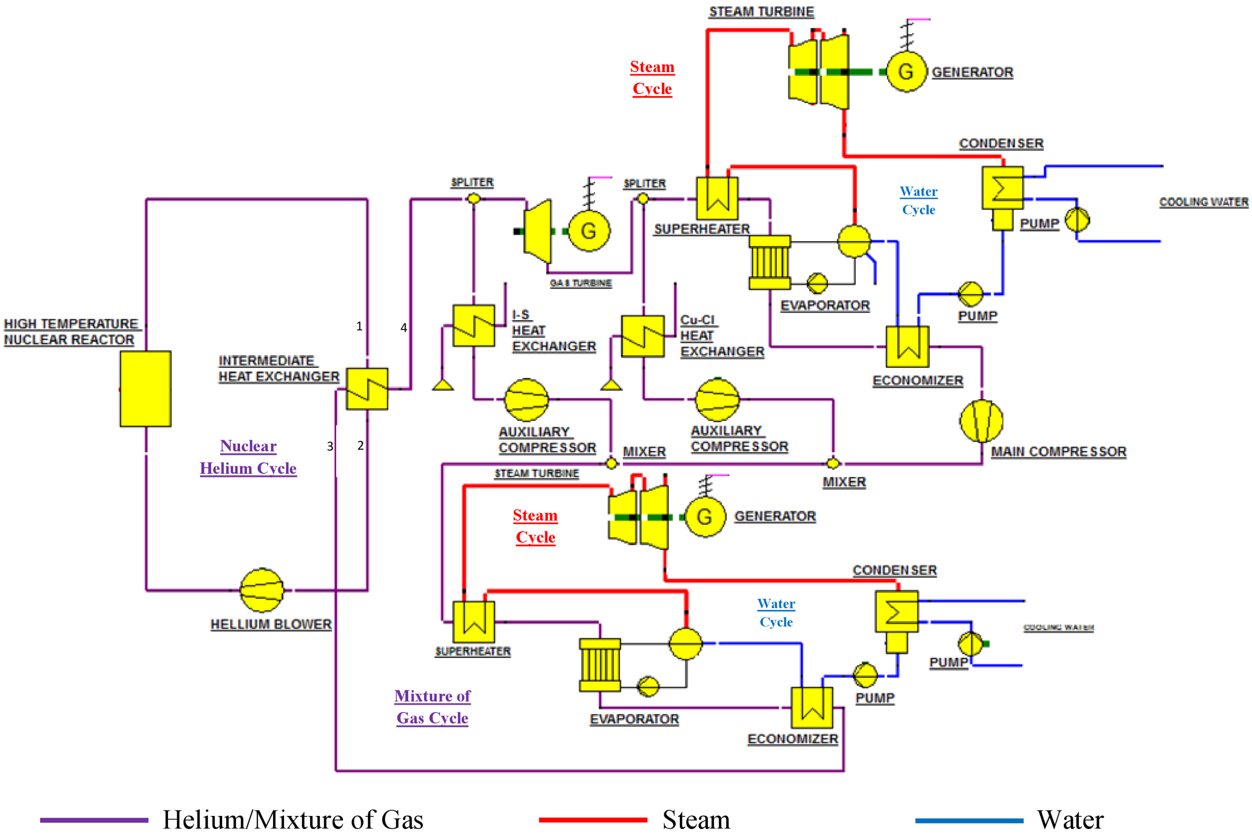

Fig. 1. Gas and steam combined cycle for the HTGR/VTHR with hydrogen production [4].

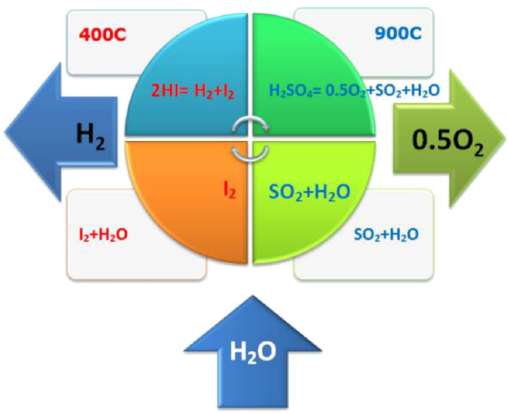

Fig. 2. High-temperature I-S cycle scheme.

Thermochemical process (I-S) is carried out with the involvement of three major chemical reactions (1–3). The reaction proceeding at the highest temperature of at least 850°C is the thermal decomposition of sulphuric acid (VI) in which the main products of the reaction are oxygen (O_2), sulphur dioxide (SO_2) and water (H_2O) [12, 13, 16]. The process of hydrogen production is completed according to the reaction (2) which is a thermal decomposition of iodo-hydrogen to hydrogen-iodide gas. The only element to be completed in the system and coupling the process is water. The temperature increase above 850°C affects effective increase in the amount of hydrogen generated, but at the same time increases the investment costs due to the need for specialized high-temperature and chemically resistant materials.

