CONCEPT DESIGN OF A LIQUID HYDROGEN FUEL GAS SUPPLY SYSTEM FOR APPLICATION IN LH2 FUELED SHIPS AND ANALYSIS OF WASTE HEAT UTILIZATION FOR SYSTEM IMPROVEMENT

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ABSTRACT

This study proposes a liquid hydrogen (LH2) fuel gas supply system (FGSS) and analyzes several ways to utilize waste heat for performance improvement in a 4 MW-class LH2-fueled tug boat. The main function of the FGSS is to deliver LH2 fuel and vaporize it into a gaseous state to satisfy the thermodynamic conditions of a polymer electrolyte membrane fuel cell (PEMFC). The heat generated from the PEMFC can be utilized as a heating medium for LH2 FGSS itself or for ship services (such as a hot water system) if not expelled outside. When this wasted heat is utilized for LH2 process, three applications are available: glycol water (GW) heating medium, pressure build-up unit (PBU) heating medium, and LH2 fuel heating medium. Firstly, this study presents the concept design of the LH2 FGSS to meet the pressure, temperature, and flow rate requirements of the hydrogen fuel. Secondly, a hazard and operability (HAZOP) study is performed to identify potential hazards associated with the design and operation of the LH2 FGSS using design and operational data. Finally, the effect of wasted heat recovery is analyzed, considering its various application methods.

1 INTRODUCTION

International efforts towards carbon neutrality to mitigate global warming are underway. In particular, regulations for protecting the marine environment are overseen by the International Maritime Organization (IMO), an organization affiliated with the United Nations (UN) [1]. Among the international conventions aimed at preventing marine pollution from ships, the MARPOL agreements, which were introduced on January 1, 2023, include ANNEX 6, which addresses air pollution prevention requirements from ships. According to this agreement, various air pollutants emitted from ships must be reduced below certain levels. The sulfur content in ship fuel oil must be lowered from 3.5 % to 0.5 %, and carbon dioxide emissions must be gradually reduced to 50 % by 2050 compared to 2008 levels [2]. Currently, there is no clear direction or consensus on carbon-free alternative fuels. However, alternative fuels such as hydrogen, ammonia, and methanol are being developed in the marine sector to reduce air pollutants [3, 4, 5, 6, 7]. Each alternative fuel has its own distinct advantages and disadvantages. It is anticipated that they will be utilized for specific purposes, and their market share will be determined by considering the characteristics of the ship and the economic feasibility of the infrastructure environment.
Among the alternative fuels, liquid hydrogen (LH2) is particularly promising as it addresses the shortcomings of compressed gas hydrogen (CGH2). LH2 fuel boasts storage and transportation efficiency that is almost 2 times higher than CGH2 at 700 bar due to its significantly smaller specific volume; it is 780 times higher than GH2 at 1 bar. Consequently, liquid hydrogen storage containers are being considered for future hydrogen cars by various advanced companies, and LH2-based propulsion systems are being developed, especially for large-capacity mobility such as ships, buses, and truck.
Propulsion using liquid hydrogen can employ either direct combustion or fuel cell technology. Both methods require a Fuel Gas Supply System (FGSS) to condition the fuel to meet the operating conditions (pressure, temperature, and flow rate) required by hydrogen engines and fuel cells. However,

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the LH2 FGSS has not yet been developed and commercialized at the prototype level. There is not much analysis information available on the system design.

As for a risk analysis, it is difficult to find related studies for LH2 systems. Jones provided a schematic design for a Hazard and Operability (HAZOP) study on a LH2 filling station, but there were no results for the HAZOP [8]. Kikukawa et al. studied risk for liquid hydrogen fueling stations using a Failure Mode and Effect Analysis (FMEA) and the HAZOP study [9]. Totally, 131 accident scenarios were identified, but the results were a Hazard Identification (HAZID), not the HAZOP. Several HAZOP studies were conducted for hydrogen applications including high-pressure hydrogen fueling stations, methanol steam reforming, electrolytic hydrogen generation, and organic hydride hydrogen refueling stations [10, 11, 12, 13].

