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# Development of a marine hydrogen fuel system (MHFS)

New Engine Concepts & Systems

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## ABSTRACT

Since the entry into force of the Paris Agreement, public concerns have changed from a low-carbon society to a decarbonized society, and the movement toward decarbonization has also become more active in the shipping sector. Therefore, as one of the decarbonization technologies, the potential market of marine engines using hydrogen as fuel will exist, and commercialization and prevalence of marine hydrogen-fueled engines will be anticipated in the very near future. Considering such circumstances, the Japanese Government has established the Green Innovation Fund to achieve carbon neutrality by 2050, including a project of development of hydrogen-fueled ships. Thus, Kawasaki Heavy Industries, Ltd. was entrusted as the lead managing company to advance the development of marine hydrogen engines and their hydrogen fuel supply system, because KHI has a wide range of hydrogen-related technologies, achievements, and experiences as a marine equipment manufacturer including engines as well as a shipyard.

The marine hydrogen fuel system (hereinafter called MHFS) is the designation of a hydrogen fuel supply system under development by KHI, which can supply hydrogen fuel within the predetermined range of temperature and pressure from a liquefied hydrogen (hereinafter called LH2) fuel tank to marine hydrogen-fueled engines. Before commercialization of MHFS, verification tests and operations are planned on board actual ships with a hydrogen-fueled engine and MHFS installed. At present, KHI is developing two types of MHFS for marine hydrogen engines which are concurrently being developed by other two Japanese engine manufactures. Verification tests and operations for each type of MHFS together with the hydrogen-fueled engine will be carried out on board the actual ships in the late of the 2020s, to confirm safety, reliability, and functionality required for marine use.

Through development steps of MHFS, KHI has already recognized some key technical issues regarding the use of hydrogen as marine fuel. In this paper, the authors introduce the outline and technical matters about MHFS, and explain challenges already solved and to be addressed later on.

## 1 INTRODUCTION

The current public concerns for the global environment is moving from a low-carbon society to a decarbonized society, and many countries around the world are accelerating challenges for GHG emission reduction to achieve carbon neutrality by 2050.

While measures against the global warming are urgently needed, the Japanese government adopted funds entitled Green Innovation Fund (hereinafter called GI Fund) to support technological developments in various fields toward carbon neutrality by 2050. One of the projects under GI Fund is " Next-generation Ship Development", which was adopted based on the belief that zero-emission ships by utilizing clean energies should be put into service by around 2030 and beyond, and that it is necessary to promptly advance technological developments and demonstrations of the zero-emission ships.

In order to develop the zero-emission ships, it is of course necessary to develop propulsion machinery such as reciprocating engines and fuel cells that can operate with clean and sustainable fuels. Furthermore, systems for supplying those fuels to such kinds of machinery in a safe and reliable manner are also essential. Therefore, KHI develops such systems under the project of “Development of Hydrogen Fueled Ships”, which is one of “Next-generation Ship Development”, because KHI especially focuses on hydrogen as ultimate one among various clean energies and is working to build global hydrogen supply chains with a particular focus on production, storage, transportation and use of hydrogen. Thus, KHI is currently developing hydrogen fuel supply system called MHFS for hydrogen fueled engines.

In "Development of Hydrogen Fueled Ships", different types of hydrogen fueled engines, low-pressure hydrogen fueled four-stroke engines and high-pressure hydrogen fueled two-stroke engines, are being developed by two Japanese engine manufacturers with the aim to installing them on hydrogen fueled ships. These two types of engines require different temperatures, pressures and an amount of fuel, thus MHFS has to be developed respectively to meet the requirements of each type of engine. Details of each MHFS are described in the following chapters. Regarding the two types of MHFS, low pressure type (MHFS-LP) and high pressure type (MHFS-HP), the development is scheduled as shown in Figure 1.

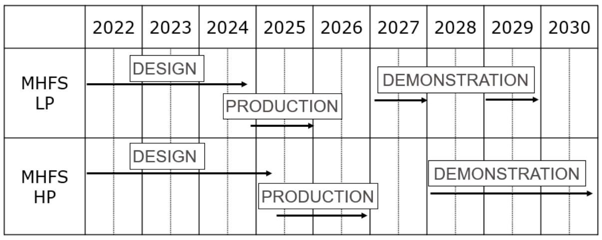


Figure 1. Development schedule of MHFS

As mentioned above, the goal to be achieved is completion of the developments and demonstrations of both MHFS-LP and MHFS-HP. In the forthcoming future, KHI anticipates that the global needs for hydrogen fueled ships will rapidly expand in the marine sector to achieve carbon neutrality by around 2050. KHI will further proceed the developments of MHFS standardized, packaged and modularized for installation on various types of ships to satisfy such demands and make positive contributions to carbon neutrality in the world.

