

Hydrogen Production by Thermal Decomposition of Natural Gas

Second Report : Results of the Continuous Operation

ITO Takamasa : Doctor of Engineering, Energy Conversion Department, Technology Platform Center, Corporate Research and Development Division, IHI Corporation

SAWANO Sota : Energy Conversion Department, Technology Platform Center, Corporate Research and Development Division, IHI Corporation

MIYAGI Hiroya : Energy Conversion Department, Technology Platform Center, Corporate Research and Development Division, IHI Corporation

KUMAGAI Yasuzo : Energy Conversion Department, Technology Platform Center, Corporate Research and Development Division, IHI Corporation

Hydrogen production by thermal decomposition of natural gas is expected as the key technology to achieve both low cost and low CO₂ emissions since the energy consumption in the production process is lower than that of conventional technologies and the carbon in the natural gas is collected in the solid phase. In the previous report⁽¹⁾, the technical concept adapting the fluidized bed for the reactor was introduced. After then, the continuous operation over 24 hours with new experimental equipment (10 kg-H₂/d) was achieved. This report informs the results of the continuous operation.

1. Introduction

In the transition toward a decarbonized society, hydrogen is expected to play a key role because it does not emit CO₂ when burned. However, recent policy changes in the United States, including the reduction of tax incentives for hydrogen-related projects under the Inflation Reduction Act (IRA), established in 2022, have increased the need for cost-effective hydrogen production. Under these circumstances, IHI has been developing hydrogen production technology based on the thermal decomposition of natural gas, whose main component is methane and which has long been used as a primary energy source such as city gas. This process uses less than one-seventh the renewable energy of water electrolysis and enables hydrogen production with reduced CO₂ emissions.

In the previous report⁽¹⁾, the advantages and disadvantages of the thermal decomposition process were discussed in comparison with conventional hydrogen production technologies such as steam methane reforming and water electrolysis. A summary of this comparison can be found in

Table 1. Fundamental experimental results using iron ore and a fluidized-bed reactor were also presented in the previous report.

In this report, continuous operation for more than 24 hours was achieved using a newly developed experimental system with a hydrogen production capacity of 10 kg-H₂/d. Stable hydrogen production was successfully demonstrated, and results are reported in detail. In addition, prospects for commercialization are discussed.

2. Hydrogen production by thermal decomposition of natural gas developed at IHI

First, the specifications of the hydrogen production plant for commercialization are outlined in **Fig. 1**. This technology uses a fluidized-bed reactor to enable large-scale operation and aims to serve as an alternative to steam methane reforming, which is the current mainstream method for hydrogen production. The final target of this project is a plant with a hydrogen production capacity of 100 t-H₂/d. The values in the figure represent the estimated mass and energy

Table 1 Representative technologies for the hydrogen production

Name	Thermochemical equation	Characteristics
Hydrogen production by steam reforming of natural gas	$\text{CH}_4 + 2\text{H}_2\text{O} = 4\text{H}_2 + \text{CO}_2$ -253 kJ/mol (63 kJ/mol-H ₂)	(Advantage) High hydrogen yield per 1 mol of methane. (Disadvantage) Necessity of collecting, storing, or utilizing CO ₂ .
Hydrogen production by water electrolysis	$\text{H}_2\text{O} = \text{H}_2 + 0.5\text{O}_2$ -286 kJ/mol (286 kJ/mol-H ₂)	(Advantage) CO ₂ emissions are zero if the electricity derived from renewable sources is used. (Disadvantage) High energy consumption per 1 mol of hydrogen produced.
Hydrogen production by thermal decomposition of natural gas	$\text{CH}_4 = 2\text{H}_2 + \text{C}$ -75 kJ/mol (38 kJ/mol-H ₂)	(Advantage) Least energy consumption per 1 mol of hydrogen produced. Solid carbon can be collected. (Disadvantage) Lower hydrogen yield per 1 mol of methane compared to steam reforming.