The second process analyzed in this paper is thermochemical Cu-Cl cycle, which is recommended to use when the working fluid is in low temperature but still at least 500°C (the efficiency of hydrogen production is 47% [3, 16, 17]). This process can be realized in several ways; the embodiment of a four is carried out in a lower temperature range and requires thermal and electric demand. The main reactions of Cu-Cl are as follows:

1. **HCl production**:

$$2\mathrm{CuCl_2} + \mathrm{H_2O} \rightarrow \mathrm{Cu_2OCl_2} + 2\mathrm{HCl} \qquad [450°\mathrm{C}]. \tag{4}$$

2. **Oxygen production:**

$$\mathrm{Cu_2OCl_2} \rightarrow 2\mathrm{CuCl} + 0.5O_2 \qquad [500°\mathrm{C}]. \tag{5}$$

3. **Copper production:**

$$4\mathrm{CuCl} \rightarrow 2\mathrm{CuCl_2} + 2\mathrm{Cu} \qquad [30\text{–}80°\mathrm{C}]. \tag{6}$$

4. **Hydrogen production:**

$$2\mathrm{Cu} + 2\mathrm{HCl} \rightarrow 2\mathrm{CuCl} + \mathrm{H_2} \qquad [450°\mathrm{C}]. \tag{7}$$

3. Mathematical model

The mathematical model of the high-temperature combined cycle presented in Fig. 1 consists of the following equations:

Primary loop

- Reactor thermal power is calculated as follows:

$$N_R = q_j \sum_f \phi V = q_j \sigma_f \phi m \frac{\mathrm{N_A}}{\mathrm{A}}, \tag{8}$$

where q_j – the heat generated in one act cleavage, σ_f – the microscopic cross section [cm^2], ϕ – the average neutron flux [$1/cm^2 s$], m – the mass of fissile material [kg], $\mathrm{N_A}$ – Avogadro's number, A – the mass number.

- Heat received from the reactor by refrigerant:

$$\dot{Q}_R = \dot{m}_{\mathrm{He}} c_{p\mathrm{He}} \left(T_{\mathrm{out}} - T_{\mathrm{in}}\right), \tag{9}$$

where $c_{p\mathrm{He}}$ – helium specific heat capacity [kJ/kgK], T_{in}, T_{out} – the reactor inlet and outlet temperature respectively [K].

- The heat flux supplied in primary helium circuit:

  $$\dot{Q}_s = \dot{m}_{\mathrm{He}}\left(h_1 - h_2\right), \tag{10}$$

  where h_1, h_2 – the helium specific enthalpy at the inlet and outlet from heat exchanger at hot side [kJ/kg], $\dot{Q}_s$ – heat supplied to heat exchanger [kW].

- The heat flux received in the second circuit:

  $$\dot{Q}_r = \dot{m}_{\mathrm{He-N_2}}\left(h_4 - h_3\right), \tag{11}$$

  where $\dot{m}_{\mathrm{He-N_2}}$ – the helium and nitrogen mass flow rate [kg/s], h_4, h_3 – the specific enthalpy at the inlet and outlet from the heat exchanger at cold side [kJ/kg], and $\dot{Q}_r$ – the heat received from heat exchanger [kW].

- Specific heat of the gas mixture (He-N_2):

  $$c_{p\mathrm{He-N_2}} = g_{\mathrm{He}} c_{p\mathrm{He}} + g_{\mathrm{N_2}} c_{p\mathrm{N_2}}(\mathrm{T}), \tag{12}$$

  where g_{He} – the helium mass fraction, $g_{\mathrm{N_2}}$ – the nitrogen mass fraction, $c_{p\mathrm{He}}$ – the helium specific heat [kJ/kgK], $c_{p\mathrm{N_2}}(\mathrm{T})$ – the nitrogen specific heat [kJ/kgK].

- Intermediate heat exchanger **(IHX)** enthalpy balance:

  $$\dot{m}_{\mathrm{He}} c_{p\mathrm{He}}{}_{T0}^{T1}\left[T_1 - T_0\right] + \dot{m}_{\mathrm{He-N_2}} c_{p\mathrm{He-N_2}}{}_{T0}^{T3}\left(T_3 - T_0\right) = \dot{m}_{\mathrm{He}} c_{p\mathrm{He}}{}_{T0}^{T2}\left(T_2 - T_0\right) + \dot{m}_{\mathrm{He-N_2}} c_{p\mathrm{He-N_2}}{}_{T0}^{T4}\left(T_4 - T_0\right), \tag{13}$$

  where $\dot{m}_{\mathrm{He}}$ – the helium mass flow rate [kg/s], $c_{p\mathrm{He}}$ – the helium specific heat capacity [kJ/kgK], $\dot{m}_{\mathrm{He-N_2}}$ – the mixture of gases mass flow rate [kg/s], $c_{p\mathrm{He-N_2}}$ – the mixture of gases specific heat capacity [kJ/kgK], T_1, T_2 – the inlet and outlet temperature from heat exchanger at hot side [K], T_3, T_4 – the inlet and outlet temperature from heat exchanger at cold side [K], and T_0 – ambient temperature [K].

Brayton's cycle

The computations have been carried out with partial support of the General Electric GateCycle software used for system design and steam/gas turbine power evaluation of plant systems. The equations are as follows. Gas turbine relationship between the inlet pressure, flow rate and inlet temperature at gas turbine is as follows [4]:

$$C = \frac{\dot{m}\sqrt{T}}{\kappa A_{\mathrm{nozzle}} p}, \tag{14}$$

where $\dot{m}$ – the mass flow rate at the inlet to the gas turbine [kg/s], κ – kappa function, A_{nozzle} – nozzle area, p – pressure [Pa], C – constant.

