Feasibility Assessment of Hydrogen Production Capability through a Passive Molten Salt Fast Reactor with SCO2 Cycle and High Temperature Steam Electrolysis

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1. Introduction

The global pursuit of reliable, low-carbon energy sources has renewed interest in alternative energy technologies, particularly nuclear power. Generation IV reactors are considered a promising solution due to their enhanced efficiency, inherent safety features, and high-temperature operation capabilities [1].

Molten salt reactors (MSRs) represent a next-generation reactor concept that utilizes molten salt as the fuel and primary coolant. Due to its high melting and boiling points, molten salt enables low-pressure operation and exhibits chemical stability, significantly reducing the risk of pressurization-related accidents compared to light water reactors.

As one of the next-generation small modular reactors, the Passive Molten Salt Fast Reactor (PMFR), is currently under development in the Republic of Korea. The PMFR is being developed by the Research Center for the Development of Innovative Original Technology for a Severe Accident-Free Multi-Purpose Long-Lifetime Small Modular Molten Salt Reactor (I-SAFE-MSR) [2, 3]. The PMFR is a chloride-based reactor with a long-lifetime fast-spectrum and a thermal power output of 300 MWt. It employs natural circulation within the reactor loop, thereby eliminating the need for mechanical pumps. Figure 1 presents a schematic of the PMFR system.

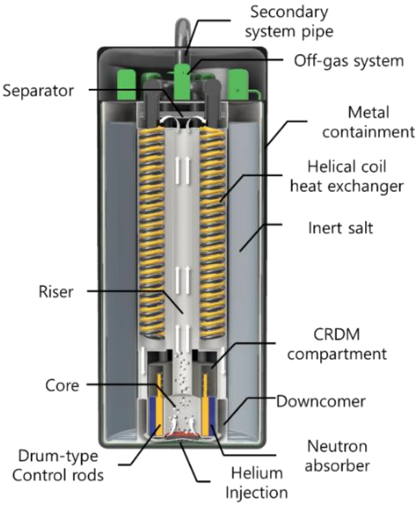

Figure 1 Schematic diagram of PMFR system [2,3]

Potential applications of the PMFR include hydrogen production for clean energy supply. The PMFR offers several advantages for hydrogen production, including ease of on-site installation and extremely low radiation risk. Furthermore, its high operating temperatures enable high power conversion efficiency by a supercritical CO_2 (SCO_2) power conversion cycle. Despite these advantages, the hydrogen production potential of PMFR remains largely unexplored.

This paper presents a preliminary evaluation of hydrogen production using the PMFR. A power conversion system and a hydrogen production system tailored to the primary characteristics of the PMFR are proposed, accompanied by a thermodynamic analysis.

2. Hydrogen production technologies for PMFR

Hydrogen production technologies can be broadly categorized into three methods: hydrocarbon reforming, thermochemical water splitting, and water electrolysis [4]. Among these, hydrocarbon reforming is economically viable but not carbon-neutral, while thermochemical water splitting requires significantly high operating temperatures over 950°C than those achievable with molten salt reactors, limiting its practical implementation.

From these aspects, two hydrogen production methods suitable for PMFR applications have been selected: low-temperature water electrolysis (LTWE) and high-temperature steam electrolysis (HTSE). A methodology has been established to evaluate hydrogen production potential for both methods.

Figure 2 shows the schematics of these electrolysis cells. LTWE involves the direct decomposition of water molecules using electrical energy to produce hydrogen and oxygen. This is currently the only commercially viable green hydrogen production method. Electrolysis technologies are categorized into atmospheric or pressurized alkaline water electrolysis (AWE) and membrane electrolysis, primarily using proton exchange membranes (PEM) [5].

