



## Original Article

## Exergy and exergoeconomic analysis of hydrogen and power cogeneration using an HTR plant

Nima Norouzi <sup>a</sup>, Saeed Talebi <sup>a,\*</sup>, Maryam Fani <sup>a,\*</sup>, Hossein Khajehpour <sup>b,\*</sup><sup>a</sup> Energy and Physics Department, Amirkabir University of Technology, 424 Hafez Ave., Tehran, Iran<sup>b</sup> Energy Engineering Department, Sharif University of Technology, Ostad Moeen, Tehran, Iran

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## ABSTRACT

This paper proposes using sodium-cooled fast reactor technologies for use in hydrogen vapor methane (SMR) modification. Using three independent energy rings in the Russian BN-600 fast reactor, steam is generated in one of the steam-generating cycles with a pressure of 13.1 MPa and a temperature of 505 °C. The reactor's second energy cycles can increase the gas-steam mixture's temperature to the required amount for efficient correction. The 620 ton/hr 540 °C steam generated in this cycle is sufficient to supply a high-temperature synthesis current source (700 °C), which raises the steam-gas mixture's temperature in the reactor. The proposed technology provides a high rate of hydrogen production (approximately 144.5 ton/hr of standard H<sub>2</sub>), also up to 25% of the original natural gas, in line with existing SMR technology for preparing and heating steam and gas mixtures will be saved. Also, exergy analysis results show that the plant's efficiency reaches 78.5% using HTR heat for combined hydrogen and power generation.

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## 1. Introduction

Although hydrogen is the second most abundant element in nature, hydrogen is not available as an element like conventional fossil fuels. Hydrogen can be obtained from fuels such as coal, oil, or natural gas [1,2]. Hydrogen gas can be produced in biology and chemistry laboratories. This gas is usually the by-product of other reactions. In the laboratory, hydrogen can be obtained from the reaction of acids with metals such as zinc with a cape device, i.e., Water electrolysis is also an easy way to produce hydrogen [3]. Bypassing a low-voltage current through the water, oxygen gas can be collected at the anode, and hydrogen gas can be collected at the cathode [4]. The cathode is usually made of platinum or another intermediate metal to collect hydrogen. Of course, since there is a possibility of fire and oxygen also contributes to this combustion, the metal cathode and anode are considered as both intermediates (iron is oxidized and reduces the amount of oxygen obtained) [5]. This reaction's highest theoretical efficiency is the ratio of electricity to hydrogen produced between 80 and 94%. Chemists discovered in 2007 that they could produce hydrogen if they pelleted an alloy of gallium and aluminum into water [5]. This process also produces alumina. In the meantime, gallium does not allow a layer of oxygen to form on the pellet, and of

course, gallium can be reused after the reaction, which is important because of the metal's high cost. This method is also noteworthy in cost reduction because hydrogen is produced there and no longer needs to be moved. In industry: Various ways have been found for the industrial production of hydrogen. But the best of them all is economically extracting hydrogen from hydrocarbons. In this method, water vapor reacts at high temperatures with fossil fuels such as methane in natural gas [6] to form a mixture of carbon monoxide and H<sub>2</sub>, called water gas or synthesis gas. This reaction's high temperature means 1000–1400 K, 700–1100C, 1300 to 2000 Fahrenheit. Ammonia production is also obtained from natural gas [7]. In addition to the production of sodium hydroxide and chlorine release, saltwater's electrophoresis also releases hydrogen. Due to the corrosion and flammability of hydrogen gas, it is difficult to be transported and stored. Therefore, in many of these industrial processes, the hydrogen produced is consumed on the spot without refining or separation. Today, hydrogen can be obtained from water electrolysis, natural gas reform, and partial oxidation of fossil fuels [8]. At present, 98% of the world's hydrogen is produced from fossil fuels; Soon, hydrogen fuel will be used to power vehicles, heat, and cook at home. At present, hydrogen produced in the industry is considered a chemical product and not fuel [9]. The commercial sale of hydrogen is less than 10% of the world's production, which is estimated at 20 million tons per year; This means that 90% of the hydrogen produced is consumed at the production site; Today, for example, the hydrogen industry in the United States produces nine

\* Corresponding authors.

E-mail address: [khajehpour@energy.sharif.edu](mailto:khajehpour@energy.sharif.edu) (H. Khajehpour).

million tons of hydrogen annually, which provides the fuel needed for the 3 to 6 million Suzuki hydrogen vehicles of 6 to 3 million households. Today, only a small fraction of the hydrogen produced is an energy carrier [10]. Different methods of producing hydrogen from different energy sources have unique needs and produce or distribute unique by-products. Further research and development and prototyping are needed to optimize and diversify commercial methods of hydrogen production. Advanced methods for the separation of pollutants are needed to reduce the price of hydrogen produced and increase efficiency [11]. More appropriate methods are needed for both stationary and dispersed hydrogen production, and efforts should be made on existing commercial processes such as methane reforming, electrolyzers, and so on. Focus on developing advanced techniques such as pyrolysis of biomass materials and water separation by thermochemical methods, photo-electrochemical electrolysis, and biological methods [1,5]. Hydrogen will be produced in large refineries, industrial areas, energy parks, refueling stations in different communities, and easily distributed in rural areas and customers' homes. Hydrogen production and distribution methods are very diverse and designed according to need. In this study, we produce hydrogen in nuclear power plants [4].