Kappa function κ was calculated with the following equation [4]:

$$\kappa = \sqrt{\frac{2g}{R_{\mathrm{gas}}}\left[\frac{\gamma}{\gamma - 1}\right]\frac{p_{\mathrm{out}}}{p_{\mathrm{in}}}^{2/\gamma}\left[1 - \left[\frac{p_{\mathrm{out}}}{p_{\mathrm{in}}}\right]^{(\gamma-1)/\gamma}\right]}, \tag{15}$$

where g – gravity [m/s^2], R_{gas} – the universal gas constant [kJ/kmolK], γ – the specific gas gravity [N/m^3], p_{out} – the outlet pressure for mixture of gas [Pa], p_{in} – the outlet pressure mixture of gas x [Pa]. Critical expansion ratio (CER) was calculated as follows [4]:

$$\mathrm{CER} = \frac{1}{\left[\dfrac{2}{\gamma + 1}\right]^{\gamma/(\gamma-1)}}. \tag{16}$$

Compressor efficiency was calculated from equation [4]:

$$\eta_s = \eta_{\max}\left[1 - \mathrm{SEC}\left|\frac{\mathrm{CS} - \mathrm{CS}_{\eta\max}}{\mathrm{CS}_{\eta\max}}\right|\right]\left[1 - \mathrm{MVEC}\left|\frac{\mathrm{CMV} - \mathrm{CMV}_D}{\mathrm{CMV}_D}\right|\right] PF\,(1 - \alpha VEC)\,, \tag{17}$$

where SEC – the speed correction for efficiency, CS – the current corrected speed, CMV – the current compressor map variable, and MVEC – the compressor map variable correction for efficiency.

Net electrical power of the gas turbine was calculated from the following equation:

$$P_{GT} = \eta_{\mathrm{gen}}\dot{m}_{\mathrm{He-N_2}}(\eta_{\mathrm{i}GT}\eta_{\mathrm{mech}GT}w_{GT} - w_C/(\eta_{\mathrm{mech}C}\eta_{\mathrm{i}C})), \tag{18}$$

where η_{gen} – electric efficiency for generator, $\eta_{\mathrm{i}GT}$ – the isentropic efficiency for gas turbine, $\eta_{\mathrm{mech}GT}$ – the mechanical efficiency for gas turbine, $\eta_{\mathrm{i}C}$ – the isentropic efficiency for compressor, $\eta_{\mathrm{mech}C}$ – a mechanical efficiency for compressor, $\dot{m}_{\mathrm{He-N_2}}$ – the mass flow rate of a mixture of gas (helium-nitrogen) [kg/s], w_{GT} – a specific work for gas turbine [kJ/kg], and w_C – a specific work for compressor [kJ/kg].

- The gas turbine outlet temperature is modeled by:

$$\mathrm{T}_{GT\mathrm{out}} = \mathrm{T}_{GT\mathrm{in}}\eta_{\mathrm{i}GT}\mathrm{T}_{GT\mathrm{in}}\left[1 - \left(\frac{p_{\mathrm{out}}}{p_{\mathrm{in}}}\right)^{(\gamma-1)/\gamma}\right], \tag{19}$$

  where $\mathrm{T}_{GT\mathrm{out}}$ – the gas turbine outlet temperature [K], $\eta_{\mathrm{i}GT}$ – an isentropic efficiency of gas turbine, $\mathrm{T}_{GT\mathrm{in}}$ – the gas turbine inlet temperature [K], p_{out} – outlet pressure [Pa], p_{in} – inlet pressure [Pa], and γ – the gravity specific heat [N/m^3].

- Net electrical power of steam turbine was calculated from the following equation:

$$\begin{aligned} P_{ST} = {} & \eta_{\mathrm{gen}}\eta_{\mathrm{mech}g}\dot{m}_{p1}(\eta_i\eta_{\mathrm{mech}}w_{\mathrm{HPST1}} + \eta_i\eta_{\mathrm{mech}}w_{\mathrm{LPST1}}) \\ & + \eta_{\mathrm{gen}}\eta_{\mathrm{mech}g}\dot{m}_{p2}(\eta_i\eta_{\mathrm{mech}}w_{\mathrm{HPST2}} + \eta_i\eta w_{\mathrm{LPST2}}) \\ & - \dot{m}_{w1}w_{\mathrm{P_1}}/(\eta_{ip}\eta_{\mathrm{mech}p}) - \dot{m}_{w2}w_{\mathrm{P_2}}/(\eta_{ip}\eta_{\mathrm{mech}p}), \end{aligned} \tag{20}$$

  where η_{gen} – the generator electrical efficiency, $\eta_{\mathrm{mech}g}$ – the generator mechanical efficiency, η_i – the steam turbine isentropic efficiency, η_{mech} – the steam turbine mechanical efficiency, η_{ip} – the pump isentropic efficiency, $\eta_{\mathrm{mech}p}$ – the pump mechanical efficiency, $\dot{m}_{p1}$ – the steam mass flow for first cycle [kg/s], w_{HPST1} – a specific work of the first high-pressure steam turbine [kJ/kg], w_{LPST1} – a specific work of the first low-pressure steam turbine [kJ/kg], w_{P_1} – a specific work for the first pump [kJ/kg], $\dot{m}_{p2}$ – the steam mass flow for the second cycle [kg/s], w_{HPST2} – a specific work for the second high-pressure steam turbine [kJ/kg], w_{LPST2} – a specific work for the second low-pressure steam turbine work [kJ/kg], and w_{P_2} – the second pump work [kJ/kg].