The aim of this study is to outline the LH2 FGSS specifications and identify potential risks along with methods to enhance system efficiency, through the concept design. Firstly, the study designs the concept of a LH2 FGSS for a propulsion system utilizing a liquid hydrogen-based fuel cell in a ship application. Secondly, the HAZOP study is conducted to identify potential risk factors associated with operation based on the conceptual design. Finally, the effects are analyzed by considering the application method of waste heat recovery from the fuel cell. Some information is omitted due to confidentiality and the limitation of paper.

2 CONCEPT DESIGN OF LH2 FGSS

2.1 Target ship

The target ship is a tugboat with a power rating in the 4MW class. The tugboat requires high engine power to relative to its size in order to push and pull large ships entering and leaving the port at coast. In this process, a large amount of pollutants is generated and it highly affects air quality in the city because it is close to shoreline. The Republic of Korea has enacted the 'eco-friendly ship law'. Among the candidates for adopting eco-friendly fuels the tugboat is one of potential choice for implementing hybrid propulsion using hydrogen-fueled and battery. Below is information regarding the target ship. The layout of the target ship is not provided due to confidentiality reasons.

Table 1: Main particulars of target ship

Item	Unit	Value
Gross tonnage	ton	544.00
Length overall	m	44.00
Length between pp	m	36.80
Breadth	m	12.50
Draft(D.L.W.L, MLD.)	m	3.70
Main engine power(fuel cell)	kW	4,000
Tank room space		
- Length	m	8.25
- Width	m	7.93
- Height	m	6.40

2.2 System description

The LH2 FGSS undergoes a sequential process to meet the operating conditions of the Polymer Electrolyte Membrane Fuel Cell (PEMFC). The main processes involve pressurization and heating, achieved through the operation of the Pressure Build-Up Unit (PBU) to deliver LH2 from the fuel storage tank to the PEMFC system and heat exchange with glycol water (GW). The stored LH2 in the fuel tank is delivered to the PBU, where it is heated and vaporized. The vaporized hydrogen then enters the fuel tank, pressurizing it up to the target operating pressure of 5 bar. Once the operating pressure is reached, the LH2 flows to the main heat exchanger, where its temperature increases. Finally, the conditioned hydrogen fuel is supplied to the PEMFC. This sequential process is illustrated with stream line number in Figure 1 and designed using Aspen HYSYS V.14, a commercial process design software. The process is simulated under the following conditions: For the hydrogen fluid, 100% para-H2 is

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considered using the modified Benedict-Web-Rubin (MBWR) equation of state. The GW is a mixture of ethylene glycol and water in equal parts and is modeled using the Peng-Robinson equation of state.
The LH2 FGSS consists of three lines: the fuel supply line, the PBU line, and the GW line. The fuel supply line includes the LH2 storage tank, vaporizer, and buffer tank. The LH2 fuel tank is of type C according to the International Code of Safety for Ships Using Gas or Other Low-Flashpoint Fuels (IGF) code with double-walled insulation, and a lattice pressure vessel (LPV) is applied in this design to maximize storage capacity through a free-form shape [14, 15]. The required LH2 fuel is estimated based on the voyage conditions of the tugboat presented in Table 2. The estimated liquid hydrogen requirement is 288kg per service, and the LH2 storage tank is sized to accommodate 10 services available with a 20% margin. The main function of the fuel supply line is to deliver hydrogen fuel and heat it from the LH2 storage tank to the PEMFC system, with the buffer tank providing a stable fuel supply. The PBU system comprises the LH2 tank and the PBU, enabling the pressure of the LH2 storage tank to be controlled as power requirements change. The control of the tank pressure pushes LH2 fuel out of the storage tank and delivers it to the PEMFC system. The function of the PBU line is to pressurize the LH2 storage tank for fuel delivery from the tank. The GW system includes a GW expansion tank, circulating pump, electrical heater, PBU, and vaporizer. GW serves as the heating medium for pressure build-up and for fuel supply with circulation.