(Notes) - Figures inside parentheses in the thermochemical equations represent energy input per 1 mol of hydrogen to be produced.
- This table can be found in Reference (1).

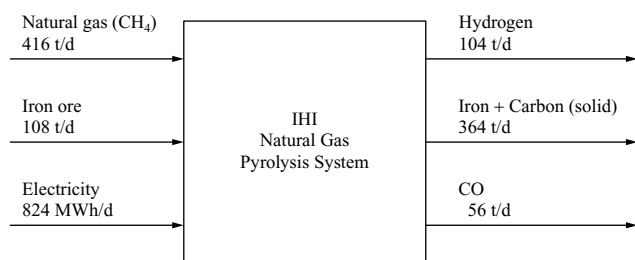


Fig. 1 Hydrogen production by the thermal decomposition of natural gas by IHI

balance of the system. The energy balance includes not only the energy required for methane pyrolysis but also heat for preheating feed, reducing iron ore, and recovering heat.

3. Continuous operation with an experimental system (10 kg-H₂/d)

We demonstrated the continuous operation of an experimental system (10 kg-H₂/d). **Figure 2** shows the configuration of the system. The main modification from the previous study is the addition of a feed system for iron ore at the top of the reactor. In addition, a discharge system for the carbon byproduct deposited on iron was installed at the bottom of the reactor. These modifications enable continuous feeding of iron ore and removal of the produced carbon, allowing stable and continuous hydrogen production.

3.1 Experimental conditions

Table 2 summarizes a typical operating condition for continuous operation. City gas 13A was used as the feed gas, and the iron ore described in the previous report was employed as the catalyst. The reactor was heated by an

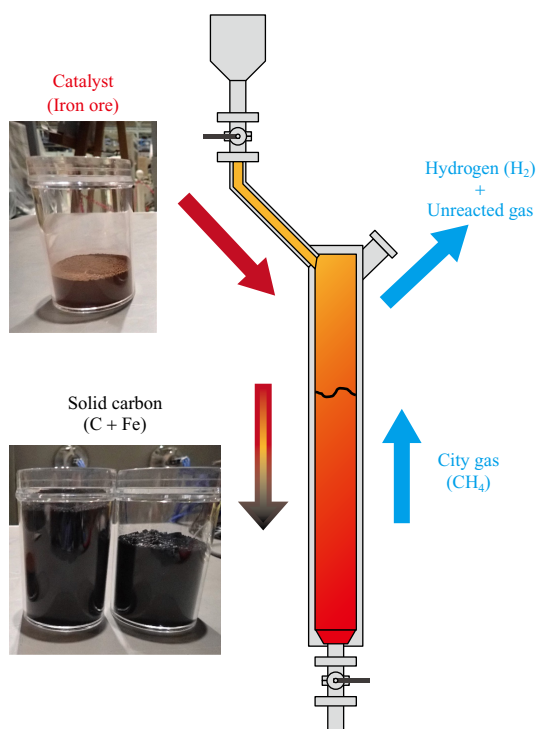


Fig. 2 Experimental equipment for the hydrogen production by the thermal decomposition of natural gas

Table 2 Experimental condition with the prototype model

Item	Condition
Feed gas	City gas 13A
Catalyst	Iron ore
Bed temperature	900 to 950°C

electric heater, and the temperature was controlled between the range of 900 to 950°C.

For reference, the composition of city gas 13A⁽²⁾ reported by the gas supplier is shown in **Table 3**. The gas mainly consists of alkanes with carbon numbers up to four. Since higher carbon content leads to increased carbon formation per unit of hydrogen produced, the consumption of iron ore used as the catalyst is expected to increase accordingly. City gas 13A was used in this study, and other gas compositions will be investigated in future work.