- The efficiency of high-temperature combined cycle without hydrogen production was calculated as follows:

$$\eta_c = \frac{P_{GT} + P_{ST}}{N_R}, \tag{21}$$

  where P_{GT} – the gas cycle power [kW] and P_{ST} – the steam cycle power [kW].

  Efficiency of high-temperature combined cycle with hydrogen production is as follows:

$$\eta_{\mathrm{c1}} = \frac{P_{GT} + P_{ST} + \eta_{\mathrm{IS}}\dot{Q}_{\mathrm{IS}} + \eta_{\mathrm{CuCl}}\dot{Q}_{\mathrm{CuCl}}}{N_R + \dot{Q}_{\mathrm{IS}} + \dot{Q}_{\mathrm{CuCl}}}, \tag{22}$$

where P_{GT} – the gas turbine electric power [kW], P_{ST} – the steam turbine electric power [kW], η_{IS} – the efficiency of iodine sulphur cycle, η_{CuCl} – the efficiency of copper chlorine cycle, $\dot{Q}_{\mathrm{IS}}$ – the energy gain from iodine sulphur cycle, $\dot{Q}_{\mathrm{CuCl}}$ – the energy gain from copper chlorine cycle [kW], and N_R – the thermal reactor power [kW].

The main model parameters and the assumptions for calculations of high-temperature combined cycle are listed in Table 3–5.

Table 3. Main model parameters of high-temperature combined cycle.

Parameter	Value	Unit
Nuclear Reactor Cycle		
Coolant	He	–
Power	300	[MW_{th}]
Pressure	6	[MPa]
Temperature	1073–1273	[K]
Volume Flow Rate	50	[m^3/s]
Mass Flow Rate	113–134	[kg/s]
Desired Helium Pressure Ratio	1	–

Table 4. Main model parameters of gas turbine cycle.

Parameter	Value	Unit
Gas Turbine Cycle		
Working Fluid	He/N_2 [1:1]	–
Pressure	6	[MPa]
Temperature IXH	750–950	[C]
Mass Flow Rate	334–402	[kg/s]
Sluice Header 1	1–0.9	–
Sluice Header 2	1–0.9	–
Desired Outlet Pressure Compressor 2	6	[MPa]
Gas Turbine Expansion Ratio	1.2–5	–
Gas Turbine Isentropic Efficiency	0.9	–
Desired Outlet Pressure Main Compressor	6	[MPa]
Desired Outlet Pressure Auxiliary Compressor	6	[MPa]
I-S Heat Exchanger Effectiveness	0.9	–
Cu-Cl Heat Exchanger Effectiveness	0.9	–

Table 5. Main model parameters of rankine cycle.

Parameter	Value	Unit
Steam Turbine Cycle		
HP Steam Turbine Isentropic Efficiency	0.97	–
LP Steam Turbine Isentropic Efficiency	0.97	–
HP Steam Turbine Outlet Pressure	4	[MPa]
LP Steam Turbine Outlet Pressure	0.120	[MPa]
Rotational Speed Steam Turbine	3600	[rpm]

4. Results

The net power of cycle and the power of cycle components and thermal efficiency of the high-temperature combined cycle (presented in Fig. 1) for the case without hydrogen generation *versus* expansion ratio are shown in from Fig. 3. The results show changes of net cycle power without hydrogen production, Brayton's cycle power, Rankine's cycle power, compressor energy consumption, the HTGR energy supply versus the gas turbine expansion ratio. There graphs show that an increase of the gas turbine expansion ratio from 1 to 5 dramatically reduces the amount of total power cycle and thermal efficiency for the cases without hydrogen production process. From

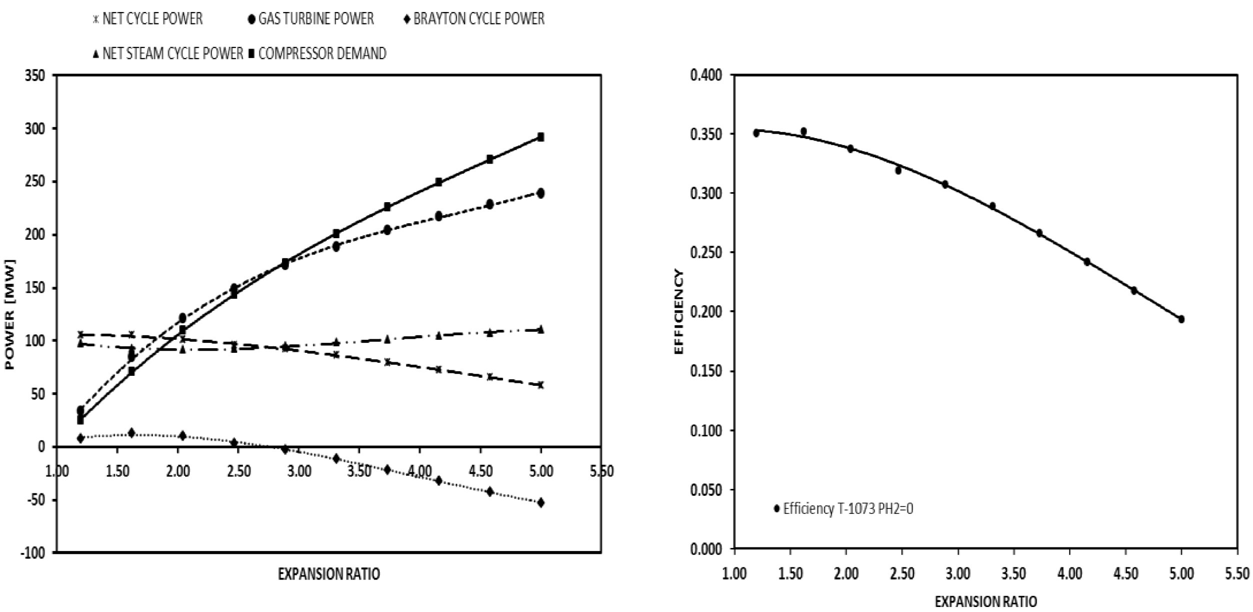

Fig. 3. Power and thermal efficiency versus expansion ratio for the case without hydrogen production at the outlet reactor temperature T = 1073 K.