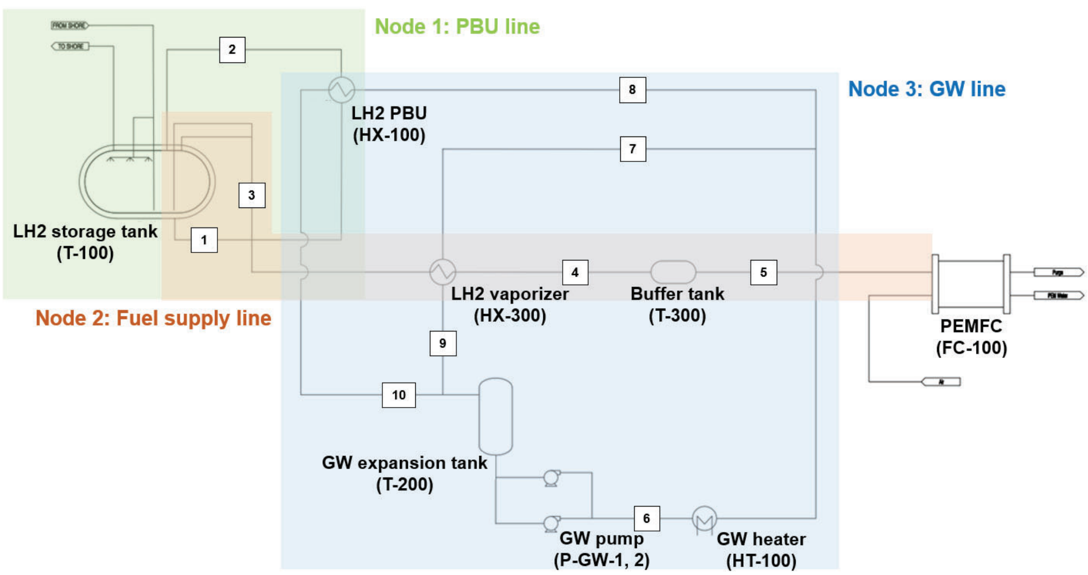

Figure 1: Process flow diagram of LH2 FGSS and T-S diagram of fuel supply process and node settings for HAZOP study

Table 2: Estimation of LH2 fuel consumption

Operation	Duration (min)	Energy consumption (kWh)	Fuel consumption (kg)
Maneuvering(Departure)	10	115	6.9
Normal sailing(Departure)	50	810	48.6
Towing service	60	2150	129.0
Normal sailing(Arrival)	50	810	48.6
Maneuvering(Arrival)	10	115	6.9
Total	180	4,000	240.0

The stream data of LH2 FGSS and the specifications of each equipment are provided in Table 3 and Table 4 through process simulation.

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Table 3: Process stream data of LH2 FGSS

Stream no.	Unit	1	2	3	4	5	6	7	8	9	10
Fluid		LH2	H2	LH2	H2	H2	GW	GW	GW	GW	GW
Flow rate	ton/day	1.3	1.3	5.7	5.7	5.7	221.5	205.1	7.4	205.1	7.4
Operating pressure	bar	0.5	0.5	0.5	0.48	0.15	2.00	0.19	0.19	0.17	0.17
Operating temperature	°C	-246	-246	-246	50	50	30	70	70	30	30
Density	kg/m^3	60.8	2.5	60.8	2.5	0.1	1092	1059	1059	1092	1092

Table 4: Specification of main equipment

Equipment	Unit	Value	Remark
LH2 storage tank			Type: Lattice pressure vessel(Type C)
- Design pressure	bar	10.0	Insulation: Vacuum-MLI
- Design temperature	°C	-253.0	Size: 45(3,400m×3,400m×4,600m)
- Volume	m^3	45.0	Filling ratio: 90%
PBU			Type: Plate-fin
- Heat duty	kW	10.0	
- Flow rate (LH2/GW)	kg/hr	54.8/306.1	
- Operating pressure	bar	5.0	
- Inlet temperature (LH2/GW)	°C	-246.0/70.0	
- Outlet temperature (LH2/GW)	°C	-223.1/30.0	
Vaporizer			Type: Plate-fin
- Heat duty	kW	280.0	
- Flow rate(LH2/GW)	kg/hr	238.1/8,548.0	
- Operating pressure	bar	5.0	
- Inlet temperature (LH2/GW)	°C	-246.0/70.0	
- Outlet temperature (LH2/GW)	°C	20.0/30.0	
Buffer tank			Type: Cylindrical pressure vessel
- Design pressure	bar	10.0	
- Volume	m^3	5.7	
- Back up time	min	1.0	