This paper provides the overview of MHFS and details and progress of the developments.

## 2 OUTLINE OF MHFS

The outlines for each MHFS are as follows.

### 2.1 MHFS-LP

MHFS-LP is being developed as a hydrogen FGSS for a medium-speed four-stroke low-pressure hydrogen-fueled engine of Otto-cycle. As the basic concept, MHFS-LP is packaged in the footprint of the 40-feet container and is designed as a compact unit that can readily be mounted on small and medium-sized ships.

#### 2.1.1 OUTLINE OF DEMONSTRATION SHIP

Table 1. Outline of demonstration ship

| | |
|---|---|
| Ship type | Domestic and coastal oil tanker |
| Shipowner | Japanese Owner |
| Flag | Japan |
| Class | ClassNK |
| Shipyard | Japanese Shipyard |
| Gross tonnage | 4,500 ton |

| | |
|---|---|
| Propulsion system | Refer to Figure 2. |

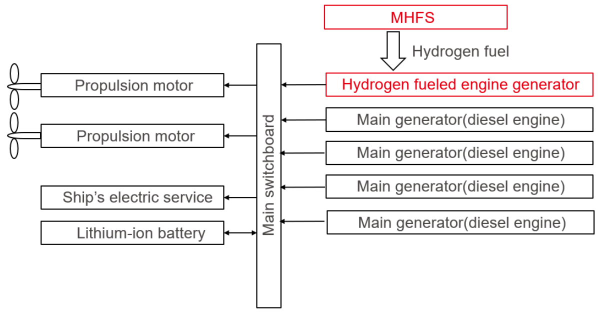


Figure 2. Propulsion system of demonstration ship

The hybrid type electric motor system consists of a hydrogen-fueled engine generator set, conventional diesel engine generator sets, a large-capacity battery, and so on.

### 2.1.2 OUTLINE OF HYDROGEN FUELED ENGINE

Table 2. Outline of hydrogen fueled engine

| | |
|---|---|
| Manufacturer | Yanmar Power Technology Co., Ltd. |
| Engine type | Medium-speed four-stroke, dual fuel (hydrogen / oil), Otto-cycle |
| Bore | 220 mm |
| Output | approx. 0.8 MW |
| Hydrogen supply pressure | Less than 0.7 MPaG |
| Hydrogen supply temperature | 0 to 60 °C |

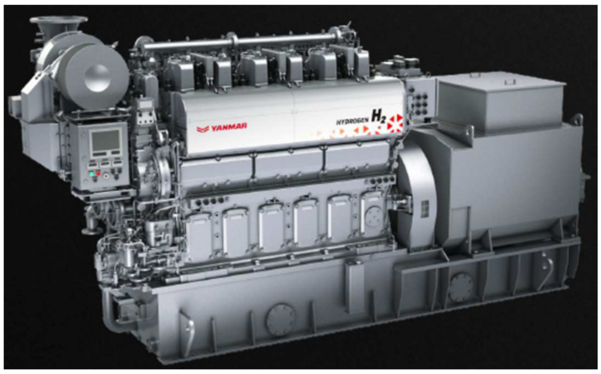

Figure.3 Outside view of hydrogen fueled engine (Courtesy of Yanmar Power Technology Co., Ltd.)

### 2.1.3 INSTALLATION OF MHFS-LP UNIT

MHFS-LP on the demonstration ship is readily installable as a complete unit of 40-feet container footprint on the exposed deck above a cargo oil tank. Hydrogen fuel is pressurized and heated within the predetermined ranges inside the unit and then sent to the hydrogen-fueled engine generator set.

### 2.1.4 SYSTEM CONFIGURATION

MHFS-LP consists of three assemblies, $LH_2$ fuel tank, TCS and BS. $LH_2$ fuel tank and TCS are combined as one unit. Cryogenic hydrogen piping is designed for -253 °C and VIP is basically used so as to block heat transfers to / from the surrounding atmosphere. In addition, drip trays are fitted below cryogenic hydrogen pipes in order to protect the ship's steel structures from low-temperature embrittlement in case of abnormalities where liquefied air generates on cryogenic hydrogen pipes and drips off.

Basic operations of MHFS-LP are as follows.