economic and thermodynamic points of view the optimal operation conditions of this system are achieved for expansion ratio in a range of 1.6 to 2.2.

Figure 4 shows the results of calculation with hydrogen production changes of net cycle power with hydrogen production (where the amount of thermal power used in hydrogen production in iodine-sulphur cycle is equal to 30 MW), Brayton's cycle power, Rankine's cycle power, compressor energy demand, HTR energy supply *versus* gas turbine expansion ratio. This graph shows that simultaneous production of electric energy and hydrogen in iodine-sulphur cycle causes an increase of power and thermal efficiency to 35%. From economic and thermodynamic point of view the optimal operation conditions of this system are achieved for expansion ratio in a range of 1.6 to 2.2.

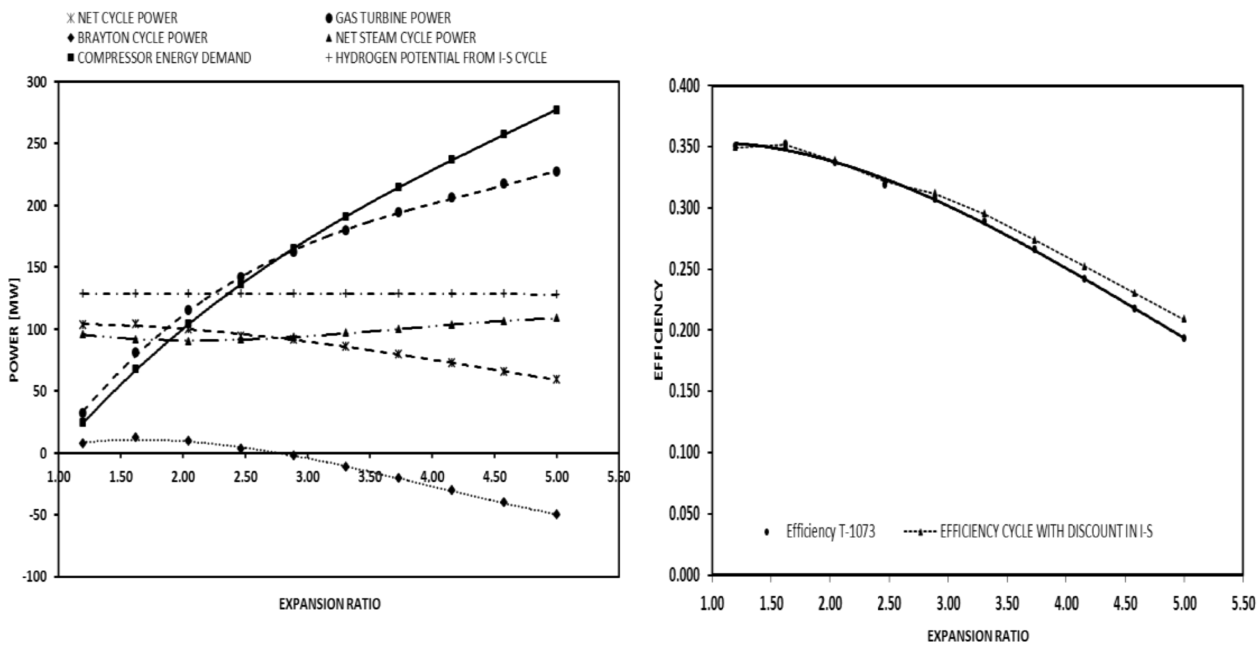

Fig. 4. Power and thermal efficiency versus expansion ratio for the case with hydrogen production using I-S cycle P_{H2} = 30 MW at the outlet reactor temperature T = 1073 K.

Figure 5 shows the calculation results in which hydrogen is produced in two thermochemical cycles: I-S and Cu-Cl, and simultaneously with electric energy co-production. The results show that thermal efficiency of the process is possible at about 38%. From thermodynamic point of view, optimal operation conditions of this system is possible for change expansion ratio of 1.4 to 2.6.