2.3 Operational philosophy

The LH2 FGSS operates following the sequences outlined in Figure 2 corresponding to the target ship's voyage. Each step involves checking the preparation state of equipment, valve opening, and satisfaction of reference values. Purging operation is conducted to remove oxygen and moisture from the LH2 storage tank, piping, and equipment which has the possibility to contain GH2 and LH2 during initial operation, with the atmosphere replaced by nitrogen, ensuring oxygen concentration and dew point are lower than 0.1% and -50°C, respectively. Gassing-up operation is carried out on the LH2 storage tank and other fluid lines to prevent the freezing of purging gas (nitrogen) due to cryogenic formation during normal operation, with the hydrogen concentration reaching 99.999%. Cooldown operation is performed to prevent damage to plant facilities, including piping, from excessive thermal stress caused by rapid temperature drops before LH2 is filled, completing the process when the average temperature is below -230°C. Bunkering operation involves transferring LH2 from an external terminal to the LH2 storage tank, ensuring the filling ratio remains under 90%.

After bunkering, normal operation commences, beginning with a level check of the LH2 storage tank. Initially, the GW system is activated and checked for stable circulation to mitigate the risk of freezing at heat exchangers. Subsequently, LH2 flow is initiated only after confirming the stable circulation of the GW system. Once the GW system circulation is stable, the PBU is activated. The pressure of the LH2 storage tank increases to the set value, and finally, LH2 fuel is supplied to the PEMFC, with the control logic operating at each operational step.

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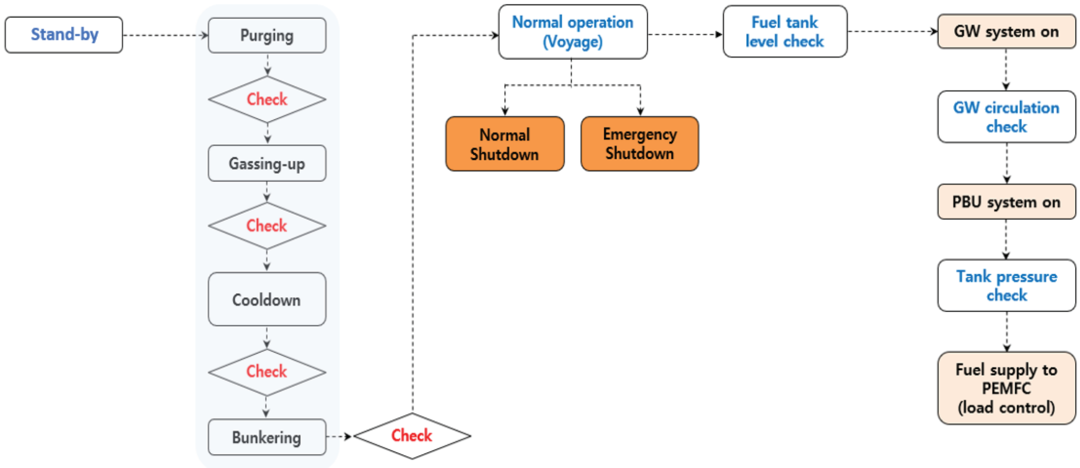

Figure 2: Operational sequences of LH2 FGSS

3 RISK ANALYSIS

3.1 Process of HAZOP analysis

This study utilizes qualitative risk assessment methods, employing the HAZOP technique. This approach aims to identify existing risk factors and operational issues within the process, with the goal of eliminating causes that could potentially reduce process efficiency. The HAZOP establishes process sections as nodes for risk review, combining guide words (such as more, less, none, reverse, part of, as well as, and other than) with parameters (such as flow, pressure, temperature, level, composition, etc.) to predict deviations and the associated risk consequences. Finally, it calculates the risk level based on the frequency of the cause and the criticality of the results.

