Enhancement of the energy efficiency of hydrogen SOFC system by integrated cold energy utilization and waste heat recovery method

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Abstract : *Hydrogen is bridge fuel with high energy content and environmentally friendly to satisfy the stringent IMO regulation relating to greenhouse gas (GHG) emissions. There is growing interest in hydrogen in numerous nations and regions illustrated by an extensive range of research and development in technology. Regarding maritime applications, researchers have recognized the utilization of hydrogen as a fuel for fuel cells, a device that converts the chemical energy of the fuel to electrical energy. Solid oxide fuel cell (SOFC), with high working temperature, is easy to combine with the waste heat recovery cycles/devices to increase output power and thermodynamic performances as well. Furthermore, the cold energy from liquid hydrogen supplied to SOFC can also be used to generate more power. In this study, we proposed a SOFC integrated system with the idea of combining the waste heat recovery from the SOFC exhaust stream and cold energy utilization from LH2. The designation is aimed to target small-scale vessel which uses electric propulsion for short distances voyage.*

Key words : *Liquefied hydrogen, SOFC, waste heat recovery, cold energy, refrigeration system*

1. Introduction

The shipping industry receives dramatic attention as a marine environmental pollution remarkable source. In 2020, the International Maritime Organization (IMO) publicized the International Convention for the Prevention of Pollution from ships. According to this convention, the sulfur content of all ships' fuel oil in the world should not exceed 0.5%. The IMO GHG initial strategy also pledged a 40% reduction of CO_2 in 2030 and a 50% reduction of annual total GHG emissions in 2050 compared to 2008 (IMO, 2020). The development and transformation of the ship's power system are facing big challenges. Many technologies have been studied and applied to decline the NO_x, SO_x, and CO_2 emissions from shipping. One of the optimal resolutions is hydrogen (both liquid and gaseous phase) which is a green fuel and can support achieving the IMO target in GHG reduction in 2050. Hydrogen can be directly burned in the internal combustion engine or can be converted to electricity by employing fuel cells to provide the shipping industry with low-emission alternative.

Being the most predominant element in the universe, hydrogen is not naturally found by itself, but attached to other elements such as oxygen to form water or carbon to form methane. Having the highest energy content per mass of all chemicals fuel (120MJ/kg), hydrogen fuel can satisfy higher engine efficiency with specific fuel consumption reduction. The use of hydrogen as a fuel for fuel cells and combustion engines has recently received dramatic increasingly attention.

Fuel cells using hydrogen depict a fine alternative technology for the maritime industry decarbonization. The concept of hydrogen supply for SOFC integrated systems was studied and researched with several proposed systems. (Duong et al., 2022) designed SOFC system integrating gas turbine (GT), steam Rankine cycle (SRC), and exhaust gas boiler (EGB) as waste heat recovery cycles with energy and exergy efficiency of 64.49% and 61.10%, respectively. The result showed an increase of 10.57% in energy efficiency and 1020.6 kW in output power production compared to SOFC stand-alone system. (Yang et al., 2021) proposed a method to utilize the cold energy from liquid hydrogen (LH_2) before supply to SOFC by an inlet air of a compressor cooling and an accessories cooling system. The new system can save up to 15% (18kW) of total parasitic power consumption compared to the initial LH_2 system without cold energy utilization. The combination of systems with different target applications must be considered in case of cost investment, efficiency, and availability. Our research suggested the idea of combining the waste heat

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recovery from the SOFC exhaust stream and cold energy utilization from LH_2 which is stored at -253℃ and 1atm to design a power plant for the small-scale vessel.

2. Waste heat recovery and cold energy utilization

The working temperature of SOFC is elevated, which allows the internal reformation of hydrocarbon fuels such as methane and ammonia. On the other hand, using hydrogen as a fuel for SOFC requires a simpler process of direct supply. Being stored at 1 bar and -253℃ as liquid phase, hydrogen must be vaporized to obtain the working temperature of fuel cells (Faye et al., 2022). A lot of heat released can be classified as a waste of cold energy during the preheating process. The recovery of this energy will be necessary. The high-temperature, high-pressure exhaust gas of SOFC is also categorized as waste heat if it is not utilized intelligently. Several bottoming cycles can be applied for waste heat recovery besides the preheating process.

3. Proposed conceptual design of combined system

In this study, we proposed a SOFC integrated system for a small boat that uses a type of electric propulsion unit (300kW) powered by liquefied hydrogen. The system is designed based on the idea of combining the waste heat recovery from the SOFC exhaust stream and cold energy utilization from LH_2 which is stored at -253℃ and 1atm to fully take advantage of the possible energy budget of the fuel. The schematic of the proposed system is given in figure 1.

The designed multiple-generation system consists of 3 main parts: (i) A SOFC technology main power production, (ii) A refrigeration system that takes advantage of the liquefied hydrogen, and (iii) The waste heat recovered by

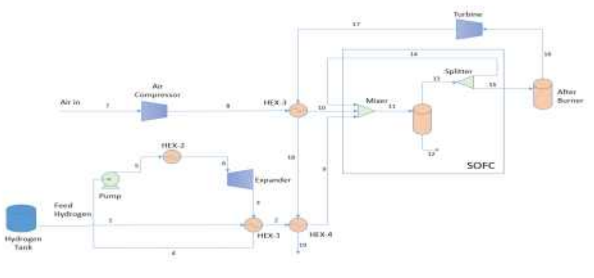

Fig. 1 The Schematic of SOFC integrated system

several bottoming cycles. Hydrogen after the storage tank will release heat and the fuel cold energy will be utilized before the preheating step and supplied to the anode side of SOFC. A refrigeration cycle is applied to utilize the cold energy of hydrogen. The high-temperature, high-pressure exhaust gas afterburner will be expanded in a gas turbine to generate more electricity to increase the energy and exergy efficiency of the integrated system. The exhaust gas is used to preheat air and hydrogen before being discharged into the environment.

4. Conclusion

Hydrogen is a probable ideal energy vector in the future for its high energy efficiency and environmentally friendly characteristics. In this research, we suggest a SOFC integrated system utilizing the cold energy of hydrogen by a refrigeration cycle and recovering the high-temperature, high-pressure waste heat from SOFC through a gas turbine to gain the highest possible energy and exergy efficiency. However, for the stage of commercialization, further attempts should be put into investigation and research to cope with the impediments to across-the-board system utilization.

Acknowledgement

This research was supported by Korea Institute of Marine Science & Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries, Korea (20180048). This research was supported by Korea Evaluation Institute of Industrial Technology (KEIT) grant funded by the Korea Government (MOTIE) (RS-2022-00144116). This research was supported by BB21plus, funded by Busan Metropolitan City and Busan Institute for Talent and Lifelong Education.

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