The importance of limiting human impact on the environment is a basic issue that requires the improvement of scientific aspects. Most GHGs, especially CO<sub>2</sub> emitted to the atmosphere, come from fuel and energy installations that use coal and other fossil fuels. In this regard, the economics and ecology of hydrogen suggest a gradual reduction in the volume of carbon fuel used and, in the long run, its widespread replacement with hydrogen fuel. In the future, it is expected that new methods of power engineering will be formed, and hydrogen will become one of the main sources of energy with economical consumption [7,12]. Nuclear energy is a technology that can significantly reduce greenhouse gas emissions in the atmosphere to generate electricity. Thus, according to the IEA, 56 billion tons of carbon dioxide emissions have been prevented from being emitted in nuclear power plants worldwide since 1971.

In nuclear facilities, a high temperature of about 850–950 °C required to convert coal to gas, and convert methane to hydrogen is only possible in high-temperature gas-cooled nuclear reactors. Such reactors are being introduced in some countries, but all developed cases are in the experimental stage. A successful Russian project is the BN-600 commercial fast reactor, most likely to be in the industrial stage by 2025. The initial inlet temperature of sodium is a maximum of 550 °C. The BN series is developed for power generation, but it can be applied to other commercial and technical uses, including potentially commercial H<sub>2</sub> generation [3,13]. The average cooling temperature of sodium-cooled reactors cannot effectively modify methane to produce hydrogen. Additional heating is suggested in Ref. [4] to increase the methane-gas mixture's temperature. This paper aimed to analyze the possibility of modifying steam gas to H<sub>2</sub> using the intermediate temperature stream of the reactor (T = 505 °C) supported by an additional utility heating of the steam-gas mixture to the required temperature (T = 700 °C) using a duct burner or additional heat energy provided by the electricity produced in the same reactor [14,15].

## 2. Methods and materials

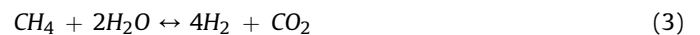
### 2.1. Methane reforming method

Methane steam reforming is the most important industrial route for hydrogen fuel production. Equilibrium reactions control this process. The overall reaction process is endothermic, and high temperatures are required to achieve a satisfactory methane conversion rate. In the present paper, the behavior of a methane steam

reforming reactor is modeled. This model includes partial differential equations to describe physical and chemical processes in a steam reforming reactor. In recent years, the desire to find methods and processes to reduce emissions from mobile sources such as internal combustion engines and diesel engines has become common and important. One possible solution to this problem is to use PEM fuel cells in vehicles that use hydrogen fuel [1]. One of the best and most economical methods of hydrogen production is methane steam reforming [2]. Methane gas vapor reforming reaction (SRM) was first performed in 1868. Introduced by Mottai and Marshall as an outstanding industrial process [3]. This reaction is used to produce hydrogen and carbon monoxide on a large scale and produce synthetic gas (a mixture of hydrogen and carbon monoxide). On the other hand, this reaction is used to produce synthetic gas, which is the raw material of Fisher-Traps synthesis, methanol production, formaldehyde, etc. Although noble metals such as Pt, Rh, Pd, and Ru are very active for steam reforming, Ni is the most common catalyst due to its cheapness, high-temperature stability, and easy availability [2]. In this paper, a steam reforming reactor is modeled, and a genetic algorithm is used to optimize the reactor. In a steam reforming process, methane and water vapor are often converted to carbon monoxide and hydrogen, and some carbon dioxide will be produced during the reaction. Excess water can also be present in the reaction output. The steam reforming reaction is according to Equation (1) [5]:



There are other reactions in the reactor defined according to Equations (2) and (3).



Equilibrium constants can be expressed as a function of partial pressure (in terms of atmosphere) and temperature (Kelvin). Equilibrium tabs are expressed in terms of Equations (4)–(6) [6].

$$K_1 = \exp\left(30.42 - 27106 \frac{1}{T}\right) \tag{4}$$

$$K_2 = \exp\left(-3.798 - 4160 \frac{1}{T}\right) \tag{5}$$

$$K_3 = \exp\left(34.218 - 31226 \frac{1}{T}\right) \tag{6}$$

In the reactor, methane and water are produced as feed and carbon dioxide, carbon monoxide, and hydrogen on a nickel catalyst bed. An inert gas such as helium may also be present on a laboratory scale. Reaction rates are expressed by Equations (13)–(16) [7].