Finally, necessary safety measures for high-risk items in the design are implemented. Risk levels are classified into high risk, which must be reduced unconditionally, medium risk, which are considered as low as reasonably practical (ALARP) areas and can be reduced if necessary, and low risk. Particularly, the decision to implement measures to reduce the risk level in the ALARP area is made by experts during the HAZOP workshop. Table 5 presents a risk assessment matrix indicating the degree of consequence and frequency. The design should be modified for high-risk rankings and could be adjusted for medium levels as well. For low-risk rankings, design improvements are not necessary. Figure 1 and Table 5 present the HAZOP nodes of the system.

Table 5: Risk assessment matrix

Consequence		Increasing Frequency			
Severity rating	Damage	1	2	3	4
		Has occurred in industry	Has occurred in operating company	Occurred several times a year in operating company	Occurred several ties a year in location
0	Zero	Low	Low	Low	Low
1	Slight	Low	Low	Low	Low
2	Minor	Low	Low	Medium (ALARP)	Medium (ALARP)
3	Local	Low	Medium (ALARP)	Medium (ALARP)	Medium (ALARP)
4	Major	Medium (ALARP)	Medium (ALARP)	High	High
5	Extensive	Medium (ALARP)	High	High	High

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3.2 Results of HAZOP analysis

After conducting the HAZOP analysis, a total of 27 recommendations have been identified as action items to prevent or mitigate potential risks in the operations of the LH2 FGSS. These recommendations are presented in Table 7 and mainly address issues related to fire and explosions caused by hydrogen leakage at each main equipment. To address these risks, several recommendations have been issued, including dispersion analysis, gas detection, installation of anti-discharge rings, and implementation of alarm systems. In particular, measures to cool down the line have been modified to prevent piping failure induced by repeated thermal contraction during the system's operation and shutdown. As part of the preparation for ship voyage, the pipeline should be prepared for cooling down in the liquid hydrogen area, specifically at the PBU vaporizer (HX-100) and LH2 vaporizer (HX-300). Before opening the LH2 fuel valve, the vapor fuel cools the fuel supply line by adjusting the control valve (FCV-301 in Line 5). The HAZOP work sheet is presented partially in Table 6.

Table 6: Partial HAZOP sheet of Node 2(example)

Deviation	Cause	Consequence	Safeguard	Risk level		
				F	S	R
No/less flow	Line 3 (XV-300), Line 4 (XV-301), and Line 5 (XV-302) fails closed	No H2 supply to PEMFC, leading to loss of FGSS	PAL	3	2	M
		Potential blackout and loss of FGSS	Battery backup	3	2	M
	Dust filter clogging	No H2 supply to PEMFC, leading to loss of FGSS	PAL	3	2	M
		Potential blackout and loss of FGSS	Battery backup	3	2	M
High pressure	Low fuel consumption	Continuous vaporization at LH2 vaporizer, leading to over-pressurization and damage	PAHH Closing Line 3 (XV-300)	3	2	M
	Line 5 (PRV-300) fails open	High H2 pressure ingress to PEMFC leading to potential damage	FI-302 closing FCV-301 in Line 5	2	3	M
			PRV at PEMFC	2	3	M
Low pressure	Spurious opening of Line 4 (SV-300) and Line 5 (SV-301)	No H2 supply to PEMFC, leading to loss of FGSS	PAL	3	2	M
		Potential blackout and loss of propulsion	Battery backup	3	2	M
		Continuous venting of H2, potential fire and explosion due to gas dispersion	PAL	1	3	L
	LH2 vaporizer leakage	Rapid vaporization and over-pressurization of GW piping and damage	TALL, initiating FGSS shutdown	3	2	M
			Vent at GW tank	3	2	M
High temperature	Temperature control failure of GW heater	GW degradation		3	2	M
		No H2 supply to PEMFC, leading to loss of FGSS	PAL	3	2	M
		Potential blackout and loss of propulsion	Battery backup	3	2	M
Low temperature	Temperature control failure of GW heater	Potential liquid carryover to buffer tank, leading to piping and buffer tank damage	TALL Closing Line 3 (XV-300) and Line 4 (XV-301)	2	2	L
	Line 7(FCV-202) closed/GW pump to low speed	Potential liquid carryover to buffer tank, leading to piping and buffer tank damage	TALL Closing Line 3 (XV-300) and Line 4 (XV-301)	2	2	L

