THE ARCHIVE OF MECHANICAL ENGINEERING

VOL. LV 2008 Number 2

DOI: 10.24425/ame.2008.131619

Key words: nuclear power, hydrogen turbine, energy storage, overall energy conversion efficiency

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INVESTIGATION ON A NEW WATER-STEAM SYSTEM WITH PEAK-LOAD HYDROGEN TURBINE FOR POWER UNITS WITH GAS-COOLED NUCLEAR REACTORS

The aim of the investigation presented in this work was to realise complex calculations of a new, combined water-steam system with peak-load hydrogen turbine to be applied in nuclear units with gas-cooled reactors. The system's characteristic feature is the presence of two heat sources: a nuclear steam generator; and a hydrogen-oxygen combustion chamber. The main idea is to create a system capable to operate in two modes, with one or two heat sources, which leads to a significant output change. The investigation included also the overall efficiency of conversion of the nuclear energy, assumed the heat needed for producing hydrogen and oxygen comes from such a source. This part of the work included an analysis of the rationality of hydrogen production and utilisation. An additional aim of the research was to determine the optimal solution regarding the system performance and the capability of its technical realisation. The obtained results are promising: the system performance is very high, and its operating parameters are technically realisable in today's conditions. In addition, it enables an emission-free, dispatchable electricity generation during the daytime demand peak.

Nomenclature

Symbols:

G – mass flow rate, [kg/s];
k – isentropic index;
N – generated electric power, [W];
p – static pressure, [Pa];
$\dot{Q}$ – thermal capacity, or heat flow, [W];

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$\overline{\dot{Q}}$ – normalised heat flow;
T – temperature, [°C];
t – time, [s];
s – specific entropy, [kJ/kg·K];
v – specific volume, [m^3/kg];
ε_T – temperature effectiveness;
η – net electric efficiency;

Subscripts:

cr – relates to critical values;
in – relates to inlet quantities;
h – relates to hydrogen source;
max – relates to maximum values;
n – relates to nuclear source;
$night$ – relates to nighttime mode;
out – relates to outlet quantities;
0 – relates to nominal (rated) values.

Superscripts:

$cold$ – relates to heated medium;
hot – relates to heating medium.

1. Introduction

A growing interest in hydrogen technologies could be observed in recent years. It is caused by the conviction, that the product of combusting hydrogen with pure oxygen does not contaminate the environment. This would be true, weren't organic fossil fuels used for its production, and it is not the case today. In addition, the notorious omission or reduction by the supporters of hydrogen applications in the power industry and transport of the importance of two facts – that it is not a primary energy carrier, and that its properties are disadvantageous regarding storage and distribution – is rather confusing.

Hydrogen is the most widespread chemical element on the Earth and in space. However, on our planet it occurs almost exclusively in compound form – it is present in the majority of inorganic compounds (e.g., in water, acids, alkali) and in all organic compounds (e.g., hydrocarbons, fats, sugars, alcohols, proteins, acids). There are also negligible amounts of its free form (e.g., in the air and natural gas). This means that hydrogen has to be produced by decomposing its chemical compounds, which requires energy supply. Therefore, in the process of conversion of energy from its primary to final (usable) form, the production and utilisation of hydrogen is an additional stage. The rationality of its introduction could depend on different criteria, but first of all the effect on the overall energy conversion efficiency and the total amount of pollutants emitted to the environment should be taken into account.

Since the end of the nineties of the last century, a distinct return of the interest in nuclear power technology is observed. It seems that four main reasons could be distinguished in this case. First of all, because of the record-high and increasing prices of organic fossil fuels, the electricity generation cost in the nuclear power sub-sector became the lowest in the thermal power sector. In addition, the standardisation, introduction of modular structure, and project simplification, together with the unification and acceleration of the verification and construction/operation licensing procedures for units with reactors of generations III, III+ and IV, and the extension of their designed operation lifetime to 60 years are to result in reduction of that cost down to 3 US¢/kWh.

At the same time, the nuclear safety is a priority in designing reactors of new generation. The development of information systems and automatics, together with the new solutions in the scope of active and passive safety systems and the significant reduction of the length and number of pipeline components and cables cause that today in the nuclear power plants under construction the probability of an accident introducing danger of emission of radioactive products to the environment is reduced almost to zero. For instance, the probability of core damage of the AP-series reactors (600 or 1000 MW_e units) during one year of operation equals $0.3 \cdot 10^{-6}$, similarly in the European EPR (1600 MW_e units), while the requirements state for $1.0 \cdot 10^{-5}$.

The limited resources of organic fossil fuels are also important. Selected data from the World Energy Council's Survey of Energy Resources 2007 [1], concerning proved resources of fossil primary energy carriers, are set in Table 1. There are no data about the additional, assessed resources of organic fuels. However, even assumed the real resources are twice higher than the proved ones, one could expect that this will be equalised by the growing consumption, so the terms of their exhaust will be similar to those given in the last column of Table 1. The case of uranium is different, as the opportunity to breed nuclear fuel extends the perspective of its utilisation to thousands of years.

Table 1.

Proved resources and consumption of fossil fuels in 2005

Primary energy carrier	World resouces – end of 2005	World consumption in 2005	Res./cons. in 2005
Crude oil	159,644	3,725.5	43
Natural gas	176,462	2,796.6	63
Hard coal	697,733	4,989.7	140
Lignite	149,755	860.6	174
Uranium	4.7429	0.0417	114

Another argument in favour of developing nuclear power, connected with the need to reduce the emission of pollutants and greenhouse gases (GHG), is the practical incapability to replace fossil fuels with renewable sources. The utilisation of solar energy, wind energy, biomass, and biofuels is limited by the space, needed for their conversion or production, connected also with the climatic conditions. In addition, the undispatchability of the first two is a negative factor, so is the energy-consuming production of biofuels. It seems that the mechanical energy of water remains the only alternative, but its resources are almost fully utilised in the developed countries, and in the others the gigantic investment costs (and often also environmental costs) are an effective barrier for the development of this energy generation branch.

In the last years, a political argument has been added to the above-mentioned four economical-technical reasons: the energy security. Significant majority of the countries imports needed primary energy carriers and could feel endangered by the permanent growth of their prices, and supply uncertainty. Because of the relatively small volumes, facilitated transport and storage, and multiplicity of potential suppliers, the nuclear fuel is a promising alternative to the organic fossil fuels. Today this concerns mainly the power industry, but projects of using high-temperature reactors of generation IV to produce hydrogen for coal gasification (methane synthesis) or carbon dioxide sequestration (methanol synthesis) are already being developed. The intention is to reduce the import of liquid and gaseous primary energy carriers by the means of the so-called “nuclear-coal synergy”, and the methanol synthesis concept could additionally contribute to reduction of GHG emission.

All known – developed and under investigation - hydrogen production methods lead to a decreased overall energy conversion efficiency. Along with obvious losses, in the case of using organic fossil fuels this means an increase of the emission of pollutants and greenhouse gases (GHG) to the atmosphere. Therefore, it seems that the only relevant technology, the implementation of which could be reasonable, are the thermochemical water dissociation cycles supplied with nuclear heat. This would be the only emission-free hydrogen production method.