$$R_1 = \frac{\frac{k_1}{P_{H_2}^{2.5}} \left[ P_{CH_4} P_{H_2O} - \frac{P_{H_2}^3 P_{CO}}{K_1} \right]}{DEN^2} \tag{7}$$

$$R_2 = \frac{\frac{k_2}{P_{H_2}} \left[ P_{CO} P_{H_2O} - \frac{P_{H_2} P_{CO_2}}{K_2} \right]}{DEN^2} \tag{8}$$

$$R_3 = \frac{\frac{k_3}{P_{H_2}^{3.5}} \left[ P_{CH_4} P_{H_2O}^2 - \frac{P_{H_2}^4 P_{CO_2}}{K_3} \right]}{DEN^2} \quad (9)$$

$$DEN = 1 + K_{CH_4} P_{CH_4} + K_{CO} P_{CO} + K_{H_2} P_{H_2} + \frac{K_{H_2O} P_{H_2O}}{P_{H_2}} \quad (10)$$

Besides, the coefficients in Equations (16)–(13) are given by Arrhenius relations in Equations (17)–(23) [8]:

$$k_1 = 1.336 \times 10^{15} \exp \left( -240.1 \frac{1}{RT} \right) \quad (11)$$

$$k_2 = 1.955 \times 10^7 \exp \left( -67.13 \frac{1}{RT} \right) \quad (12)$$

$$k_3 = 3.226 \times 10^{14} \exp \left( -243.9 \frac{1}{RT} \right) \quad (13)$$

$$K_{CO} = 8.23 \times 10^{-4} \exp \left( 70.65 \frac{1}{RT} \right) \quad (14)$$

$$K_{H_2} = 6.12 \times 10^{-8} \exp \left( 82.90 \frac{1}{RT} \right) \quad (15)$$

$$K_{H_2O} = 1.77 \times 10^5 \exp \left( -88.68 \frac{1}{RT} \right) \quad (16)$$

$$K_{CH_4} = 6.65 \times 10^{-3} \exp \left( 38.28 \frac{1}{RT} \right) \quad (17)$$

Note that the constant R of the gases is 8.314 J/(mol·K) in the above equations. Stoichiometry reacts as the number of moles increases with increasing reactor length. Therefore, with a slight pressure drop in the reactor, the gas expands with an increasing volumetric flow rate. For mathematical modeling of the process, mass and energy balance equations must be written, which are presented below [9–15]:

Crime balance for component ith:

$$\frac{dF_i}{dz} = W S \sum_{j=1}^3 v_{ij} r_j \quad (18)$$

Energy balance:

$$\sum F_i C_{p_i} \frac{dT}{dz} = S \sum_{j=1}^3 r_j (-\Delta H_j) + Q \quad (19)$$

The exergy balance of the system is as follow:

The method for exergoeconomic analysis is similar to an exergoenvironmental analysis (see Table 1). It combines an exergy analysis of the energy conversion system with an economic analysis based on the Total Revenue Requirements (TRR) method, covering the energy conversion system's entire life cycle. Initially, the total capital investment is calculated [13]. The total annual revenue needed is calculated based on economic, financial, operational, and market input parameters [9]. This TRR represents the cost of producing system products and offsets all costs incurred each year of the project's economic life to guarantee an industrial plant. After that, the product's annual variable costs related to investment, operation, maintenance, fueling, and other costs (cost categories) are leveled [16]. This equipment is converted into a series of fixed

payments equivalent to the annuity. Next, by calculating each material and energy flow's specific cost rate, the costs are assigned to the respective exergy flows [17]. Since the exergoeconomic analysis is well established, only the analogy formulas with those used for environmental analysis are presented in Table 2.

### 2.2. Nuclear hydrogen plant

Commercial reactor BN-600 has a storage design [5]. The storage consists of primary cycle components, i.e., the reactor core, intermediate thermal exchangers, and main cooling water pumps. The core's heat is transmitted to the steam generation utilities through three parallel loops of a three-cycle system. The basic performance data of the three independent energy loops of the BN-600 reactor include the following characteristics [5] of 200 MW power production capacity, the steam production capacity of 640 ton/hr, intermediate pressure of 132 bar, and intermediate stream temperature of 505C.

About 50% of commercial hydrogen is currently produced by steam-natural gas through a reform reaction [2]. During the reaction, the vapor-methane mixture's pressure is  $p = 20\text{--}30$  bar, the molar ratio of water to methane is  $m = 2$ , and the reforming reactor temperature is  $T = 700$  °C. Catalysts are also used in the process (Fig. 1).

The commercial steam-natural gas modification consists of two steps. In step 1, steam with a maximum pressure of 30 bar is pre-heated in a chamber with a maximum temperature of 500 °C and mixed with natural gas-fed in a ratio of 2:1. This process requires a maximum of 12% of the supplied natural gas to form steam and heat the streams. In step 2, the prepared gas-vapor mixture is entered into a high-temperature modifier reactor or MSR with a temperature of  $T = 700$  °C, which contains Ni catalysts and hydrogen separation membranes. For this purpose, 13% of the gas supplied must be burned to heat the MSR reactor. Thus, commercial steam natural gas modification involves the consumption of 25% of the gas entered into the modifier by releasing the combustion product (carbon dioxide) into the atmosphere. To achieve high levels of hydrogen production, save a large amount of natural gas, and prevent the release of combustion products into the atmosphere, in this study, it is suggested that to prepare a steam gas mixture, steam generator BN should be used and to increase the temperature Steam gas mixture use electric heaters supplied by BN power system.