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Start-up/Shutdown/Maintenance	Repeated running and stopping in short-term, without cool-down process	Thermal contraction in piping and potential failure, leading to potential risk of fire and explosion		1	4	M
Others	Degradation of valve hermeticity	Pressure build-up in the piping failure	Use of certified cryogenic valves	2	2	L
	Corona discharge at vent	Potential fire and explosion at vent	Regular inspection	3	1	L

Table 7: Main recommendations for HAZOP analysis

Node	No.	Main recommendations
1	1	Consider providing gas detector (sampling type) at GW tank vent outlet that initiates FGSS shutdown Deviation: low pressure (for rapid vaporization and over pressurization of GW piping and damage when occurring leakage at LH2 PBU)
	2	Consider providing a measure to cooldown Line 3. Deviation: start-up/shutdown/maintenance (for thermal contraction in piping and potential failure, leading to potential risk of fire and explosion when occurring repeated running and stopping of FGSS operation in short-term, without cool-down process)
2	1	Consider performing a dispersion analysis Deviation: low pressure (for continuous venting of H2, potential fire and explosion due to gas dispersion when occurring spurious opening PSV on Line 3 and 4(PSV-300/301))
	2	Consider providing gas detector (sampling type) at GW tank vent outlet that initiates FGSS shutdown Deviation: low pressure (for rapid vaporization and over pressurization of GW piping and damage when occurring leakage at LH2 vaporizer)
	3	Consider rearranging the GW temperature operating range Deviation: high temperature (for GW degradation when occurring temperature control failure of GW heater)
	4	Consider providing anti discharge ring at the vent outlet Deviation: others (for potential fire and explosion at vent when occurring corona discharge at vent)
3	1	Consider providing level alarm of GW tank (PAL-200/PALL-200) triggering a FGSS shutdown Deviation: no/less flow (for loss of GW circulation, leading to loss of FGSS when occurring GW pump failure, on/off valve on Line 6, 7, and 8(XV-200/201/202) fails closed, or flow control valve on Line 7 and 8 (FCV-202/203) fails closed)
	2	Ensure regular inspection of liquid trap (filter) of GW vent gas detector Deviation: start-up/shutdown/maintenance (for degraded gas detection, leading to potential fire and explosion when occurring high humidity condition at GW vent line)

4 WASTED HEAT RECOVERY

4.1 Application design of wasted heat from PEMFC

The LH2 FGSS operates to supply hydrogen gas fuel to a fuel cell (PEMFC). After the reaction in the PEMFC, the reaction products are water, electricity, and heat. This generated heat can be utilized as a heating medium for the LH2 process itself and for ship services (such as a hot water system) if not expelled outside. When this wasted heat is utilized for the LH2 process, three applications are available: GW heating medium, PBU heating medium, and LH2 vaporizer heating medium. Section 4.2 estimates the effect of wasted heat recovery quantitatively, demonstrating how this heating source can increase the efficiency of the LH2 FGSS.

Each application is calculated using Aspen HYSYS V.14. According to the reaction equation, one mole of water is produced. In this design, the produced water condition is 118.1 kgmol/hr (2,128

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kg/hr) molar flow with a temperature of around 70 °C. This value is based on the 4 MW-class LH2 fuel supply.