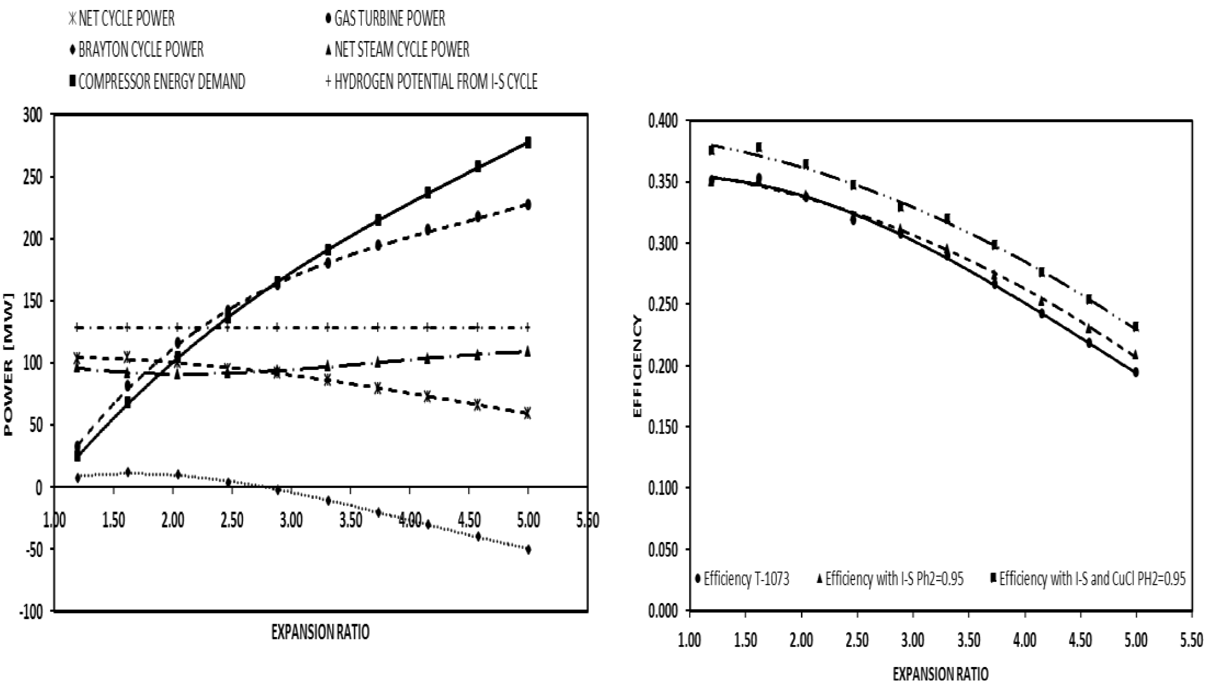

Fig. 5. Thermal power and thermal efficiency versus expansion ratio for the case with simultaneous hydrogen production with I-S and Cu-Cl cycle power, P_{H2} = 30 MW for I-S cycle and 27 MW for Cu-Cl cycle at the outlet reactor temperature T = 1073 K.

From thermodynamic point of view it is possible to increase the thermal efficiency of the cycle presented in Fig. 1. The results presented in Figs. 6, 7 and 8 show the impact of temperature rise

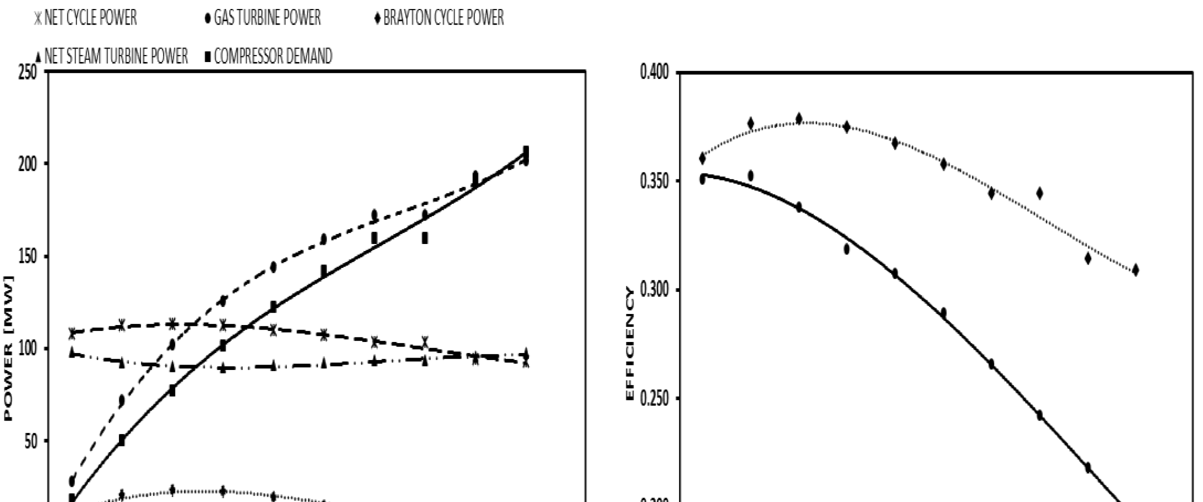

Fig. 6. Power and thermal efficiency at two different outlet reactor temperature T = 1073 K and T = 1273 K for the case without hydrogen production.