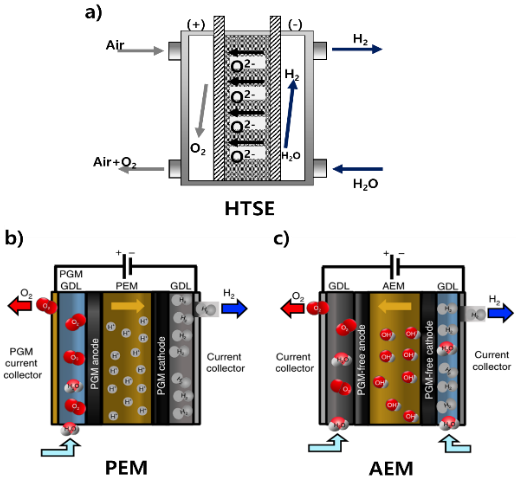

Figure 2 Schematic of a) high temperature steam electrolysis cell and low-temperature water electrolysis cells: b) proton exchange membranes c) alkaline water electrolysis [5]

HTSE differs from LTWE in that it heats water to high-temperature steam at 700 – 900°C before electrolysis. In the electrolysis process, the energy corresponding to the Gibbs free energy change must be supplied as electrical energy. As the operating temperature increases, the required Gibbs free energy decreases, reducing electricity consumption and allowing more hydrogen to be produced for the same electrical input. However, additional energy is required to heat water from ambient temperature to high-temperature steam, and this energy requirement must also be considered in efficiency evaluations.

3. Power conversion and hydrogen production system

We previously developed and validated an analysis model for the SCO_2 recompression cycle [8]. The SCO_2 recompression cycle improves upon the simple recuperated SCO_2 cycle by incorporating an additional compression process. In a simple recuperated cycle, the SCO_2 exiting the turbine is cooled through a recuperator and a precooler before being recompressed. However, due to variations in specific heat with pressure, a pinch-point problem arises in the recuperator, limiting heat recovery efficiency. The recompression cycle mitigates this issue by splitting the SCO_2 mass flow, compressing a portion of the less-cooled SCO_2 separately. This approach reduces the mass flow rate of the colder stream, which has a relatively higher specific heat, thereby improving overall cycle performance. Table 1 summarizes the key parameters for the SCO_2 cycle components.

Table 1. Parameters of the SCO_2 recompression cycle.

Parameters	**Values**
Isentropic efficiency of compressors	0.85
Isentropic efficiency of turbine	0.92
Minimum pitch point temperature differences of the heat exchangers	10 °C
Compressor inlet temperature	32 °C
Turbine inlet pressure	25 MPa

Figure 3 shows the schematic of LTWE system coupled with PMFR and its power conversion cycle. The hydrogen production capacity of PMFR through LTWE can be estimated by multiplying the expected electricity output of PMFR by the unit efficiency of the electrolysis device. Based on the higher heating value of hydrogen (285.8 kJ/mol) and the minimum energy consumption per unit of hydrogen production, the expected efficiency of LTWE can be estimated to be approximately 88% [4-6].

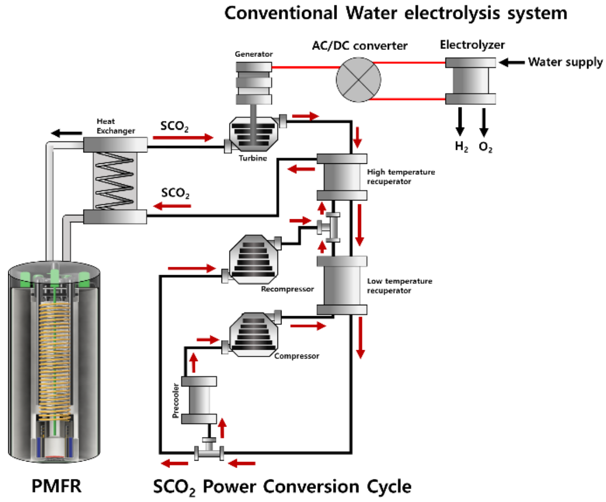

Figure 3 Layout of LTWE system coupled with SCO_2 cycle

Unlike LTWE, HTSE involves heating water and steam to 700–900°C before electrolysis. In this process, the energy required for electrolysis is determined by the Gibbs free energy change, which is supplied in the form of electrical energy. As the operating temperature increases, the Gibbs free energy requirement decreases, resulting in lower electricity consumption and higher hydrogen production for the same electrical input. However, additional energy is required to heat water from ambient temperature to high-temperature steam, and this energy demand must be considered in efficiency evaluations.