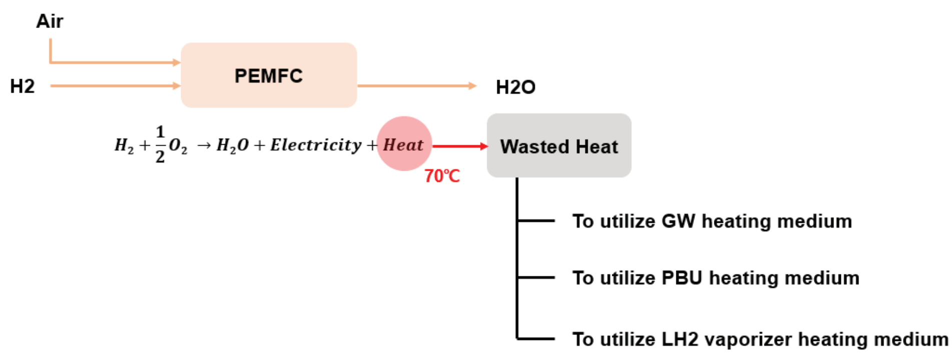

Figure 4: Applicable designs of wasted heat from PEMFC

4.2 Possibility of wasted heat recovery

The GW system plays a role in vaporizing LH2 to increase and maintain tank pressure and to supply hydrogen fuel by vaporizing and heating it. Therefore, the GW system requires an electrical heater to deliver heat to the LH2. If the wasted heat is recovered for GW heating, the heat duty is decreased by around 27%, resulting in a decrease in input power from 289.9 kW to 212.9 kW. The GW heater is still implemented in the system, but it is able to save the electrical power of the system.

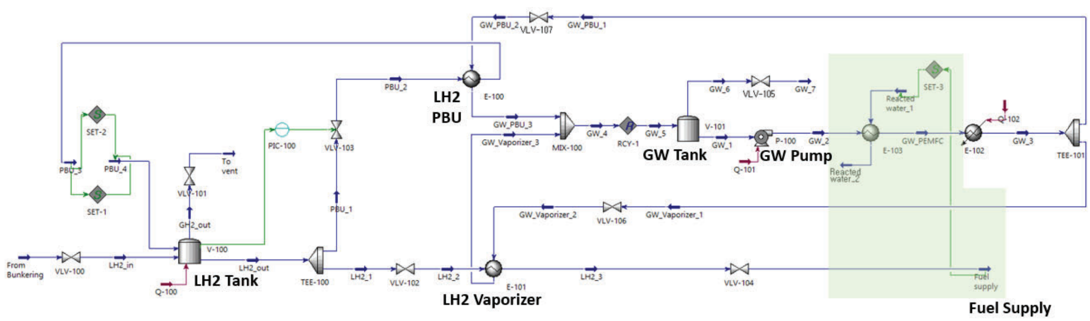

Figure 5: Wasted heat application for GW heating system

For the PBU application, the wasted heat is sufficient to vaporize the LH2 with a heat duty of 10 kW. In this application, the GW line can be omitted by replacing it with a wasted heat recovery system.

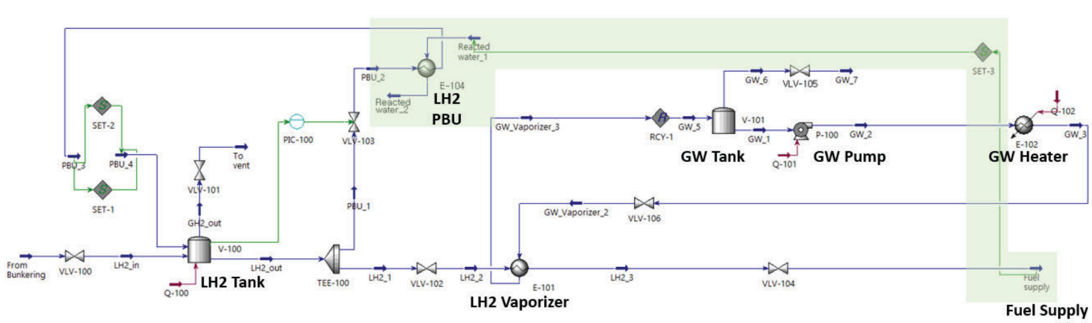

Figure 6: Wasted heat application for PBU heating system

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For the LH2 vaporizer application, the wasted heat is capable of vaporizing and increasing the temperature of LH2 fuel. The heat duty is reduced by approximately 50%, resulting in a decrease in input power from 280.0 kW to 139.5 kW. It still requires LH2 vaporizer, but it saves the electrical power in the GW heater.