Simultaneously with the energy inefficiency, hydrogen is effectively eliminated from application in transport by technical problems, connected with medium- and long-term storage, and distribution. More efficient, cheaper, and easier to be realised is here the electric motor in the future, and hybrid drive today. The use of hydrogen in the power industry seems to be rational only under the condition that it will serve to cover peak electricity demand (an emission-free cover of the basic demand could be realised directly by nuclear power units).

Hama *et al* [2] made an overview and concise thermodynamic analysis of recently designed hydrogen turbine systems. The Graz system, its modified version MGraz, systems proposed by Toshiba and Westinghouse, and MNRC (Modified New Rankine Cycle) were taken under consideration. Some of their operation and performance parameters are set in Table 2.

Table 2.

Comparison of inlet parameters of the most loaded components and efficiency of selected hydrogen turbine systems

	Graz	MGraz	Toshiba	Westinghouse	MNRC
$T_{\max}/p(T_{\max})$	1700 / 5	1700 / 5	1700 / 7.3	1700 / 25	1700 / 25
$p_{\max}/T(p_{\max})$	35 / 650	35 / 650	34.3 / 876	25 / 1700	25 / 1700
η(HHV)	0.58	0.599	0.583	0.606	0.647

The common features of those systems are: using the hydrogen combustion as only heat source; and presence of a high-pressure part with supercritical operating parameters and of a low-pressure part with a condenser. Taking this into account, every-day start-up and shut-down of such systems would be either technically impossible/inadvisable or, in case of idle run, too expensive. Therefore, they should operate continuously, with a significant load difference between the daytime demand peak and nighttime demand trough periods, which would result in lower system net electric efficiency and – more important – low overall energy conversion efficiency. It has to be noted here that the MGraz system was found the most prospective among the above-mentioned ones, and its net electric efficiency was calculated equal to 59.9%.

The assumption of using hydrogen in the power industry only for covering the daytime peak demand imposed the need of working out a new system, the configuration of which would make every-day quick start-up and shut-down of the hydrogen turbine possible.

2. Rationality of hydrogen production

The advantages and disadvantages of using hydrogen as a fuel are well known. Its physical properties (lowest density, highest diffusivity) cause that it mixes perfectly with oxidiser, and than burns completely. Very high efficiency of hydrogen turbine systems is obtainable, assumed pure oxygen is applied and heat is directly supplied to the working medium. At the same time, hydrogen gives relatively low energy density and is difficult to be stored and distributed, especially as a transport fuel.

All the hydrogen production technologies are energy consuming; i.e., the relevant chemical processes are endothermal, and the electrolysis requires electricity supply. This means that the hydrogen fuel is an additional, intermediate stage of the energy conversion process. An advantageous introduction of such an additional stage is possible only if, in result of it, the overall energy conversion efficiency increases compared to the existing technologies using the same primary energy carriers. However, from financial and/or environmental point of view, a solution, in result of which this efficiency does not increase, but the emission of pollutants and GHG considerably decreases, could also be profitable. However, in such cases certain opposition of financial priorities to political ones (connected with environment protection) may appear. The settlement of this opposition could be different in different countries.

The steam methane reforming (SMR) is the most often-applied hydrogen production method today. It is used for producing about 95% of the hydrogen in the United States, and about 48% in the world. In the matter of fact, it is a natural gas reforming. The method's name comes from the fact, that methane's share in that gas equals 75-80%, and the basic chemical reaction is similar for different hydrocarbons. The method consists of two stages. Within the first one, methane and the other hydrocarbons react with steam in a temperature of 750-800 °C:

$$C_nH_{2n+2} + nH_2O \rightarrow nCO + (2n+1)H_2. \tag{1}$$

The second stage, called Water Gas Shift (WGS), is a catalytic reaction of carbon oxide and steam:

$$CO + H_2O \rightarrow CO_2 + H_2. \tag{2}$$

Reaction (2) is realised in two steps: first in a temperature of 350 °C; and next in a temperature of 190-210 °C.

The obtained hydrogen contains small amounts of carbon oxide and dioxide. In order to remove them, it undergoes relevant absorption processes.

Toxic compounds, mainly sulphur- and chlorine-based, are removed from the natural gas before its reforming. In result, in the newest installations the product consists of hydrogen in up to 99.99%.

The energy, needed for the realisation of Reaction (1), is most often supplied by burning a part of the consumed natural gas. The efficiency of the newest SMR installations reaches 75%, and it seems that there is no more room for improvement.

The second, most popular hydrogen production method is now the coal gasification using steam. Its first stage is the reaction of carbon and steam in a temperature of about 1000 °C:

$$C + H_2O \rightarrow CO + H_2. \tag{3}$$

The energy, needed for the realisation of Reaction (3), is provided by burning a part of the consumed coal.

Similarly to the SMR method, the second stage is the WGS reaction; i.e., Reaction (2).

Because of the relatively high content of pollutants (e.g., sulphur) in the coal, its gasification technology requires (along with the processes of carbon oxide and dioxide removal from hydrogen) a number of additional processes to remove products of reactions of those pollutants with steam, which significantly complicates the installations and reduces their efficiency - today it does not exceed 60%. The capabilities to improve it in the future seem very limited.

The last of the today more broadly applied (although almost exclusively for laboratory needs) hydrogen production methods is the electrolysis of water. The development of material science recently resulted in a considerable performance increase also in this field: Yamaguchi *et al* [3] presented results of research on a high-temperature water electrolysis installation, permanently obtaining efficiency exceeding 92% and making an industrial-scale production possible. However, the use of electricity for such a purpose seems to be unreasonable, as it is the most convenient final form of energy (it is often called the highest form of energy or the energy of highest quality). In addition, the application of this method for power generation purposes would be conditioned with a special limitation: the hydrogen production and utilisation processes could not be realised simultaneously. In other words, in such a case the hydrogen fuel could be used only as an energy storage medium.

The energy needed for the realisation of electrolysis could be supplied from different sources, incl. nuclear or renewable ones; i.e., zero-emission ones. Another advantage of this method compared to the previously discussed ones is the simultaneous production of oxygen, which is necessary for future clean hydrogen combustion.

The technology development of the world, and in particular the development of nuclear fuel element production technology, resulting in lower production costs, caused return of the interest in helium-cooled high-temperature reactors. The level of coolant temperatures obtained in the eighties of the last century – 750-950 °C – enables not only electricity generation with an efficiency of 45-52%, but also application of this type of reactors in hydrogen production. The research and development works on high-temperature reactors of generation IV are now advanced in the United States [4] and the Republic of South Africa [5]. The projects provide helium maximum temperature in the range of 850-950 °C. One of the possible applications of these reactors is as heat sources in SMR installations (i.e., as a substitute for burning natural gas). At the same time, the research and development works on thermochemical water dissociation cycles were intensified. Combining such cycles and high-temperature reactors [6] would result in a zero-emission hydrogen production.

The report of the General Atomics company, prepared by Brown *et al* [7], is one of the most complex studies on thermochemical water dissociation cycles. 115 such cycles, proposed in the last four decades, were identified, and their efficiency and technical realisability compared. Two of them were found most prospective: the UT-3 cycle, elaborated in the University of Tokyo; and the sulphur-iodine (S-I) cycle, presented by General Atomics.