HTSE remains under development, with ongoing research focused on various electrode materials and electrolytes. The operating temperature and electrolysis efficiency vary depending on the composition of the HTSE cell. Therefore, instead of defining fixed design parameters, this paper proposes a thermodynamic evaluation methodology that incorporates 'HTSE operating temperature' and 'HTSE efficiency' as input variables.

To ensure steam reaches the required operating temperature of the HTSE cell, a steam heater powered by the generator is installed upstream of the cell. Additionally, since the hydrogen and oxygen produced in the HTSE process remain at high temperatures, a recuperator is implemented to recover heat from these high-temperature gases. In the recuperator, hydrogen and oxygen exchange heat with room-temperature water, generating steam. The resulting steam is then combined with steam from the steam generator before entering the steam heater. Figure 4 shows a schematic of the HTSE system including these components.

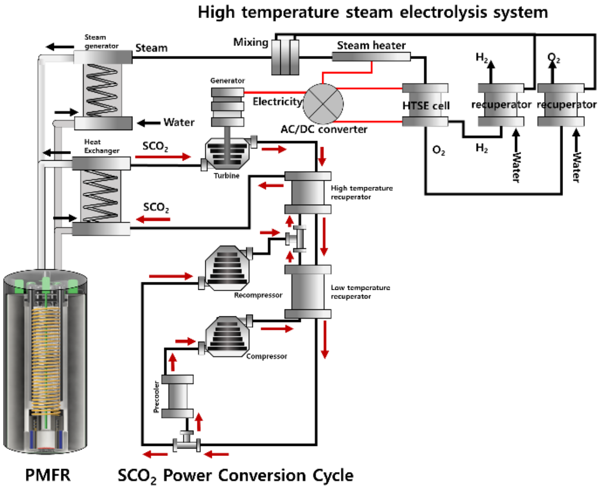

Figure 4 Layout of HTES electrolysis system coupled with SCO$_2$ cycle, steam generators and heat recovery units

All recuperators were calculated according to the temperature difference conditions in Table 1. In addition, the heat generation of the steam heater was assumed to be equal to electric power consumption. In the HTSE cell, 75% of the applied electric power was assumed to be converted to Gibbs free energy, and the remaining 15% was modeled as heat generation in the cell. The heat absorption due to the hydrogen production reaction was calculated as the change in the thermal energy of hydrogen and oxygen generated in the cell, i.e., temperature. Above interpretation methodology was implemented by using MATLAB, and case analysis was performed with an 'HTSE operating temperature' range of 700–900°C.

4. Results of hydrogen production capacity evaluation

In our previous study, we analyzed a power conversion system incorporating a helical coil heat exchanger, which has been identified as a suitable option for PMFR [3]. Figure 5 presents the secondary salt outlet temperature and power conversion efficiency of the PMFR from that study. These results were utilized as input parameters in this preliminary evaluation of hydrogen production capacity.

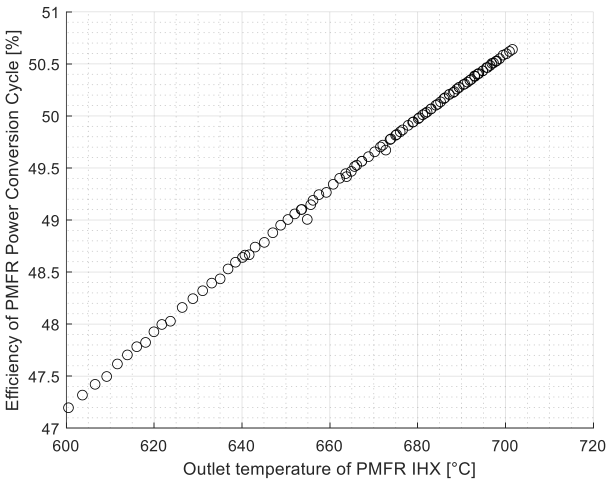

Figure 5 the outlet temperature range of PMFR and efficiency [3]

Figure 6 shows the hydrogen production rates of LTWE and HTSE for PMFR. The hydrogen production rates were calculated to be 3,739.4 - 4,012.2 kg/h in LTWE and 6,406.0 - 6,588.5 kg/h in HTSE. This indicates that the hydrogen production rate can be improved by about 70% in the same power reactor using the HTSE method. Therefore, in high-temperature reactors such as PMFR, it is advantageous from the perspective of nuclear energy utilization to use HTSE instead of the existing low-temperature electrolysis.