The iron ore used as a catalyst in this report is the same as that described in the previous report, and its composition is shown in **Table 4**. The iron content is 67.3 wt%, while silicon (Si), which can adversely affect brittleness and workability during steelmaking, is present at 0.6 wt%, and phosphorus (P), which is known to cause cold brittleness and reduce ductility and toughness, is present at 0.1 wt%. Based on these values, the iron ore used in this study can be considered of relatively high quality for steelmaking. Although this was the only type of iron ore used in this study, the effect of different iron ores, including variations in iron content, will be investigated in future work.

3.2 Results of continuous operation

Representative results of the gas composition and carbon characteristics obtained during continuous operation are presented as below.

3.2.1 Composition of product gas during continuous operation

Figure 3 shows the major components of the product gas. The gas mainly consists of hydrogen (H₂), carbon monoxide (CO), and unreacted methane (CH₄). Periodic decreases in

Table 3 Properties of city gas 13A

Composition	Unit	Value
CH ₄ (Methane)	vol%	89.6
C ₂ H ₆ (Ethane)		5.6
C ₃ H ₈ (Propane)		3.4
C ₄ H ₁₀ (Butane)		1.4

Table 4 Properties of the iron ore used

Element	Unit	Value
Fe	wt%	67.3
Al		0.6
Si		0.6
Mn		0.1
P		0.1
Ti		0.1
Others		31.2

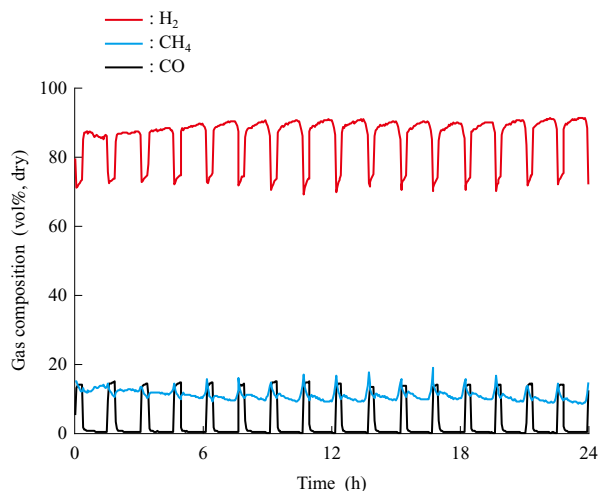
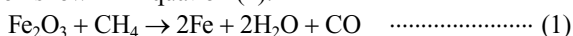


Fig. 3 Major components in the product gas

H₂ concentration accompanied by increases in CO concentration are observed. This behavior is attributed to the intermittent feeding of iron ore catalyst. When iron ore is supplied, it reacts with methane through the reduction reaction shown in Equation (1).



The methane which is the feed for hydrogen is consumed to reduce the iron ore, forming CO and temporarily decreasing H₂ concentration. Once the reduction reaction is completed, the CO concentration decreases and the H₂ concentration increases again. As shown in Fig. 3, the average H₂ concentration exceeds 85%, which is higher than the theoretical value of 80% for steam methane reforming. This high H₂ concentration is one of the advantages of the thermal decomposition process and is expected to reduce the burden of downstream purification in hydrogen utilization.

Figure 4 shows the components with a carbon number of two or higher in the product gas. These components are mainly ethane (C₂H₆) and ethylene (C₂H₄), and their concentrations remain below 0.2 vol% at most. As the reactor

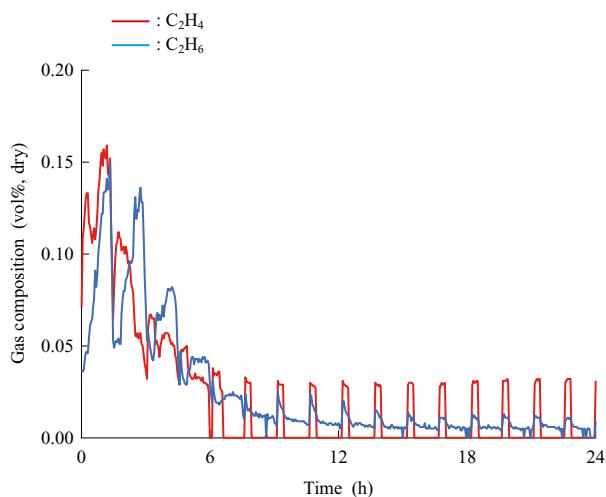
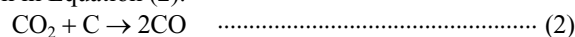


