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Concerning hydrogen production based on nuclear technologies

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Abstract

The paper presents the possibility for the sodium-cooled fast reactor technologies to be used for the steam methane reforming (SMR) into hydrogen. The three independent energy loops available in the Russian BN-600 fast reactor make it possible to use the steam generator in one of the loops for the generation of steam with a pressure of $p = 13.2\,\mathrm{MPa}$ and a temperature of $T = 505\,°\mathrm{C}$. The second energy loop of the reactor can be used to increase the temperature of the steam–gas mixture to the value required for the efficient reforming. The electric power of 200 MW generated in the loop is enough to feed the source of high-temperature helium flow ($T = 950\,°\mathrm{C}$) using which the steam–gas mixture temperature in the reformer is increased up to $T = 820\,°\mathrm{C}$. The technology proposed provides for a high hydrogen production rate (about 80 thousand normal cubic meters of H_2 per hour). This will save up to 25% of the initial natural gas that is combusted in accordance with the existing standard SMR technology for the preparation and heating of the steam-gas mixture.

Keywords: Hydrogen; Steam methane reforming; BN-600 sodium-cooled fast reactor.

A fundamental issue requiring the development of scientific approaches is the need for limiting the human impacts on the environment. The fuel and energy facilities which use coal and hydrocarbons account for most of the greenhouse gases, specifically carbon dioxide, released into the atmosphere. In this connection, the concept of hydrogen economy and hydrogen ecology suggests step by step reduction in the volume of the carbon fuel in use, and, in a longer term, on its extensive replacement by hydrogen fuel. In future hydrogen is expected to become one of the major sources of energy with hydrogen economy, a basically new type of power engineering, to be formed [1].

Nuclear power is a technology that makes it possible to reduce substantially the release of greenhouse gases into the atmosphere in the production of electricity. Thus, according to the International Energy Agency (IEA), the emission of 56 billion tons of carbon dioxide, a global two-year total emission, has been prevented since 1971 at nuclear power plants in operation worldwide.

At nuclear installations, high temperatures of about 850 to 950 °C required to gasify coal and convert natural gas to hydrogen may be achieved only in high-temperature gas-cooled nuclear reactors. Such reactors are being developed in a number of countries but have not yet reached the commercialization stage. A successful design in operation in Russia is the BN-600 commercial fast reactor with the primary circuit inlet sodium temperature of not more than 550 °C. The BN-series reactors are intended for electricity generation, still they may have other technological and commercial applications, including, potentially, commercial production of hydrogen [3]. The medium-temperature of the coolant in operating sodium-cooled reactors does not however make it possible to reform methane effectively for hydrogen production. To increase the steam–gas mixture temperature the additional heating was proposed in Ref. [4].

The goal of this study is to investigate the feasibility of the steam methane reforming into hydrogen using the medium-temperature steam of the BN-600 reactor ($T = 505\,°\mathrm{C}$) and the subsequent additional heating of the steam–gas mixture to the required temperature ($T = 820\,°\mathrm{C}$) using the electric energy generated in the same reactor.

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The BN-600 commercial reactor has a tank design [5]. The tank accommodates the primary circuit components, including the reactor core, intermediate heat exchangers, and main coolant pumps. The core heat is transferred to the steam generators through a three-circuit system via three parallel loops.

Basic performance data of the BN-600 reactor's three independent energy loops [5]:

- rated electric power – 200 MW;
- steam generating capacity – $6.4{\cdot}10^5$ kg/h;
- steam pressure – 13.2 MPa;
- steam temperature – 505 °C.

Currently, about half of commercial hydrogen is produced by steam methane reforming via the following reaction [2]:

$$CH_4 + H_2O + 206\ \text{kJ/mole}\ CH_4 \longrightarrow CO + 3H_2 \tag{1}$$

During the reaction, the steam–gas mixture pressure is $p = 2$–3 MPa, the water/methane mole ratio is $m = 2$, and the temperature is $T = 850$ °C. Catalysts are also used in the process.

Commercial steam methane reforming consists of two stages.

At stage 1, steam with a pressure of up to 3 MPa is obtained in a chamber with a temperature of up to 500 °C and mixed with the externally fed natural gas to the mole ratio of $m = 2$. This requires up to 12% of the supplied gas to be combusted for the steam formation and heating.

At stage 2, the prepared steam–gas mixture is fed into a high-temperature reformer with a temperature of $T = 850$ °C, which contains catalysts and membranes for the hydrogen separation. This requires 13% of the supplied gas to be combusted to heat the reformer.