### 3. Results and discussion

A mixture of steam and gas is produced in an intermediate-temperature utility. For this purpose, a vapor flow of 177 kg/s with temperature  $T = 500$  °C and pressure  $p = 30$  bar is supplied to the utility from the BN-600 steam generation system's supportive utilities. Simultaneously, a natural gas flow of 77.5 ton/hr with a 35 °C temperature and a pressure of 30 bar is entered into the mixing storage. After leaving the intermediate temperature utility, a mixture of steam and natural gas (MS) with a flow of 227.5 ton/hr

**Table 1**  
The thermodynamical exergy model of this system [15–22].

Description	Equation
Exergy balance	$Ex_Q + \sum m_i ex_i = \sum m_e ex_e + Ex_w + Ex_D$
Exergy equation	$ex = ex_{ph} + ex_{ch}$
Physical exergy	$ex_{ph} = (h_2 - h_1) + T_0(s_2 - s_1)$
Chemical exergy	$ex_{ch}^{mix} = \sum X_i ex_i^{ch} + RT_0 \sum \ln X_i$
Exergy Efficiency	$e = \frac{Ex_P}{Ex_F}$

**Table 2**  
Exergoeconomic formulations [15–22].

Exergoeconomics	
Exergy stream cost rate	$C_j = c_j * E_j$
Component cost balance	$\sum C_{j,k,in} + Z_k = \sum C_{j,k,out}$
Component-related cost rate	$Z_k = Z_k^{CL} + Z_k^{OM}$
Component relative cost difference	$r_k = \frac{C_{P,k}}{C_{P,k} + C_{F,k}}$

with a temperature of 505 °C and pressure of 30 bar enters the high-temperature MSR reactor utility (see results in Tables 3–5).

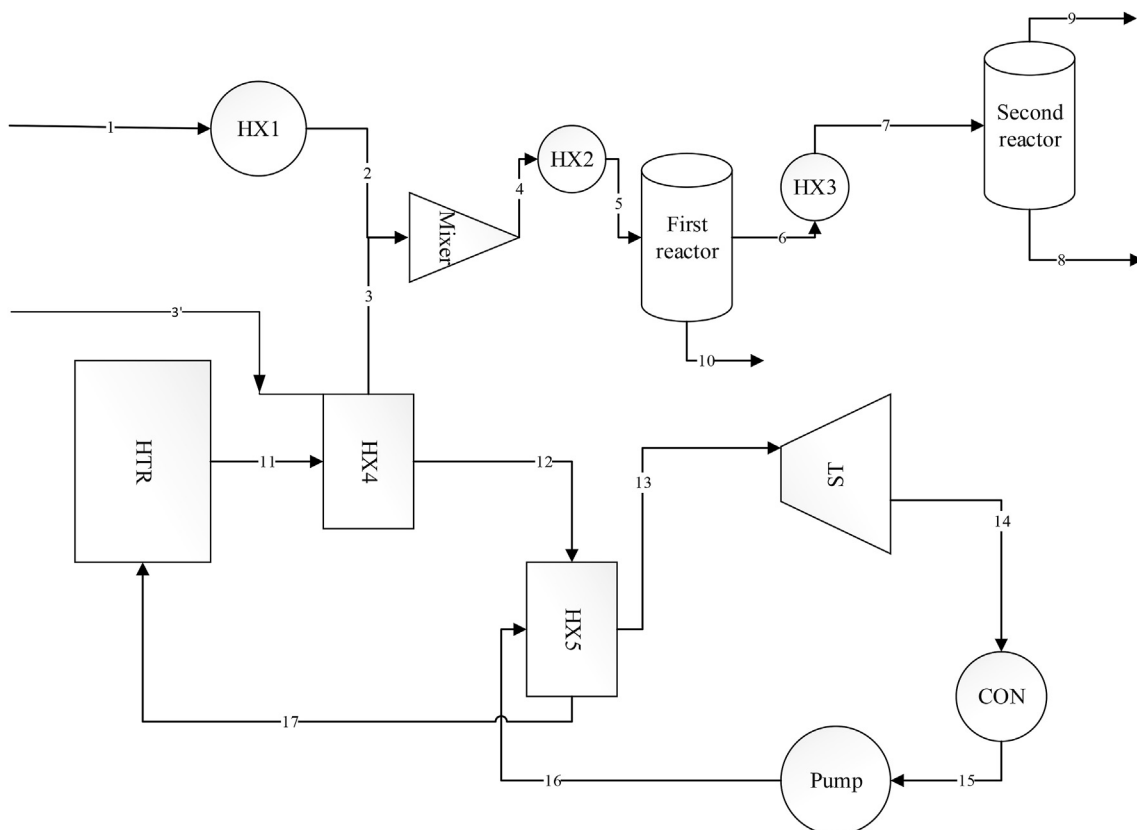
The high-temperature utility is a chemical ER reactor in which the methane-steam mixture is converted to a synthesis mix gas (CO + H<sub>2</sub>) at 700 °C in the presence of Ni catalysts. In the flow stream and along the ER reactor column, CO is partially reformed to carbon dioxide by producing excess hydrogen in the aqueous environment. Besides, in the reaction of natural gas splitting into synthesis mix gas and transferring CO to CO<sub>2</sub>, the hydrogen formed is released by diffusion from Ni membranes inside the utility. The amount of hydrogen flow out of the shaving chamber may reach 79.2 ton/hr or more. The gas-vapor mixture's residue, consisting of natural gas, CO, CO<sub>2</sub>, and hydrogen residues, does not split and leaves the chemical reforming reactor at a 227.5 ton/hr flow rate. The chemical modification reactor's residues are heated by heating to a temperature of 550 °C and enter a second ER reactor, which enhances hydrogen production by reforming CO to CO<sub>2</sub> and generates more H<sub>2</sub> reactor enhances hydrogen production to 144.6 ton/hr. In practice, the possibility of heating and a mixture of gas and steam by electrical energy up to a temperature of about 700 °C has been effectively determined by research results at the German EVA II facility in the 1980s [7].