The UT-3 cycle is a 4-step calcium-bromine-iron process:

$$Br_2 + CaO \rightarrow CaBr_2 + {}^1/_2 O_2; \tag{4}$$

$$3FeBr_2 + 4H_2O \rightarrow Fe_3O_4 + 6HBr + H_2; \tag{5}$$

$$CaBr_2 + H_2O \rightarrow CaO + 2HBr; \tag{6}$$

$$Fe_3O_4 + 8HBr \rightarrow Br_2 + 3FeBr_2 + 4H_2O. \tag{7}$$

The research on it is far advanced in Japan. The realisation of Reaction (6) requires the highest temperature here. However, it may not exceed 760 °C; i.e., the $CaBr_2$ melting point. This limits the obtainable efficiency of converting the heat supplied to the cycle into hydrogen chemical energy (heat of combustion) to 40%. Provided the hydrogen production installation is combined with a gas turbine, 9% of the reactor heat could be additionally utilised for electricity generation. Thus, the total co-generation efficiency could obtain 49%.

The S-I cycle consists of three chemical reactions:

$$H_2SO_4 \rightarrow H_2O + SO_2 + {}^{1}\!/_{2}O_2; \tag{8}$$

$$2H_2O + I_2 + SO_2 \rightarrow H_2SO_4 + 2HI; \tag{9}$$

$$2HI \rightarrow I_2 + H_2. \tag{10}$$

The catalytic Reaction (8) requires the highest temperature: its value of 830 °C provides a substrate conversion level of 83%, and the obtainable heat-to-hydrogen conversion efficiency equals 52%. Similarly to the previous case, a combination of the S-I cycle with a gas turbine enables conversion of 9% of the reactor heat into electric energy. Thus, the total co-generation efficiency could reach 61%.

Similarly to the electrolysis case, in both presented cycles the result of total reaction is pure water dissociation; oxygen is produced together with hydrogen.

In the world, research is carried out on multiple other hydrogen production methods, such as: anaerobic method (Los Alamos National Laboratory); plasma method; photoelectrolysis; biomass gasification; biological method. However, for different reasons (too high energy consumption, technical realisation difficulties, source undispatchability, etc.), it seems that they will not become an alternative to the above-described SMR method, coal gasification, electrolysis, and thermochemical cycles.

The rationality analysis was realised comparing – where it was possible – the efficiency of an energy conversion process containing a hydrogen production stage to the efficiency of an energy conversion process not containing such a stage (simple process) for the same primary energy carrier and final energy form. An example of this concept is shown schematically in Fig. 1.

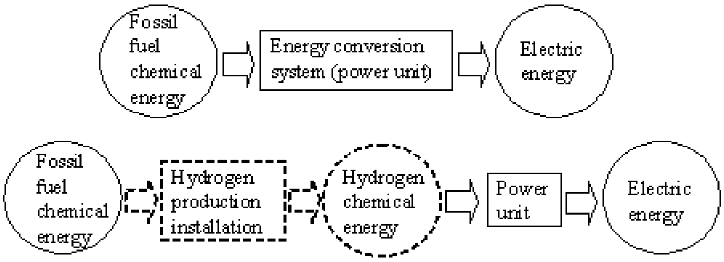

Fig. 1. Example of comparison of energy conversion processes with and without a hydrogen production stage

The analysis was limited to the proposed hydrogen applications in the utility power industry. Its synthetic results, assumed the net electric efficiency of the hydrogen turbine system equals 60% (related to the higher heating value; i.e., to the heat of combustion), are set in Table 3.

Table 3.

Comparison of energy conversion efficiency with and without a hydrogen production stage for the basic sources in the utility power industry

Primary energy carrier	Conversion process with hydrogen prod.			Simple conversion process (without hydrogen production)	
	Hydrogen production installation type	Hydrogen production installation efficiency	Overall energy conversion efficiency	Type of the simple system (power unit)	Overall energy conversion efficiency
Coal	Gasification using steam	≤ 60%	≤ 36%	Supercritical unit	45%
Natural gas	Steam methane reforming	≤ 75%	≤ 45%	Combined cycle	55%
Water	High-temp. electrolysis	92%	47%	Water turbine	85%
Nuclear fuel	High-temp. electrolysis	92%	17%	Pressurised-water reactor unit	32%
Nuclear fuel	High-temp. electrolysis	92%	29%	High-temperature reactor unit	52%
Nuclear fuel	Thermochem. cycle (S-I)	52% + 9%	40%	High-temperature reactor unit	52%

The univocal conclusion based on the comparison made in Table 3 is that the introduction of hydrogen production stage would result in decreased overall energy conversion efficiency, increased fuel consumption, and – in the case of organic fossil fuels – increased emission of pollutants and GHG. In addition, for coal and natural gas, energy losses for oxygen production should be taken into account, which would result in further decrement of the overall efficiency.

The above-presented review does not include solutions, in which the introduction of hydrogen production stage enables replacement of organic fossil fuels with nuclear or renewable sources, thus reducing or liquidating the emission of pollutants and GHG. Exactly such a case – of replacing in the utility power industry the today-applied peak sources (coal units, gas turbines, Diesel engine systems) with peak-load hydrogen turbines – was subject to this investigation. Despite of decreased overall energy conversion efficiency, such a solution would enable zero-emission covering of the whole electricity demand.

The power industry share in the consumption of organic fossil fuels equals about 40%. Their replacement in the utility power industry with nuclear and hydrogen fuel seems to be much easier than in the other industrial branches and transport. The need to apply hydrogen results from the inability to cover the daytime peak electricity demand directly by nuclear units, for the specific nuclear reactor technology precluding every-day neutron power change. At the same time, the concept of zero-emission covering of the whole electricity demand (i.e., using nuclear or renewable primary energy sources) limits the applicable hydrogen production methods to water electrolysis and thermochemical dissociation.

The water electrolysis as a hydrogen production method for electricity generation purposes is the worst possible solution, regarding the overall energy conversion efficiency (see Table 3). In addition, its application would impose a specific limitation: the hydrogen production and utilisation should take place alternately. This means that hydrogen could be treated as an energy storage medium, and its chemical energy used similarly to the potential energy of water in pumped-storage power stations; i.e., to move the electric energy generated during the nighttime demand trough to the daytime peak period. This concept is illustrated in Fig. 2.

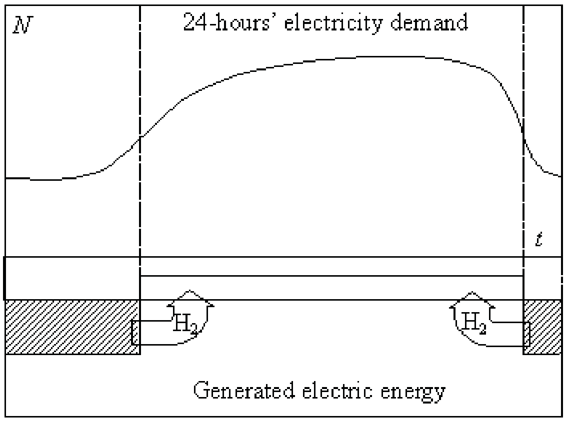

Fig. 2. Concept of a hydrogen energy storage cycle. N: Electric power; t: Time

The storage efficiency, understood as the ratio of the electric energy recovered during the daytime peak and the electric energy generated during the nighttime trough, should be compared to the efficiency of pumped-storage power stations, which reaches about 70%. In the case of hydrogen energy storage cycle, this efficiency would be equal to about 55% (electrolysis efficiency, 92%, multiplied by hydrogen turbine net electric efficiency, 60%).