$LH_2$ fuel is planned to be bunkered to $LH_2$ fuel tank from a shore by truck-to-ship bunkering. A $LH_2$ filling line and a $GH_2$ return line are to be connected to BS on board for bunkering. During the bunkering operation, $LH_2$ fuel tank can be depressurized through the $GH_2$ return line if necessary.

After the bunkering, $LH_2$ fuel tank is pressurized by using PBU vaporizer to the working pressure which is higher than the supply pressure to the hydrogen-fueled engine. Then, $LH_2$ can be supplied to the engine by utilizing $LH_2$ tank pressure through Fuel vaporizer, a pressure control valve, a buffer chamber and a master gas fuel valve, all of which are mounted on MHFS-LP unit. $LH_2$ is vaporized and heated to $GH_2$ through Fuel vaporizer on the way of hydrogen supply to the engine from $LH_2$ tank. The pressure control valve and the buffer chamber are provided to adjust hydrogen supply pressure to the engine stably.

Cryogenic hydrogen is heated to normal temperature through each vaporizer by hot glycol water.

Boil-off gaseous hydrogen in $LH_2$ fuel tank can be sent to the engine in the same manner. $LH_2$ fuel tank pressure can be decreased while consuming boil-off hydrogen.

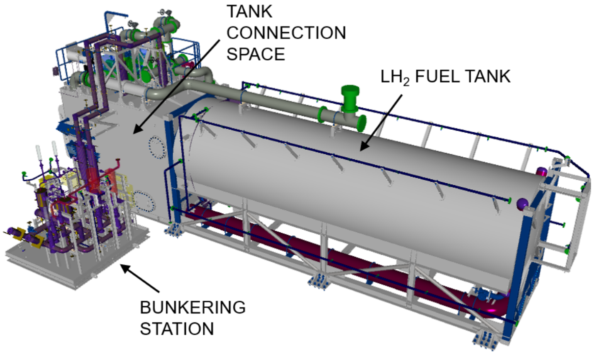


Figure 4. Outside view of MHFS-LP

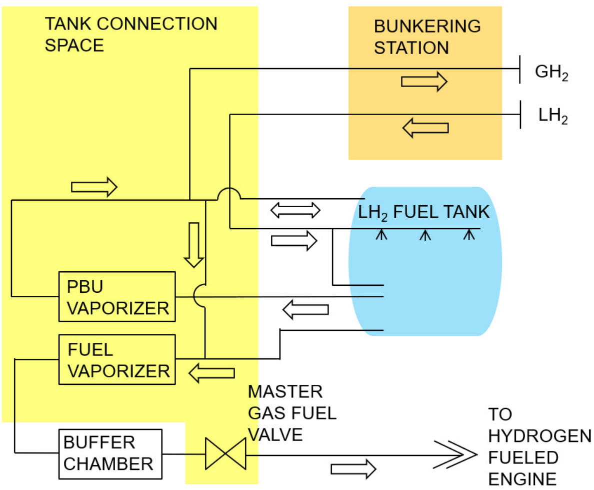


Figure 5. Schematic diagram of MHFS-LP

### 2.1.5 PARTICULARS OF EQUIPMENT

The particulars of main components of MHFS-LP are summarized as below:

- PBU vaporizer
  - Type:

    Diffusion-bonded, micro channel heat exchanger
  - Hydrogen flow:

    max. 20 kg/h, for pressure-buildup (from 0.1 MPaG to 0.7 MPaG) of $LH_2$ fuel tank within around 1 hour
  - Inlet temperature: 20 K (-253 °C)
  - Outlet temperature: 303 K (30 °C)
- Fuel vaporizer
  - Type:

    Diffusion-bonded, micro channel heat exchanger
  - Hydrogen flow:

    max. 120 kg/h, bigger than the demand flow of hydrogen-fueled engine
  - Inlet temperature: 20 K (-253 °C)
  - Outlet temperature: 303 K (30 °C)

Figure 6. Micro channel type heat exchanger (Courtesy of Kobe Steel, Ltd.)

The heat exchangers of micro channel type are used for minimizing the installation space.

- Buffer chamber:

  2 $m^3$, large-diameter pipe structure

The buffer chamber is equipped for keeping the hydrogen supply pressure stable.

### 2.1.6 $LH_2$ FUEL TANK

The latent heat of hydrogen per volume of liquid phase is about 1/7 times that of natural gas. The temperature difference between liquid temperature of hydrogen and normal temperature is about 1.5 times that of natural gas. Therefore, a much higher performance of the thermal insulation is essential for $LH_2$ fuel tank compared to LNG fuel tank.

$LH_2$ fuel tank is designed so as to accumulate boil-off gaseous hydrogen, until the pressure reaches MARVS in about one month from the atmospheric pressure.