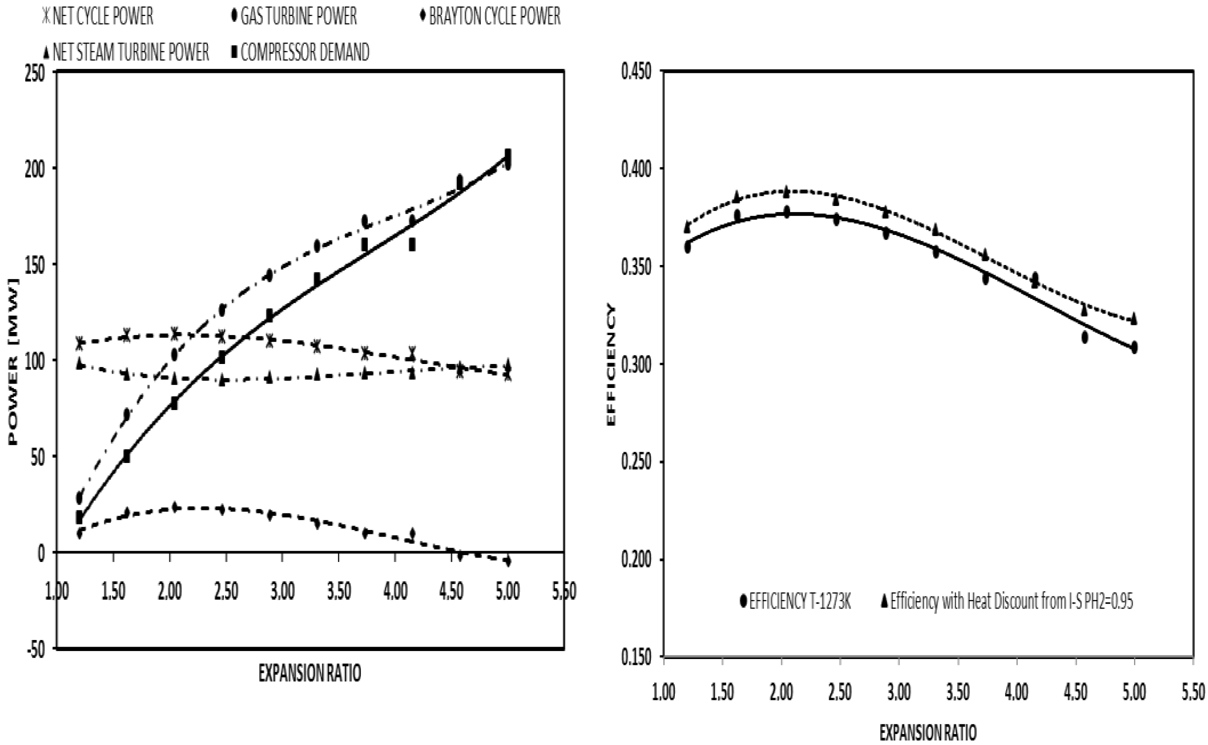

Fig. 7. Power and thermal efficiency at two different outlet reactor temperature T = 1073 K and T = 1273 K for the case with hydrogen production using I-S cycle with the dedicated power P_{H2} = 30 MW.

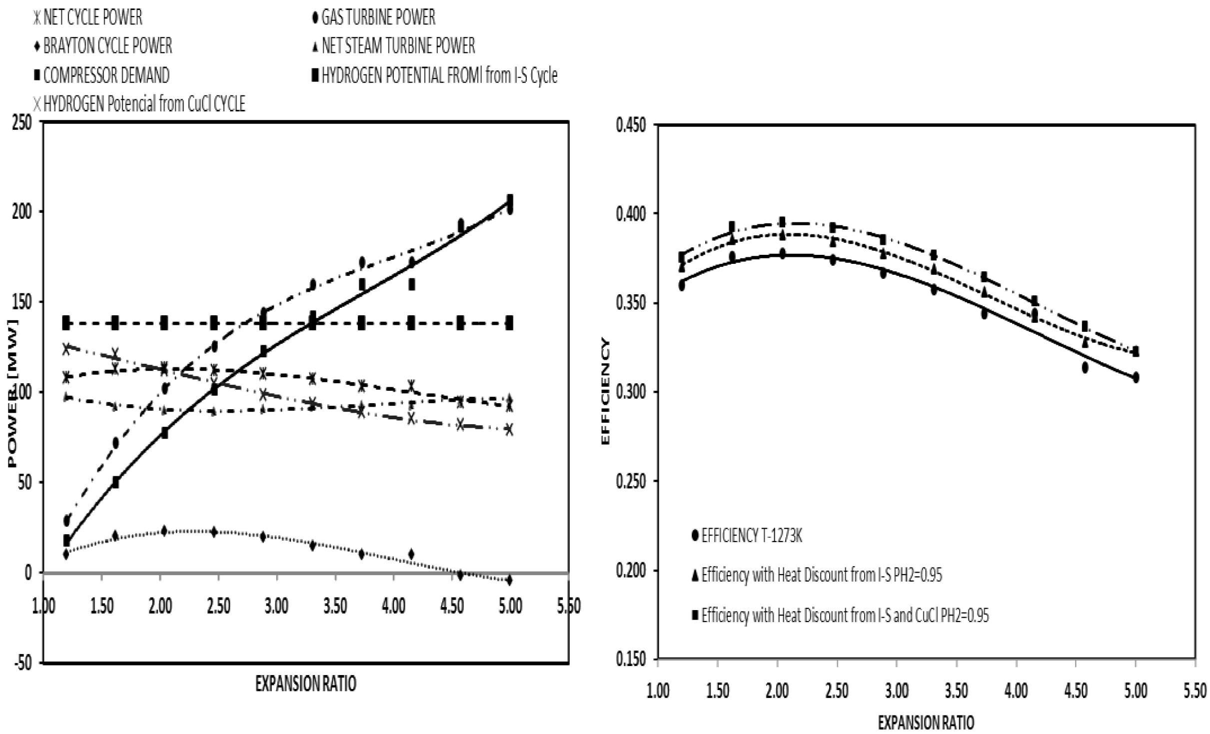

Fig. 8. Thermal power and thermal efficiency at two different outlet reactor temperatures: T = 1073 K and T = 1273 K for the case with hydrogen production using I-S cycle in which the amount of power dedicated to the production of hydrogen is equal to 30 MW for I-S cycle and 27 MW for Cu-Cl cycle.