Therefore, it is expected that the use of steam from a fast-cooled reactor energy ring with sodium BN-600 and the electrical energy from the adjacent independent cycle will create the conditions for efficient steam correction in methane flow of 88.5 kg/s, causing a hydrogen flow of about 56 kg/s. Hydrogen production based on the proposed technology will lead to commercial losses due to the potential cost of electricity generated in the two BN-600 cycles and the natural gas supply cost. BN-600 power circuits generate electricity 0.061\$ per kilowatt-hour. Given that the average retail price of electricity in Iran is 0.05\$ per kilowatt-hour, the cost of electricity generated for one hour in the two cycles, BN-600, reaches 6000\$.

The hourly rate of natural gas fed to the modifier will normally be 3.2e+5 cubic meters. According to the retail price of natural gas 0.01\$ per cubic meter, the supplied gas's hourly cost will be 3200\$. Under these conditions, 144.6 ton/hr hydrogen is produced. Therefore, the cost of preparing and additional heating of the gas-steam mixture to produce one cubic meter of natural hydrogen based on the BN-600 reactor will not be less than 0.03\$. The length of the simulated reactor is 60 m. The operating pressure of the reactor is 30 bar. The input ratio of methane to steam is 0.5. The reactor surface is assumed to be 27 m<sup>2</sup>. In modeling, the effect of different parameters on the reactor behavior is investigated. Figs. 2 and 3 show how the reactor concentration and temperature change during the reactor at a constant temperature of 1100 K for the shell.

Fig. 4 shows the conversion rate of methane during the reactor for different shell temperatures and a constant inlet temperature of 700 K for feed. Fig. 3 shows the conversion rate of methane during the reactor for different feed inlet temperatures and the shell's constant 1000 K temperature.

The results show that with increasing feed inlet temperature and reactor temperature, the reactor's conversion rate increases. This conversion is due to the calorific value of the reaction. In



**Fig. 1.** Schematics of nuclear power and hydrogen combined plant.

**Table 3**  
Energy analysis of hydrogen generation using HTR technology.

unit	T	P	S	Component molar fraction					Mass flow
	C	bar	kJ/kgmol.k	H <sub>2</sub> O	H <sub>2</sub>	CO <sub>2</sub>	CH <sub>4</sub>	CO	Kg/h
1	25	30	154.1	0.0000	0.0000	0.0000	1.0000	0.0000	77,483
2	495	30	199.1	0.0000	0.0000	0.0000	1.0000	0.0000	77,483
3	505.5	30	192.3	1.0000	0.0000	0.0000	0.0000	0.0000	150,000
3'	25	30	7.569	1.0000	0.0000	0.0000	0.0000	0.0000	150,000
4	503	30	203.5	0.6331	0.0000	0.0000	0.3669	0.0000	227,483
5	700	30	137.4	0.6331	0.0000	0.0000	0.3669	0.0000	227,483
6	405.9	30	154.5	0.2406	0.0000	0.0000	0.3812	0.3746	148,256
7	657.8	30	167.7	0.2406	0.0000	0.0000	0.3812	0.3746	148,255
8	377.6	30	186.1	0.0102	0.9800	0.0098	0.0000	0.0000	65,410
9	377.6	30	147.4	0.1708	0.0000	0.8131	0.0156	0.0005	83,023
10	405.9	30	166.5	0.0035	0.9968	0.0000	0.0000	0.0007	79,227
11	560	132	179.7	1.0000	0.0000	0.0000	0.0000	0.0000	620,000
12	445	132	111.9	1.0000	0.0000	0.0000	0.0000	0.0000	620,000
13	410	57	119.0	1.0000	0.0000	0.0000	0.0000	0.0000	508,378
14	39.42	0.012	145.7	1.0000	0.0000	0.0000	0.0000	0.0000	508,378
15	39.42	0.012	12.52	1.0000	0.0000	0.0000	0.0000	0.0000	508,378
16	44	57	12.54	1.0000	0.0000	0.0000	0.0000	0.0000	508,378
17	140	132	31.99	1.0000	0.0000	0.0000	0.0000	0.0000	620,000