The above-mentioned limitation does not concern energy conversion chains containing thermochemical water splitting cycles. In such cases, hydrogen could be used for concentrating the electricity generation during the daytime peak period, which also could be perceived as a form of energy storage. This concept is shown in Fig. 3. Direct determination of the storage efficiency is impossible here, as the input quantity is not electric energy, but heat generated in a high-temperature nuclear reactor. A more complex analysis of the overall energy conversion efficiency has to be undertaken. Preliminary results of such an analysis, assumed a hydrogen turbine system of 60% efficiency is applied, are given in Table 3, and results for the system under investigation are presented in the relevant chapter below.

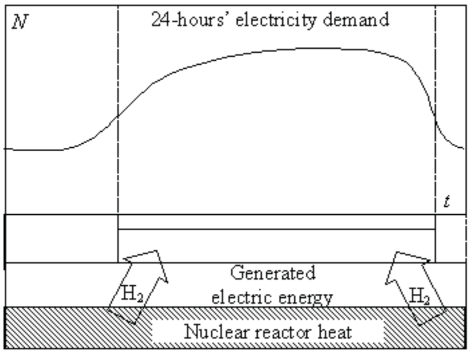

Fig. 3. Concept of electricity generation concentration using hydrogen. N: Electric power; t: Time

3. Water-steam system with peak-load hydrogen turbine

The applicability study on the hydrogen turbine systems elaborated up to now shows that none of them could be used in the frames of the above-described hydrogen energy storage cycle. Therefore, a necessity to design a new system appears, the configuration of which would allow every-day quick start-up and shut-down of the hydrogen turbine. The conclusions of the above-mentioned study, and the explicit definition of the new system's purpose allowed to introduce three initial, special requirements related to it:

- The system configuration should provide continuous operation of a maximum number of its components, especially of the high- and low-pressure components, incl. the condenser;
- Working medium parameters realisable in today's conditions should be applied, and application of extreme pressure and temperature at the same point should be avoided;
- In order to obtain a satisfactory overall energy conversion efficiency, the system should provide an efficiency of converting the hydrogen chemical energy (heat of combustion) higher than 60%.

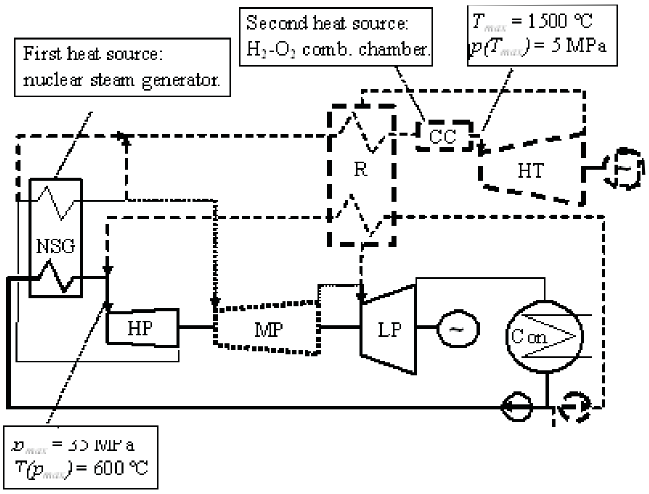

Fig. 4. Concept of the new water-steam system with peak-load hydrogen turbine. NSG: Nuclear steam generator; CC: Hydrogen-oxygen combustion chamber; HP: High-pressure steam turbine part; MP: Medium-pressure steam turbine part; LP: Low-pressure steam turbine part; Con: Condenser; HT: Hydrogen turbine; R: Recovery boiler. Solid lines: Permanently operating components; Point lines: Components operating in nighttime mode; Dashed lines: Components operating in peak mode

These requirements were met by limiting the range of the hydrogen turbine operating parameters to medium pressure and introducing one heat source more (along with the hydrogen-oxygen combustion chamber) in the form of a nuclear steam generator in order to keep the high- and low-pressure system part in continuous operation [8]. In the matter of fact, this leads to a solution, in which the hydrogen turbine is added to the water-steam loop of a nuclear power plant with a gas-cooled reactor or sodium-cooled (fast breeder) reactor. This concept is shown in Fig. 4. Its main idea is to enable system operation in two modes: basic mode, with one heat source (during the nighttime demand trough); or peak mode, with two heat sources (during the daytime demand peak). The nuclear steam generator (NSG) is the basic source here, supplying heat continuously, and the hydrogen-oxygen combustion chamber (CC) is the peak source. The whole hydrogen part of the system - recovery boiler (R), combustion chamber, and turbine (HT) – is located parallel to the medium-pressure part (MP) of the steam turbine, being a flow path alternative to it. This means that in the nighttime mode all the working medium flows through the MP turbine part, while the hydrogen part is shut down, and in the peak mode all the working medium is directed to the hydrogen part, while the MP part is shut down. In such a system, keeping the shut-down machines and devices hot and their rapid start-up is not difficult. In Fig. 4 the alternative flow paths are marked with point and dashed lines, respectively. The components operating permanently are marked with solid lines. It is assumed that the nuclear steam generator operates with constant thermal load. The need of cooling the steam downstream the hydrogen turbine (heat recovery), caused by its relatively high temperature, enables heating of an additional amount of working medium. This leads to a higher load of the high- and low-pressure turbine parts (HP and LP) and the condenser during operation in peak mode.

The following main assumptions were made in relation to the system operating parameters: for material reasons, the temperature of medium heated in heat exchangers should not exceed 600 °C; the working medium temperature at the hydrogen turbine inlet should not exceed 1500 °C; in result of the applicability study on the systems presented in the previous chapter, the maximum pressure at the steam turbine inlet was limited to 35 MPa, and at the hydrogen turbine inlet to 5 MPa. These assumptions enable implementation of the proposed concept using existing and mastered technologies.

The steam generator, being the first heat source in the system under consideration, is at the same time the cooler in the reactor heat transport loop (primary loop). The realised investigation concerned the case of application of modern, helium-cooled high-temperature reactors of the so-called generation IV, known under the common name of VHTR (Very-High-Temperature Reactors). As it was already mentioned, the works on this type of reactors are far advanced in the United States and the Republic of South Africa. The American project, called MHR (Modular Helium Reactor), is based on the concept and experience, connected with the American gas-cooled reactors of third generation, called HTGR (High-Temperature Gas-cooled Reactors). Two such power units were constructed: the reactor in Peach Bottom was operated in 1967-1974; and the reactor in Fort St. Vrain was operated in 1979-1989. The MHR fuel assemblies are hexagonal prisms, containing cylindrical blocks of suppressed TRISO elements (spheres of diameter less than 1 mm, consisting of fuel material, cladded with a porous graphite layer, and next with two layers of pyrolytic graphite and a layer of silicon carbide between them); the core is not being recharged with fuel during reactor operation.