from T_1 = 1073 to T_2 = 1273 [K] at the outlet of high-temperature nuclear reactor on the thermal efficiency. Simultaneous production of hydrogen and electric power makes it possible to increase

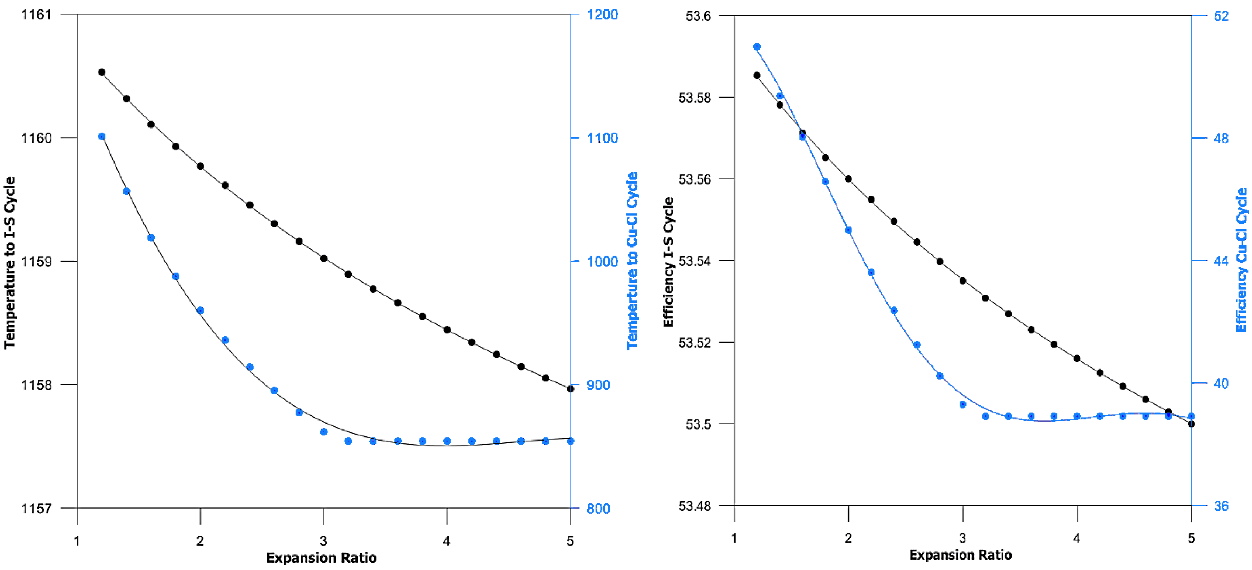

Fig. 9. Outlet temperature and thermal efficiency for I-S and Cu-Cl cycle *versus* expansion ratio for nuclear reactor outlet temperature T = 1273 K.

the thermal efficiency to about 40% with optimum expansion ratio of gas in a gas turbine equal to 2.6.

5. Conclusions

High standards in the development of high-temperature energy systems enforce solutions that require different technologies and aims. Typical examples are the increased use of cogeneration systems. Changes to the existing paradigm directly resulting from the climate package, which is especially important in the case of Poland. In the last few years, attention has been paid to the possibility of using HTGR as a high-temperature heat source in place of traditional energy systems based on fossil fuel combustion systems, coal and natural gas. Especially interesting is the use of HTGR technology in receiving gaseous fuels (coal gasification processes, hydrogen production) from simultaneously produced electric energy and high-temperature heat p. This paper shows a possibility of simultaneously combining hydrogen and electric energy production in cogeneration system. Such a solution leads to a significant increase in the efficiency in comparison to the disjoint circuits. This solution is equally important for the development of hydrogen energy. The high (HTGR) or the very high (VHTR) temperature gas-cooled nuclear reactors are the most innovative constructions and belong to the most advanced reactor technology. Those types of reactors are designed assuming the outlet temperature to be about 800°C and 1000°C for the HTGR and the VHTR respectively. The HTGR/VHTR reactor systems provide very high safety level and high thermal efficiency. These types of reactors can be effectively used to produce electrical energy and hydrogen in thermochemical I-S and Cu-Cl cycles simultaneously. The numerical analysis of high-temperature combined cycle, presented in Fig. 1, shows that it is possible to achieve a thermal efficiency of around 35% in the cycle without hydrogen. The thermodynamic analysis of high-temperature combined cycle with hydrogen production using I-S cycle makes it possible to increase the energy efficiency to 36% at the outlet temperature of the reactor equal to 1073 K. Simultaneous hydrogen production with the use of two cycles: I-S and Cu-Cl allows to increase the efficiency of the system to 38%. From a thermodynamic point of view, there is a possibility for a further increase of thermal efficiency by increasing the temperature of working fluid. Increasing the outlet temperature to 1273 K leads to an increase of the level of thermal efficiency to 40% with simultaneous production of hydrogen in I-S and Cu-Cl. Analysis shows that the thermal cycle presented in Fig. 1 operates the most effectively in the range of expansion ratio from 1.4 to 2.4. Higher value of expansion ratio leads to a significant decrease of the total power of the cycle and thermal efficiency for the cycle with hydrogen production.

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