**Table 4**  
Exergy analysis of hydrogen generation using HTR technology.

Component	E <sub>D</sub> (kW)	e (%)
R-1	14508.91	47.9
R-2	12896.646	53.2
HX1	25279.523	41.3
HX2	25279.523	39.2
HX3	18796.619	45.1
HX4	8912.278	57.2
HX5	8912.278	49.1
CON	15938.517	78.5
Pump	1265.7077	87.1
ST	7300.3075	76.2
MIX-1	155.8359	99.9
ε <sub>reform</sub>		46.4
ε <sub>rankine</sub>		73.1
ε <sub>total</sub>		78.5

superheated reactions [23], high temperatures cause the conversion rate to rise. But due to conditions and limitations, the temperature can not be raised above a certain level (see Fig. 5). It should be noted that the use of natural gas to prepare steam and heat a mixture of steam and natural gas reforming process requires about 0.053\$ per cubic meter of hydrogen. In this case, the production of 500 million cubic meters of natural hydrogen leads to the release of about 130,000 tons of carbon dioxide, which is lesser than 25% of the annual emission of carbon dioxide emitted from burning an equal amount of natural gas in the combustion of hydrocarbon fuels

**Table 5**  
Exergoeconomic analysis of hydrogen generation using HTR technology.

	PEC (K\$)	Z <sup>CI</sup> (\$/hr)	Z <sup>OM</sup> (\$/hr)	Z (\$/hr)	CF(\$/GJ)	CP(\$/GJ)	CD(\$/GJ)	r(%)
HX1	4007012.3	261.6867	6.534	268.2207	101.24037	103.56885	2.32848	0.494315
HX2	2608472.8	169.5573	4.2471	173.8044	101.250072	103.627062	2.37699	0.494199
HX3	4172012.3	271.161	6.8607	278.0217	75.956958	78.469776	2.512818	0.491864
HX4	5525012.3	363.198	8.547	371.745	72.52245	76.927158	4.404708	0.485264
HX5	4601012.3	304.161	6.864	311.025	72.52245	76.927158	4.404708	0.485264
CON	3680809.8	243.3288	5.4912	248.82	75.956958	78.469776	2.512818	0.491864
ST	8332529.2	541.6686	13.7214	555.39	11.574486	19.132344	7.557858	0.376935
Pump	152046.23	9.8836551	0.2505789	10.134234	19.132344	19.345788	0.213444	0.497226
R-1	1809498.2	117.612	2.9403	120.5523	15.3058752	15.4766304	0.170755	0.497226
R-2	2449696.9	159.1029	3.9204	163.0233	12.24470016	12.38130432	0.136604	0.497226
Mixer	364472.77	37.5573	4.2471	173.8044	1.224470016	1.238130432	0.01366	0.497226

[8]. The use of steam from a BN-600 sodium-cooled-rapid-reactor electricity production cycle and electricity from an independent cycle adjacent to the same reactor is expected to generate about 500 million cubic meters of natural hydrogen per year, which is about 0.1% of global hydrogen production is annual [2]. In this case, considering the cost of producing hydrogen more than the cost of producing it by traditional commercial technology, about 390,000 tons of carbon emission per year will be prevented from being released into the atmosphere.

#### 4. Conclusion

Hydrogen is a clean fuel and a source of new and renewable energy. Hydrogen production using the methane-steam reforming natural gas process is one of the most common and economical hydrogen production methods globally. The steam reforming process in the presence of Nickel catalyst (Ni) is done at high temperature and pressure. Temperature between 900 and 1000 K and a pressure of 30 atm which is due to the reaction of methane with water vapor, synthetic gas is produced in addition to gas synthesis due to the presence of impurities in the natural gas inlet feed that causes unwanted compounds to be produced which makes it more difficult to separate and purify hydrogen from the mixture of these gases due to the high temperature and pressure of the process, the presence of impurities in the input feed, changes in the composition of the input feed to the process and the production of impurities with hydrogen and this process are associated with several