The South-African concept, called PBMR (Pebble Bed Modular Reactor), is based on the solution implemented in West Germany in 1968-1989. Its main idea is to apply spherical fuel assemblies, made of TRISO elements suppressed in a graphite matrix, and a core structure, enabling continuous recharge with fuel during reactor operation.

In both projects, the temperature of helium at the reactor outlet is expected to reach 850-950 °C. This enables their application for production of hydrogen; e.g., in the cycles presented in the previous chapter. The other opportunity is to generate only electricity. In this case, application of Brayton cycle is provided: with a gas turbine, a two-part compressor, a recuperator, and a two-part cooler. The relevant flow diagram is shown in Fig. 5. Such a system would obtain a net electric efficiency of 48-52% (thus the value of 52% for this technology, set in the last column of Table 3).

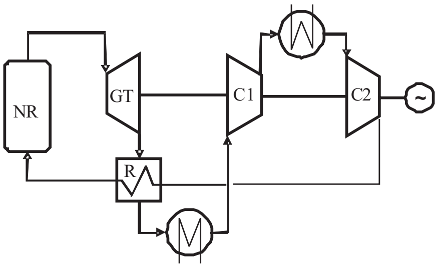

Fig. 5. Flow diagram of Brayton cycle with a helium-cooled reactor. NR: Nuclear reactor; GT: Gas turbine; R: Recuperator; C1, C2: Compressor parts

The proposed co-operation of the new water-steam system with a high-temperature reactor is in fact a return to the two-loop configuration of power units with gas-cooled reactors. However, the assumed maximum coolant temperature (950 °C) enables utilisation of a part of its enthalpy in a gas turbine upstream the steam generator, thus configuring a specific combined gas-steam cycle. This concept is shown in Fig. 6. Such an approach results in a simpler system as a whole, because it allows avoiding the application of a developed and complex feed-water heating system (regeneration system) within the secondary loop.

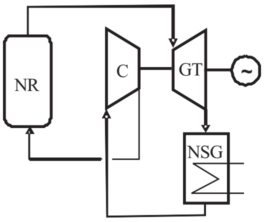

Fig. 6. Flow diagram of the primary loop of a high-temperature reactor, co-operating with the water-steam system with peak-load hydrogen turbine under consideration. NR: Nuclear reactor; GT: Gas turbine; NSG: Steam generator; C: Compressor

4. Investigation results

A detailed simulation-based investigation was realised, incl. preparation of an overall, consistent model of the system. First of all, the nuclear steam generator and gas turbine operating parameters were determined, being boundary conditions for the main model; i.e., the model of the proposed water-steam system. Next, its particular calculation modules were prepared, verified, and integrated. The highest attention was paid to the assumptions concerning the heat transfer and expansion conditions in the relevant system components. This concerned especially the high- and low-pressure steam turbine parts, the load of which could differ significantly in the two operating modes (because of the additional amount of working medium, heated in the recovery boiler in peak mode).

The research included also the overall efficiency of conversion of the nuclear fuel energy, assumed the energy needed for hydrogen and oxygen production is of the same origin. The determination of optimal performance solution was an additional, but important aim.

The basic assumptions, constituting the boundaries of the performed investigation, could be divided into two groups: general ones, concerning material and thermal-hydraulic problems; and special ones, concerning the capabilities of technical realisation. Examples of assumptions of the first group are the applied values of turbine stage group internal efficiency or compressor stage group internal efficiency, and of the second group the limitation of the lowest pressure in the recovery boiler to 1 bar in order to avoid its inclusion to the vacuum part of the system. An example of an assumption, connected with both groups, is the limitation of the heated medium temperature at the outlet of each heat exchanger stage (i.e., the nuclear steam generator stages, and the recovery boiler stages) to max. 600 °C in order to avoid application of expensive alloys as structure materials.

The most important assumptions, concerning the parameters of machines and devices and working medium parameter limitations, are set in Table 4.

Some of the above assumptions require explanation and comment. The every-day operation in two modes, very different regarding the load, is a special feature of the system under consideration. At the same time, constant operating conditions should be secured for the nuclear reactor. This means that the nuclear steam generator has to operate under identical load in the two modes. For that reason, constant operating parameters of its heating side were assumed.

A sliding-pressure operation was provided for the high-pressure part of the system. As the maximum value of the pressure at the high-pressure turbine part inlet was set to 35 MPa (i.e., on a supercritical level), its minimum value was set to the critical level. The reason was to avoid the need to separate liquid and gaseous phases, which would cause a significant complication of the system configuration.

Table 4.
Assumptions, concerning parameters of machines and devices and working medium parameter limitations

Parameter	Value
Helium temperature at the reactor outlet	950 °C
Maximum temperature of heated medium at a heat exchanger outlet	600 °C
Maximum pressure of the working medium at the high-pressure steam turbine part inlet	35 MPa
Minimum pressure of the working medium at the high-pressure steam turbine part inlet	22.1 MPa
Steam pressure at the high-pressure turbine part outlet	5.5 MPa
Working medium pressure at the hydrogen turbine inlet	5 MPa
Maximum working medium temperature at the hydrogen turbine inlet	1500 °C
Minimum pressure of the cooled medium at the recovery boiler outlet	0.1 MPa
Condensing pressure	3.6 kPa
Minimum temperature difference in the heat exchangers	20 °C
Maximum temperature effectiveness of a heat exchanger stage	0.75
Combustion chamber efficiency	100%
Gas turbine internal efficiency	93%
Compressor internal efficiency	85%
Hydrogen turbine internal efficiency	90%
HP steam turbine part internal efficiency	90%
MP steam turbine part internal efficiency	89%
LP steam turbine part internal efficiency	80%
Pump internal efficiency	90%
Product of mechanical and electric generator efficiency	97%

In order to keep the heat exchanger dimensions in a reasonable range, limitations concerning the minimum temperature difference in heat exchanger stages and their maximum temperature effectiveness were introduced. The temperature effectiveness is understood as the ratio of temperature differences of outlet and inlet streams:

$$\varepsilon_T = \frac{T_{out}^{cold} - T_{out}^{hot}}{T_{in}^{hot} - T_{in}^{cold}} \tag{11}$$

The value of the gas turbine internal efficiency was set in accordance with the latest achievements in the field of flow system design and manufacturing.

It should be marked here that the temperature of helium at the turbine inlet does not impose blade cooling. The situation is different in the case of the hydrogen turbine, thus its internal efficiency value was set on a lower level. The value of the low-pressure turbine part internal efficiency is conditioned by the losses, connected with the steam humidity (two-phase flow).

The simulation calculations were realised using the HYSYS 2004 commercial software, included in the AspenOne 2004 package. Procedures describing the thermodynamic properties of water and steam, elaborated in the Institute of Heat Engineering, Warsaw University of Technology, based on formulae determined by the ASME (American Society of Mechanical Engineers), were used as its supplement. This was necessary because the water and steam properties at temperatures higher than 800 °C are not included in the commercial code.