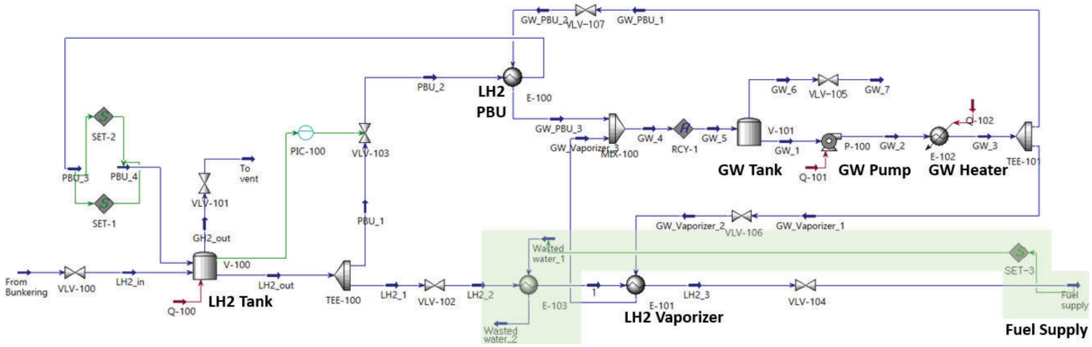

Figure 7: Wasted heat application for LH2 vaporizer heating system

The results present the wasted heat recovery from the fuel cell is feasible for three applications. However, several considerations are required when applying waste heat to each application. Firstly, operational strategy should be considered in the design step. The waste heat can be utilized as a type of water which is reacted, or as a coolant which helps in cooling the PEMFC. When utilizing the produced water directly, a reservoir is required to stabilize system operation because the quantity of products varies with changes in ship propulsion load. Secondly, the possibility of freezing of the heat exchanger should be analyzed for the water inlet line when exchanging heat with LH2 in this application. In the case of utilizing coolant for wasted heat recovery, the refrigeration cycle could be integrated between the fuel cell and each applicable candidate. During operation, the GW circulation should remain stable because the temperature difference exceeding 300 °C between the GW and the LH2.

5 CONCLUSIONS

This study proposes a liquid hydrogen fuel gas supply system for a hydrogen-fueled tugboat with a power rating in the 4 MW class. The process was designed and main equipment specified. Operational hazards were analyzed using the HAZOP method, and recommendations were issued to prevent or mitigate potential risks. The primary risk issues identified were related to fire and explosions induced by hydrogen leakage at each main equipment, stemming from various causes. Finally, the study proposes several ways to utilize waste heat from the PEMFC for performance improvement in three applicable cases: the GW system, PBU, and LH2 vaporizer. The results demonstrate that utilizing the wasted heat is thermodynamically feasible.

NOMENCLATURE

ALARP	As low as reasonably practical
CGH2	Compressed gas hydrogen
F	Frequency
FCV	Flow control valve
FGSS	Fuel gas supply system
FMEA	Failure mode and effect analysis
GW	Glycol water
HAZID	Hazard identification
HAZOP	Hazard and operability
HX	Heat exchanger
IGF	International code of safety for ships using gas or other low-flashpoint fules

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IMO	International maritime organization
LH2	Liquid hydrogen
LPV	Lattice pressure vessel
MARPOL	International convention for the prevention of marine pollution
PAL	Pressure alarm low
PALL	Pressure alarm low low
PBU	Pressure build-up unit
PEMFC	Polymer electrolyte membrane fuel cell
PSV	Pressure safety valve
R	Ranking
S	Severity
SV	Solenoid valve
TAL	Temperature alarm low
TALL	Temperature alarm low low
XV	On/off valve

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