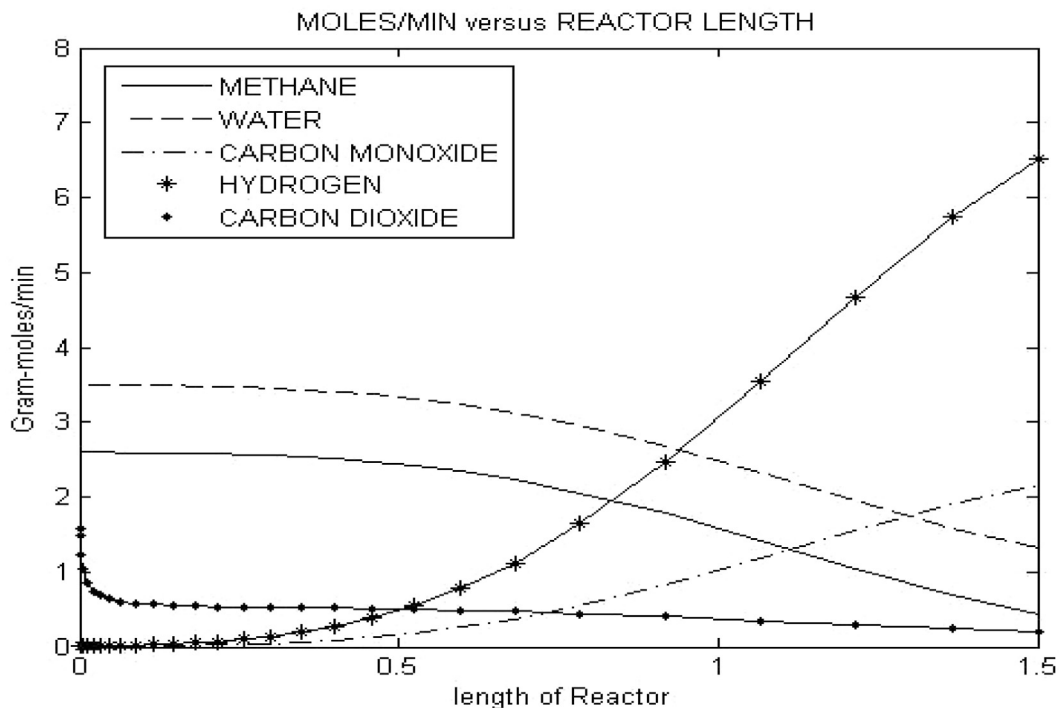


Fig. 2. Material concentration along the reactor at 1100 K shell temperature [dimentionless length (fracture of 60 m for this case study)].

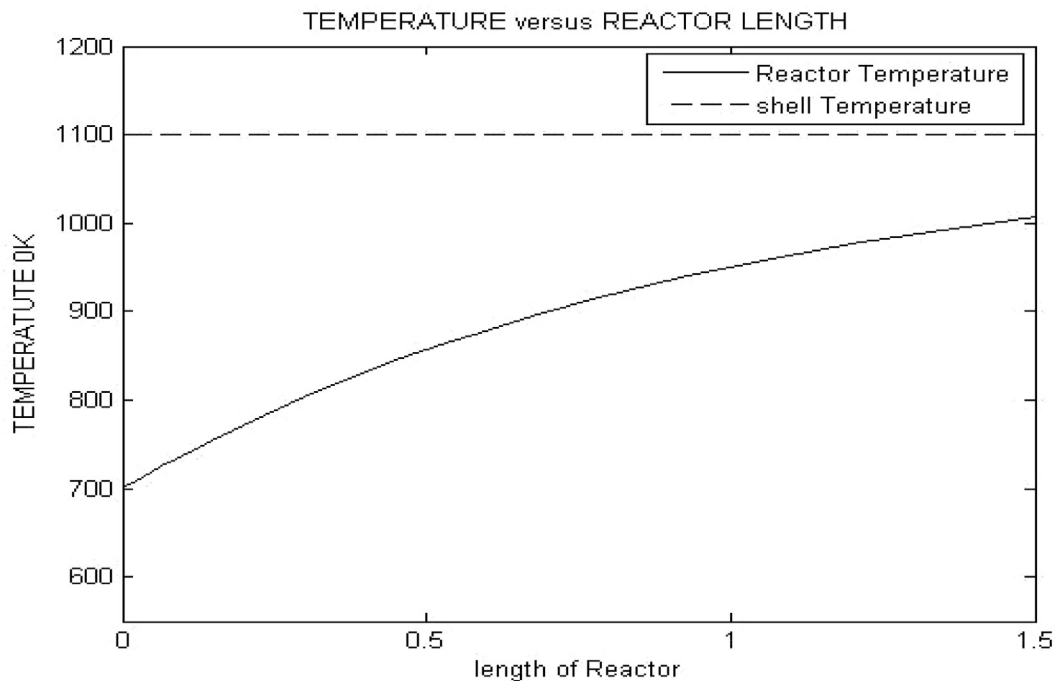


Fig. 3. The temperature during the reactor at a constant temperature of 1100 K shell [dimentionless length (fracture of 60 m for this case study)].

problems and challenges such as catalyst deactivation, equipment corrosion. In this paper, the steam methane reforming process combined with nuclear SMRs as a novel method of hydrogen production. The cogeneration of hydrogen and electricity, and hot water, which can be used in the residential sector, makes this plant

a very energy-efficient technology, and the nuclear MSR process causes a 75% decrease in the carbon emission compared to the fossil fuel to electricity processes and 45% decrease compared to the conventional MSR plants due to their higher life cycle carbon emission.