Model modules corresponding to the system components were built and tested. Next, the proper modules were integrated in two configuration versions: a basic one (for operation in nighttime mode); and a peak one (with the hydrogen part – for operation in peak mode). The operating conditions of the high- and low-pressure turbine parts were critical for the question of capability to technically realise the idea of operation of the same system in two significantly different modes. In order to obtain consistent results for the two configurations, numerous simulations were made for each set of assumed parameters (such as working medium pressure upstream the HP turbine part, or its temperature upstream the hydrogen turbine, etc.), using iteration method.

A dependence between the mass flow rate and the turbine stage group inlet and outlet parameters, based on the similarity principles, was used for the calculations:

$$\overline{G} = \frac{G}{G_0} = \frac{p_{in}}{p_{in0}} \sqrt{\frac{j_{in0}}{j_{in}}} \frac{E}{E_0} \tag{12}$$

where

$$E = \sqrt{1 - \left(\frac{\pi - \pi_{cr}}{1 - \pi_{cr}}\right)^2} \quad \text{for } \pi > \pi_{cr} \tag{13a}$$

or

$$E = 1 \quad \text{for } \pi \leq \pi_{cr}, \tag{13b}$$

and

$$\pi = \frac{p_{out}}{p_{in}}, \tag{14}$$

and

$$j = \frac{k}{k-1} pv. \tag{15}$$

Nominal parameters for the HP and LP turbine part are the parameters of operation with full load; i.e., in peak mode.

The main investigation aim was to determine the system performance, and the additional aim was to determine the optimal operating conditions (parameters). The optimal parameters were determined in result of the realised numerous simulations of system operation under different conditions. They are shown in Fig. 7 (basic, nighttime mode) and Fig. 8 (peak, daytime mode). The realised water-steam cycles are shown in the form of a $T-s$ diagram in Fig. 9. The optimal performance parameters of the system under consideration are set in Table 5.

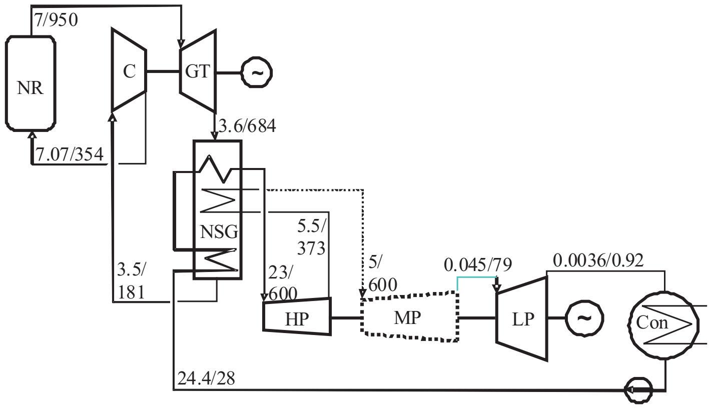

Fig. 7. Optimal system operating parameters in basic (nighttime) mode. NR: Nuclear reactor; GT: Gas turbine; C: compressor; NSG: Steam generator; HP: High-pressure turbine part; MP: Medium-pressure turbine part; LP: Low-pressure turbine part; Con: Condenser; Parameters: Pressure [MPa] / temperature [°C] or steam dryness

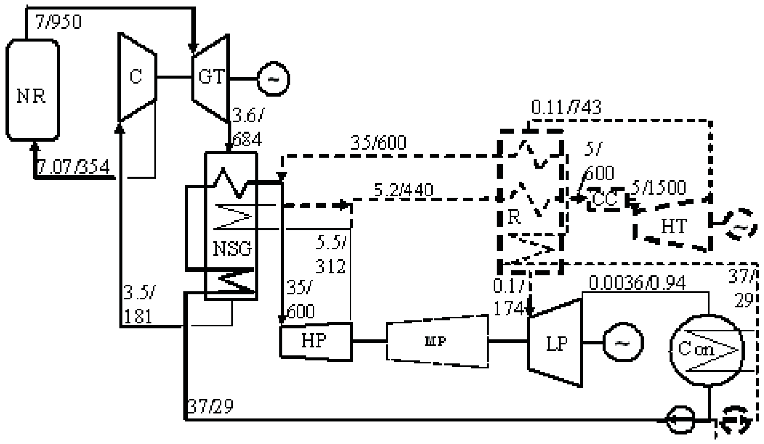

Fig. 8. Optimal system operating parameters in peak (daytime) mode. NR: Nuclear reactor; GT: Gas turbine; C: compressor; NSG: Steam generator; HP: High-pressure turbine part; MP (faded): Medium-pressure turbine part (shut down); R: Recovery boiler; CC: Combustion chamber; HT: Hydrogen turbine LP: Low-pressure turbine part; Con: Condenser; Parameters: Pressure [MPa] / temperature [°C] or steam dryness

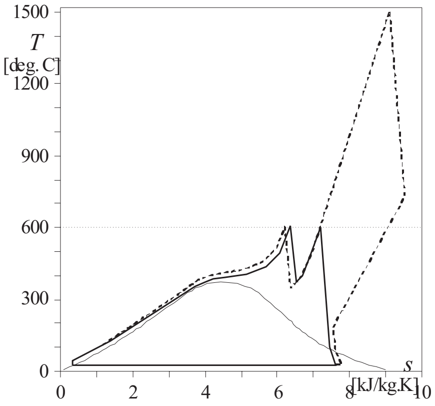

Fig. 9. Realised cycles on a $T - s$ diagram. Solid line: Nighttime mode; Dashed line: Peak mode

It seems that some of the data shown in Fig. 7 and 8 and Table 5 require a comment. First of all, the relatively high pressure of helium in the primary loop corresponds to the assumptions of the American and South-African engineers, made in order to reduce the dimensions of the particular installation components.

Table 5.
Performance parameters of the system under consideration in optimal operating conditions

Parameter	Value
System net electric efficiency in nighttime mode	49.92%
Ratio of the gas turbine net electric capacity and reactor thermal capacity	0.15
Ratio of the steam generator thermal capacity and reactor thermal capacity	0.8454
Water-steam system net electric efficiency in nighttime mode	41.31%
System net electric efficiency in peak mode	57.24%
Water-steam system net electric efficiency in peak mode	54.79%
Efficiency of converting the hydrogen chemical energy (heat of combustion) into electric energy (hydrogen efficiency)	63.04%
Ratio of the combustion chamber thermal capacity and reactor thermal capacity	1.261
Ratio of the recovery boiler thermal capacity and combustion chamber thermal capacity	0.4067
Ratio of the mass flow rate through the high-pressure turbine part in peak and nighttime modes	1.598
Ratio of the mass flow rate through the low-pressure turbine part in peak and nighttime modes	1.973
Ratio of the main electric generator power in peak and nighttime modes	0.8978
Ratio of the system power in peak and nighttime modes	2.624

Next, in agreement with the expectations, it appeared that the system performance improves with increasing the pressure and temperature at the high-pressure turbine part inlet, and with increasing the temperature at the hydrogen turbine inlet. At the same time, the amount of additional working medium, heated in the recovery boiler in the peak mode, directly depends on the medium temperature at the hydrogen turbine outlet. Therefore, any increase of the temperature downstream the combustion chamber caused increased difference in the operating conditions of the HP and LP turbine parts in the two modes.