Fig. 4 Minor components in the product gas

temperature increases, their concentrations are suppressed to below 0.04 vol%. No components with a carbon number of three or higher were detected. These results suggest that the formation of heavy hydrocarbons, such as tar, is minimal in the gas produced by the pyrolysis process.

Another notable feature is that almost no CO₂ was detected throughout the experiments. This is likely due to the large amount of solid carbon present in the reactor. Even if CO₂ is formed, it is rapidly converted into CO via the reaction shown in Equation (2).



3.2.2 Solid carbon byproduct

Figure 5 shows the carbon content of the carbon byproduct. The values were measured by elemental analysis using samples collected every 6 hours. The carbon content remained stable at around 75 wt%. Although not discussed in detail in this report, it was also observed that as the overall temperature of the system gradually increased over time, the density of carbon byproducts also increased. Potential applications of the carbon byproduct include use as a substitute for activated carbon, as a paving material for roads, as a soil additive for agricultural land, and as a carburizing agent in casting.

3.2.3 CO₂ emissions

Figure 6 shows the CO₂ emissions per unit of hydrogen produced. As described above, the carbon-containing gases observed during the experiments consisted mainly of CO, and CO₂ formation was negligible. Figure 6 shows the case in which the detected CO is converted into an equivalent amount of CO₂ for evaluation. As shown in Fig. 3, CO is mainly generated when iron ore is supplied. This corresponds to approximately 4.0 to 5.0 kg-CO₂/kg-H₂. After the reduction of iron ore is completed, CO emissions become negligible. On a time-averaged basis, the CO₂ emissions are approximately 1.0 kg-CO₂/kg-H₂. This value is about one-tenth of that of conventional steam methane reforming. In the future, the produced H₂ may be used to reduce iron ore to further lower CO₂ emissions.

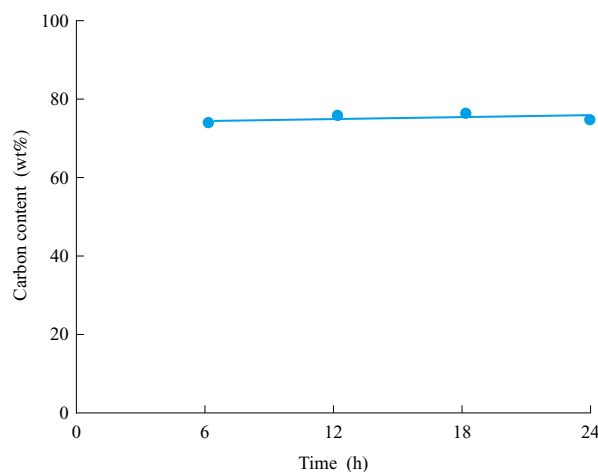


Fig. 5 Carbon content in the byproduct

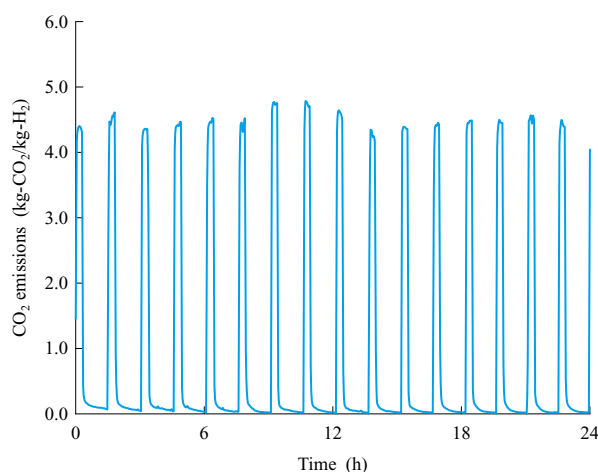


Fig. 6 CO₂ emissions of the hydrogen production by thermal decomposition of natural gas by IHI