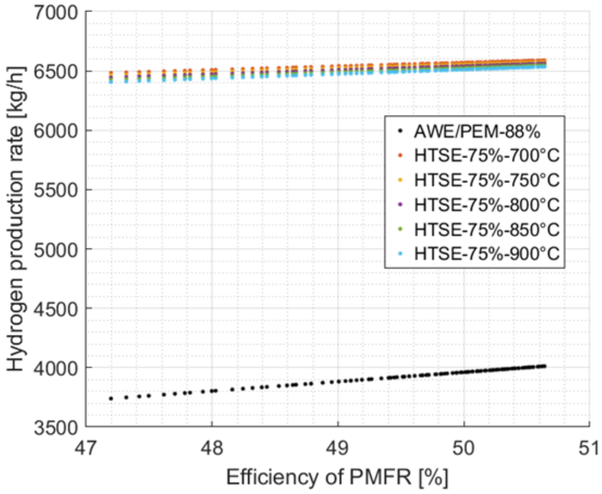

Figure 6 Hydrogen production rate according to power conversion efficiency

Figure 7 presents the calculated results with the HTSE cell’s operating temperature. The results indicate that hydrogen production decreases as the required operating temperature increases. This trend can be attributed to the additional energy required to heat the feedwater to produce high-temperature steam using an electric heater, which reduces the overall system efficiency.

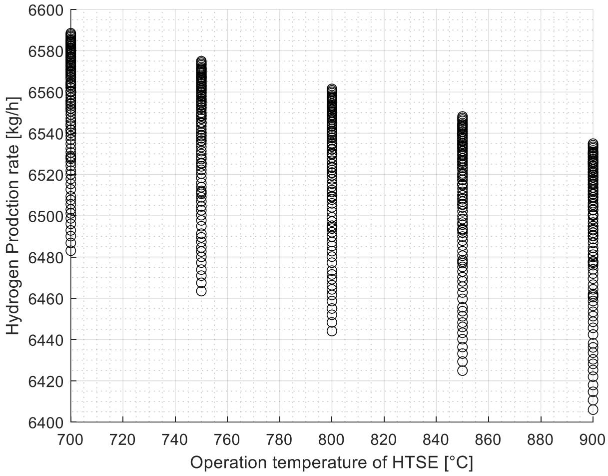

Figure 7 Hydrogen production rate according to HTSE operating temperature

In March 2024, the raw price of natural gas for fuel cells was 15.8906 KRW/MJ [9]. Based on this cost, the estimated range of PMFR's annual economic output is between 107.48 billion and 110.54 billion KRW. These findings provide a basis for establishing economic feasibility targets for PMFR.

5. Conclusion

In this paper, we proposed a hydrogen production system for the high-temperature reactor PMFR using electrolysis, integrating the next-generation power conversion system, the SCO_2 power cycle. A preliminary evaluation was conducted to assess its performance. The results indicate that PMFR can produce up to 6,588.5 kg of hydrogen per hour using HTSE and 4,012.2 kg per hour using LTWE. These findings suggest that hydrogen production with PMFR has the potential to generate an annual economic value of approximately KRW 110 billion.

Beyond demonstrating the hydrogen production capability of PMFR, this paper provides a foundational assessment of its economic feasibility. The insights gained from this research can serve for optimizing PMFR design, refining economic models, and guiding future validation. Further studies should explore system integration challenges, long-term operational efficiency, and regulatory considerations to ensure the practical deployment of PMFR for large-scale hydrogen production.

Acknowledgements

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