The power of the basic electric generator (i.e., the one driven by the steam turbine) remains almost unchanged when switching from one operating mode to the other. This is caused by the increased mass flow rate through the HP and LP turbine parts in peak mode, which compensates the shutdown of the MP part. This enables keeping the electric generator efficiency on a high level. Simultaneously, the coupling of the hydrogen turbine with a separate, peak-load electric generator enables the application of higher rotational speed, which leads to smaller turbine dimensions.

The obtained values of the system efficiency in both modes could be considered high. This concerns especially the efficiency of converting the hydrogen chemical energy (heat of combustion) into electric energy, for convenience called hydrogen efficiency. This notion has been introduced relatively lately – with the first research works on systems with two heat sources, one of which is a hydrogen-oxygen combustion chamber.

It has to be underlined here, that a combination of two heat sources is reasonable only if, in result of it, more labour (or electric energy) is obtained, compared to the same sources utilised separately. In order to evaluate the combination effect, one may try to compare the outputs directly, but this is often unrealisable, mainly because of system incomparability. An indirect method seems to be better, based on analysis of the utilisation efficiency regarding the higher-quality heat source [8][9][10]. In this case, it is the hydrogen efficiency envisaged.

Such an approach provides more readable results. The system under investigation was virtually divided into two parts, connected with the particular heat sources and generating corresponding parts of the electric power:

$$N = N_n + N_h, \tag{16}$$

where

$$N_n = \eta_n \dot{Q}_n; \quad N_h = \eta_h \dot{Q}_h \tag{17}$$

Each efficiency in Eq. (17) was considered partial efficiency, associated with a particular source. Their independent, simple calculation is impossible because of the virtual character of the division, not defining the relation between them. This imposed the necessity to introduce a reference value for the "nuclear" efficiency in order to be able to determine the hydrogen efficiency. In the case of the system under consideration, the efficiency obtained when operating only with the basic heat source (i.e., in basic, nighttime mode) in natural way became such a reference value. The hydrogen efficiency was defined as:

$$\eta_h = \frac{N - \eta_n \dot{Q}_n}{\dot{Q}_h} = \frac{N - \eta_{night} \dot{Q}_n}{\dot{Q}_h} \tag{18}$$

The combination effect could be evaluated comparing the obtained hydrogen efficiency with the efficiency of the hydrogen turbine systems designed up to now.

Special attention was paid to the heat transfer conditions in the steam generator and the recovery boiler. Those conditions are shown in Fig. 10 and Fig. 11, respectively. Each of these heat exchangers consists of three stages, the second of which is a steam reheater, and the others are feeding medium heaters (see Fig. 7 and Fig. 8). The temperature effectiveness of the particular stages, calculated in compliance with Eq. (11), is lower than the permissible (maximum) value. Its highest value corresponds to the recovery boiler's second stage and equals 0.665.

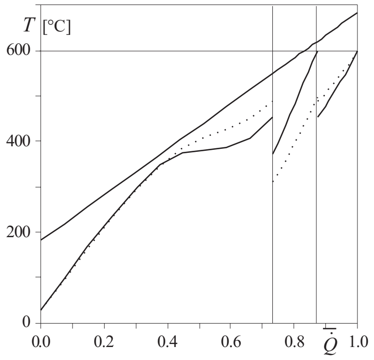

Fig. 10. Heat transfer conditions in the nuclear steam generator. Solid line: Nighttime mode; Dashed line: Peak mode

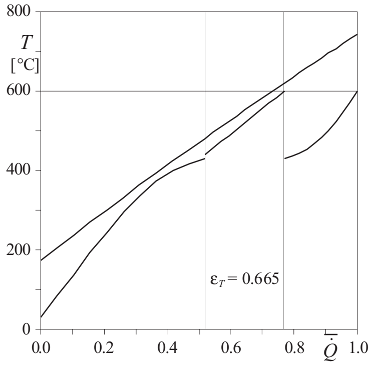

Fig. 11. Heat transfer conditions in the recovery boiler

The comparison of the hydrogen efficiency and net electric efficiency of the system under consideration with the relevant values for hydrogen turbine systems designed up to now and nuclear power systems gives promising results. However, it does not give any idea about the overall efficiency of energy conversion from its primary to final form (in this case, electric). In the meantime, this is the quantity, which should in great extent decide about the rationality of application of hydrogen.

The selection of hydrogen production method was the first step in determining the overall energy conversion efficiency. The utilisation of nuclear energy as a primary energy brings measurable advantages, such as reduction of emission of pollutants and GHG, and capability to replace the import of liquid and gaseous energy carriers by fuel synthesis. For that reason, the sulphur-iodine thermochemical water splitting cycle was selected, as it is the more efficient one among the two such cycles presented in this work. The combined installations of high-temperature reactor of generation IV, gas turbine, and thermochemical cycle provide a hydrogen production efficiency of 52%, and an electricity generation efficiency of 9%. The simultaneous production of oxygen, needed later for the clean combustion of hydrogen, is an additional advantage of this method.

The dual-mode operation of the system under consideration (with, and without the hydrogen source) caused certain difficulties in determining the overall energy conversion efficiency. However, the virtual division, applied for determining the hydrogen efficiency, was effectively used also in this case. Thanks to it, the selection of two conversion chains was possible. The first one includes the power reactor being the basic source in the system under investigation, the gas turbine within the primary loop, and the steam turbine within the secondary loop. The second one consists of a reactor for hydrogen production combined with a relevant installation and a gas turbine, and the hydrogen turbine of the system under investigation.

The ratio of duration of the daytime demand peak and nighttime demand trough is the factor, which decides the ratio of thermal capacities of the reactors used for those two purposes. In other words, the ratio of the power in the hydrogen fuel and the thermal capacity of the power reactor depends on the assumed ratio of duration of the system operation in daytime (peak) and nighttime mode. Taking into account that for both purposes the use of the same reactor type (VHTR) of the same coolant parameters is provided, and that both the American and South-African projects are called modular and their standardisation and serial production is provided, the value of the above-mentioned ratio was determined in a way enabling application of an integer number of identical reactors. In result of simple calculations, the ratio of duration of operation in peak mode and nighttime mode was determined to equal 14.83/9.17 (14 hours and 50 minutes to 9 hours and 10 minutes), which corresponds to application of 5 VHTR-type reactors of the same capacity – 3 for hydrogen production, and 2 power ones. The results of overall energy conversion efficiency calculations are shown in the form of a Sankey diagram in Fig. 12.

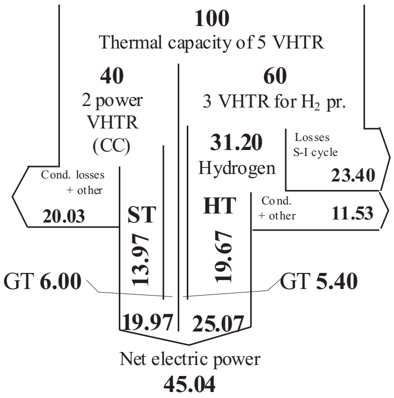

Fig. 12. Energy conversion process in the system under investigation, combined with a hydrogen production system based on S-I cycle. The ratio of duration of operation in daytime (peak) mode and nighttime mode equals 14.83/9.17, which enables application of 5 identical high-temperature reactors of new generation (VHTR). GT: Gas turbine; ST: Steam turbine; HT: Hydrogen turbine

The obtained overall energy conversion efficiency (45.04%) is lower than the net electric efficiency of the designed units with power reactors of VHTR type (52%), but this difference is much less than in the cases of other hydrogen production methods and other hydrogen turbine systems. At the same time, the emission-free generation of a much larger amount of electric power (more than 2.6 times) during the daytime demand peak compared to the nighttime trough is an unquestionable advantage of the proposed system.