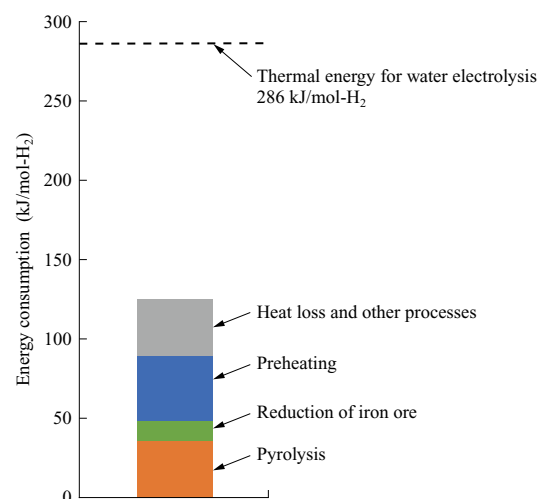


Fig. 7 Energy consumption of the 10 kg-H₂/d pilot system

Development phase		Hydrogen production	FY2023 – 2025	FY2026 – 2030
1	Lab-scale test	10 (g-H ₂ /h)		
2	Prototype system	10 (kg-H ₂ /d)		
3	Technology demonstrator	Several (t-H ₂ /d)		
4	Commercialization-ready	—		

Fig. 8 Schedule towards commercialization

3.2.4 Energy consumption

Figure 7 shows the energy consumption per unit of hydrogen produced. The total energy consumption of the experimental system (10 kg-H₂/d) is 126 kJ/mol-H₂, which is less than half of the theoretical value for water electrolysis (286 kJ/mol-H₂). Of this total, 49 kJ/mol-H₂ is required for methane pyrolysis and iron ore reduction, representing the theoretical minimum energy. The remaining 77 kJ/mol-H₂ is attributed to feed preheating, heat loss, and other factors, indicating room for further improvement in the system design. In the future, scaling up the system and improving heat recovery are expected to reduce the energy required for preheating and heat loss to less than one-third of the current level. This highlights the potential of the process for low-energy hydrogen production.

4. Prospects for commercialization

Figure 8 shows the schedule toward commercialization. In future work, further improvements in hydrogen concentration will be pursued using the experimental system described in this report. At the same time, efforts will be made to reduce both capital expenditure (CAPEX) and operating expenditure (OPEX) based on experimental data. By fiscal year 2028, a technology demonstrator using a several t-H₂/d system is planned. Completion of market introduction preparations is targeted for the end of fiscal year 2028.

5. Conclusion

This report presented the current development status of hydrogen production technology based on the thermal

decomposition of natural gas. Continuous operation was achieved by installing a supply system for the iron ore catalyst and a discharge system for the carbon byproduct in the experimental system (10 kg-H₂/d) reported previously. Under continuous operation exceeding 24 hours, a hydrogen concentration of approximately 85% was maintained on average, while CO₂ emissions were reduced to around 1.0 kg-CO₂/kg-H₂. In addition, the total energy consumption of the system was successfully reduced to 126 kJ/mol-H₂, and further improvements are expected through system scale-up. Hydrogen production by thermal decomposition has been expected to enable lower production costs due to its inherently low energy requirement compared with conventional technologies. The present results demonstrate that such performance is technically feasible.

In the transition period from fossil fuels to renewable energy, IHI considers hydrogen production by thermal decomposition of natural gas to be a meaningful technology that can contribute to the widespread use of hydrogen and ammonia, and we will continue to work toward its commercialization.

REFERENCES

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