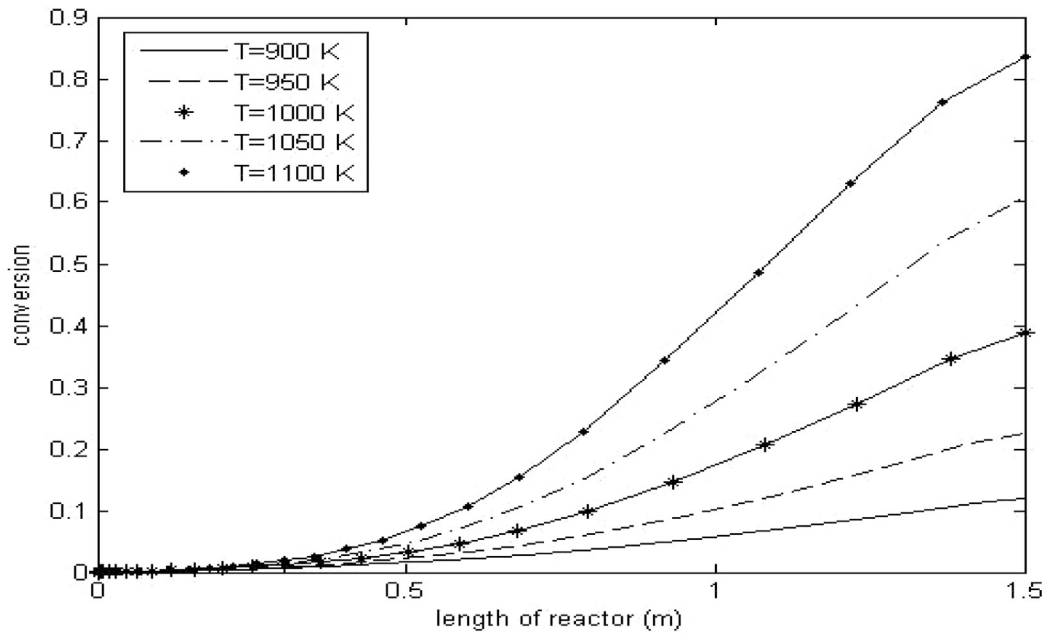


Fig. 4. Methane conversion rate during the reactor at a constant inlet temperature of 700 K for feed [dimensionless length (fracture of 60 m for this case study)].

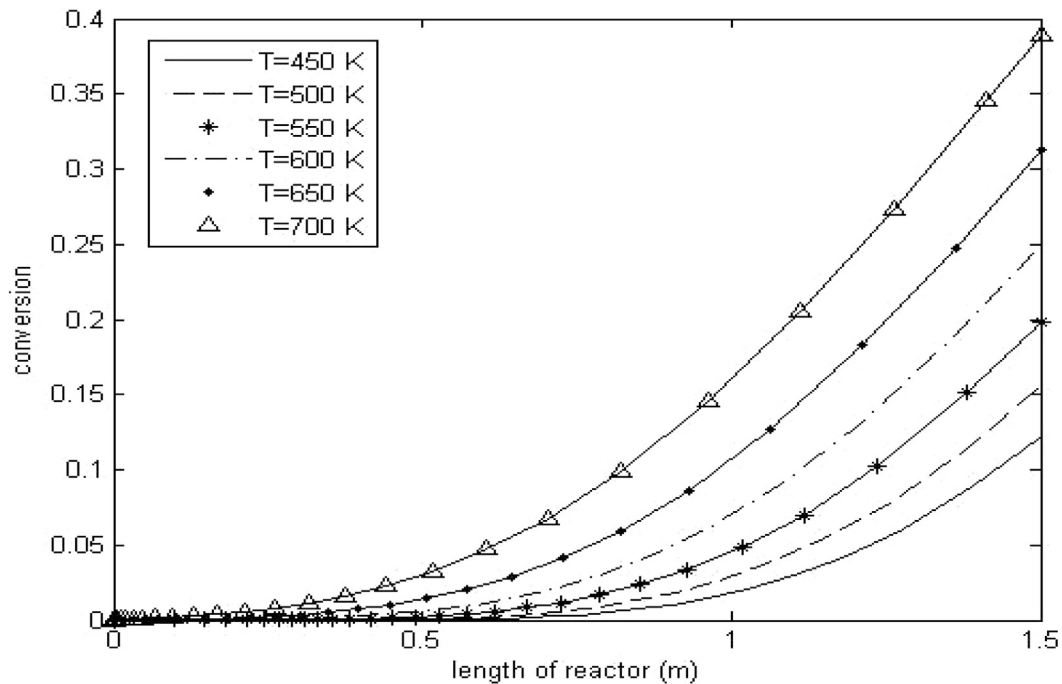


Fig. 5. Methane conversion rate during the reactor for a constant temperature of 1000 K for the shell [dimensionless length (fracture of 60 m for this case study)].

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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