5. Summary and conclusions

On the one hand, the society has to meet and solve the problems of: continuous increase of organic fossil fuel prices; finite resources of those fuels; emission of pollutants and greenhouse gases; and energy security (mainly in countries importing energy carriers). On the other hand, the modern nuclear power technologies provide high safety, low energy cost, and practically infinite resources of nuclear fuel. These are the main factors of the recently observed return of the interest in nuclear power. In addition, the use of this technology provides an emission-free electricity generation.

Among the most interesting solutions, providing application capabilities not only for direct power purposes, are the high-temperature reactors of generation IV, generally called VHTR (Very-High-Temperature Reactor). The research on them is far advanced in two centres: in the United States; and in the Republic of South Africa. Helium is the coolant in both projects, and its maximum temperature is to reach 950 °C, which enables their application also in hydrogen production processes.

The interest in hydrogen as a fuel is still very high. However, the question of its production is omitted in the large majority of publications and projects concerning its application. The problem is not in the cost of this production, but in the overall efficiency of conversion of energy from its primary form to a final, usable one. It is caused by the fact that the hydrogen production requires supplies of large amounts of energy, as this element exists on the Earth almost only in compound form. Its production and utilisation is rational only if in result the above-mentioned efficiency increases (and thus the consumption of organic fossil fuels and emission of pollutants and greenhouse gases decrease). As it was shown by the analysis of now applied or investigated hydrogen production methods, none of them secures fulfilment of this requirement.

However, a possibility of rational hydrogen production may appear, although the above-mentioned requirement is not met. For example, heat from a VHTR-type reactor could be used for hydrogen production, next the hydrogen could be used as a fuel in a technology or as a substrate for a purpose, for which nuclear energy, or electricity made of it, cannot be used directly. Covering the daytime electricity demand peak using a peak-load hydrogen turbine is such a purpose (because of the specific technology and for safety reasons, the nuclear power reactors should operate with constant capacity and should be used for direct covering only of the basic demand). Thus, fully emission-free covering of the whole electricity demand could be secured, and the profits of such a solution will be surely higher than the losses from decreasing the overall energy conversion efficiency. In this concept, the hydrogen fuel plays the role of energy storage medium, thanks to which the energy from nuclear reactors could be concentrated and utilised during the peak demand.

Several projects of hydrogen turbine systems were developed up to now. They are all characterised by applying extreme temperatures (1700 °C) and pressures (supercritical), in some cases realised at the same point, and by presence of a vacuum part with condenser. Therefore, it seems that their application as peak sources is technically impossible or inadvisable. In addition, the net electric efficiency of the Graz system (and its modified version), perceived as the most prospective, does not exceed 60% related to the heat of combustion, and this level is treated as a reference in this technology field.

The proposed and investigated water-steam system with peak-load hydrogen turbine enables a continuous operation of the high- and low-pressure components, and a quick and easy start-up and shut-down of the hydrogen part. The main idea is to apply two heat sources: a basic one, in the form of a continuously operating nuclear steam generator; and a peak one, in the form of a hydrogen-oxygen combustion chamber. The hydrogen part of the system – combustion chamber, hydrogen turbine, and recovery boiler – is in fact located parallel to the steam turbine medium pressure part, and is a flow path alternative to it. Thus, a system capability is created to operate in two modes: basic (nighttime) mode, with one, nuclear heat source; and peak (daytime) mode, with two heat sources.

Detailed simulation-based investigation was realised using commercial and author's software, incl. the preparation of an overall, consistent model of the system, preceded by preparation, verification, and integration of its particular calculation modules. The highest attention was paid to the heat transfer and expansion conditions in the relevant system components. The operating parameters of the components of the reactor primary loop (nuclear steam generator, and gas turbine) were determined. The determination of optimal solution regarding the system performance and technical realisability was an additional aim. The investigation included also the overall nuclear fuel energy conversion efficiency, assumed the energy needed for the hydrogen production is of that origin.

The basic assumption and limitations, connected with the system operating parameters, secure the capability of its realisation today. First of all, this concerns the limitation of the hydrogen part parameters to medium pressures (between 50 and 1 bar) and a maximum temperature of 1500 °C, but also a rather conservative heat transfer condition requirements. The assumed values of the internal efficiency of the particular turbomachines are realistic. The continuous operation of the basic source secures a capability to keep the shut-down system components hot using small amounts of working medium, and thus their rapid start-up.

The results of the realised simulation and optimisation calculations seem to be very good. The system net electric efficiency in both operating modes is high (49.9% in nighttime mode, and 57.2% in peak mode). At the same time, the efficiency of conversion of the hydrogen chemical energy (heat of combustion) is on a very high level of 63% and considerably exceeds the reference level (60%). The ratio of generated power in the two modes is also an important result: it equals 2.62, and this means that huge majority (about 80%) of the electricity is generated during the daytime demand peak.

However, the most important result is the obtained overall efficiency of conversion of nuclear energy into electric energy. It equals 45% – lower than the net electric efficiency of the designed units with power reactors of VHTR type (52%), but this difference is much less than in the cases of other hydrogen production methods and other hydrogen turbine systems. In return, the proposed system creates a capability of emission-free covering of the peak electricity demand.

Manuscript received by Editorial Board, March 20, 2008;
final version, April 28, 2008.

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Badanie nowego układu wodno-parowego ze szczytową turbiną wodorową do bloków jądrowych z reaktorami gazowymi

Streszczenie

Celem przedstawionych badań było przeprowadzenie złożonych obliczeń nowego, kombinowanego układu wodno-parowego ze szczytową turbiną wodorową do zastosowania w blokach jądrowych z reaktorami gazowymi. Cechą charakterystyczną układu jest obecność dwóch źródeł ciepła: jądrowej wytwornicy pary; oraz wodorowo-tlenowej komory spalania. Główną ideą jest stworzenie systemowej możliwości pracy w dwóch reżimach, z jednym lub dwoma źródłami ciepła, co prowadziłoby do znacznych zmian wydajności. Badania objęły również całkowitą sprawność przetwarzania energii jądrowej, przy założeniu, iż ciepło potrzebne do produkcji wodoru i tlenu pochodzi z takiego właśnie źródła. Ta część pracy zawiera analizę racjonalności produkcji i wykorzystania wodoru. Celem dodatkowym badań było określenie rozwiązania optymalnego pod względem osiągów i możliwości technicznej realizacji. Uzyskane wyniki są obiecujące: osiągi układu są na bardzo wysokim poziomie, zaś parametry pracy są w dzisiejszych warunkach w pełni realizowalne. Dodatkowo, układ umożliwia bezemisyjne i dyspozycyjne wytwarzanie energii elektrycznej w czasie dziennego szczytu zapotrzebowania.