Therefore, commercial steam methane reforming entails the combustion of 25% of the gas fed to the reformer with the respective release of the combustion product (carbon dioxide) into the atmosphere.

For the purpose of achieving a high hydrogen production rate, saving large quantities of natural gas and preventing its combustion products from being released into the atmosphere, it is proposed in this study that steam from the BN steam generator should be used to prepare the steam–gas mixture, and electric heaters powered from the BN turbine should be used to increase additionally the steam–gas mixture temperature.

Such capability is provided by the BN-600 reactor in operation as the third unit of the Beloyarskaya Nuclear Power Plant. The BN-600 reactor has three energy loops each of which forms an independent power unit.

The above-mentioned high parameters of the steam in one of the energy loops make it possible to use it to prepare the steam–gas mixture, thus reducing by 12% the supplied gas consumption and providing for a decrease in the carbon dioxide release into the atmosphere.

An electric power of up to 200 MW generated in the reactor's second independent energy loop can be used to increase the temperature of the prepared steam–gas mixture from 500 to 820 °C needed for the effective steam reforming, which allows saving another 13% of the gas supplied.

Assuming that a half of this loop's power, with regard for losses, will be spent for the steam reforming of methane, then, taking into account the energy required for endothermic reaction (1) to take place (206 kJ/mole of CH_4), we shall have the following reforming efficiency:

$$P = 100\,\text{MW}/206\,\text{kJ/mole}\,CH_4 \approx 5 \cdot 10^2\text{mole}\,CH_4/\text{s} \tag{2}$$

The following flow of gas is required to achieve such conversion efficiency:

$$W_{gas} = 4 \cdot 10^4\,\text{Nm}^3/\text{h} \tag{3}$$

where Nm^3 is the cubic meter of gas under normal conditions (a pressure of 760 mmHg, and a temperature of 0 °C).

It appears to be technologically feasible to supply to the reformer 40 thousand cubic meters of natural gas per hour.

Preparing the steam–gas mixture needed for the reforming will require the following steam flow:

$$\text{W}_{steam} = \text{W}_{gas} \cdot m \cdot M/22.4 \tag{4}$$

where W_{steam} is the steam flow, kg/h; W_{gas} is the natural gas flow in normal conditions, Nm^3/h; M is the molecular weight of water, 10^{-3} kg; $22.4{\cdot}10^{-3}\,\text{Nm}^3$ is the volume occupied by a mole of methane; $m = 2$ is the mole ratio of steam and gas.

Provided a natural gas flow equal to $4{\cdot}10^4\,\text{Nm}^3$/h is defined in relation (4), then preparing a steam–gas mixture with a ratio of $m = 2$ will require the following steam flow:

$$W_{steam} = 6.4 \cdot 10^4\,\text{kg/h} \tag{5}$$

which is an order of magnitude as small as the capacity of one BN-600 energy loop ($6.4{\cdot}10^5$ kg/h).

According to reaction (1), steam reforming of one mole of methane is expected to yield up to three moles of hydrogen or, at least, with losses taken into account, two moles of hydrogen [6]. Then, with a methane flow of $W_{gas} = 4{\cdot}10^4\,\text{Nm}^3$/h fed to the reformer, a hydrogen flow of about $W_{hydrogen} = 8{\cdot}10^4\,\text{Nm}^3$/h may be obtained as the result of the reaction (1).

We shall estimate the hydrogen production capacity based on the BN-600 reactor. The BN-600 reactor is known to operate for 280 days per year (6720 h). Provided 250 million cubic meters of gas is supplied to the BN-600 reactor during this time ($W_{gas} = 4{\cdot}10^4\,\text{Nm}^3$/h), which is technologically feasible in Russia, then, with the conversion of one mole of methane to two moles of hydrogen, up to 500 million cubic meters of hydrogen will be produced yearly, with much less carbon dioxide released into the atmosphere.

The facility for the methane reforming into hydrogen will consist of two units: a medium-temperature chamber and a high-temperature reforming chamber.

A flow of the steam–gas mixture is generated in the medium-temperature chamber. For this, a steam flow of 18 kg/s with a temperature of $T = 550$ °C and a pressure of $p = 30$ atm is supplied to the chamber from the BN-600 SG outlet. Simultaneously, a methane flow of 8 kg/s with a temperature of $T = 40$ °C and a pressure of $p = 30$ atm is fed to