The main specifications of $LH_2$ fuel tank are as below:

- Volume: 31 $m^3$ (100%)
- Type:

  Vacuum and multi-layer insulated, Type-C
- Material: Stainless steel, 304L
- Loading limit: 1,400 kg ($LH_2$)
- MARVS: 0.98 MPaG

## 2.2 MHFS-HP

MHFS-HP is being developed as a hydrogen FGSS for a low-speed two-stroke high-pressure hydrogen fueled propulsion engine of Diesel-cycle which is installed on an ocean-going vessel.

### 2.2.1 OUTLINE OF DEMONSTRATION SHIP

Table 3. Outline of demonstration ship

| | |
|---|---|
| Ship type | Multi purpose vessel |
| Shipowner | Mitsui O.S.K. Lines, Ltd. and MOL Drybulk, Ltd. |
| Flag | Japan |
| Class | ClassNK |
| Shipyard | Onomichi Dockyard Co., Ltd. |
| Dead weight | 17,500 MT |
| Propulsion system | Propelled by two-stroke dual fuel engine directly coupled with fixed pitch propeller |

### 2.2.2 OUTLINE OF HYDROGEN FUELED ENGINE

Table 4. Outline of hydrogen fueled engine

| | |
|---|---|
| Manufacturer | Japan Engine Corporation |
| Engine type | Low-speed two-stroke, dual fuel (hydrogen / oil), Diesel-cycle |
| Model | 6UEC35LSGH |
| Output | approx. 3 MW |
| Hydrogen supply pressure | 30 MPaG |
| Hydrogen supply temperature | 20 to 40 °C |

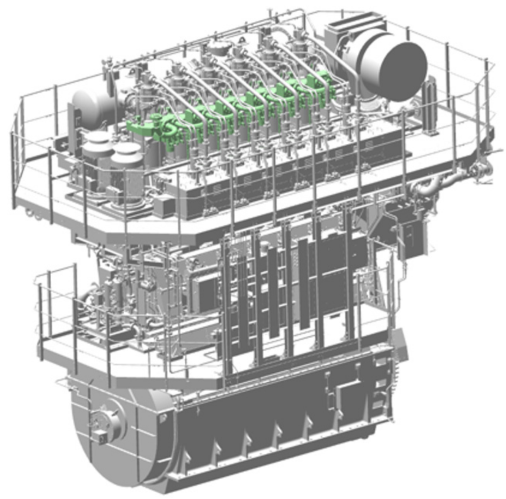

Figure 7. Outside view of hydrogen fueled engine (Courtesy of Japan Engine Corp.)

### 2.2.3 INSTALLATION OF MHFS-HP

MHFS-HP is arranged above the exposed deck of the ship’s aft peak as shown in Figure 8.


Figure 8. Outside view of Ship and MHFS-HP

### 2.2.4 SYSTEM CONFIGURATION

MHFS-HP is arranged in three areas, BS, FPR and $LH_2$ fuel tank. VIP and drip trays are equipped in the same manner as MHFS-LP. In addition, splash shields are provided as a countermeasure against splash from high pressure liquefied hydrogen piping.

Basic operations of MHFS-HP are as follows.

As to the bunkering of $LH_2$, the operation is the same as that of MHFS-LP.

After the bunkering, $LH_2$ fuel tank is kept at a moderate pressure by using PBU vaporizer or the hydrogen GCU as necessary. After departure from the bunkering port, $LH_2$ in the tank is supplied to the engine as fuel by operating Fuel booster pump and High pressure fuel pump in series, through High pressure fuel heater, a pressure control valve and a master gas fuel valve, all of which are arranged inside FPR. High pressure fuel pump with speed control and the pressure control valve precisely and steadily adjust the hydrogen supply pressure at 30 MPaG. High pressure fuel pump is used to deliver and pressurize cryogenic liquefied hydrogen efficiently with low electric power.

Boil-off gaseous hydrogen in $LH_2$ fuel tank can be accumulated in the tank. When the tank pressure reaches much higher than a normal working pressure, GCU is operated to reduce the tank pressure by consuming (combusting) boil-off hydrogen on the demonstration ship. Gaseous hydrogen is sent to GCU by $LH_2$ tank pressure through BOG heater. GCU is arranged in the engine room. However, when hydrogen fueled ships and their MHFS are commercialized, it is necessary to install hydrogen gas consuming machinery such as hydrogen fueled generators in order to utilize boil-off gas without wasting it.

Cryogenic hydrogen is heated to normal temperature by hot glycol water through each vaporizer and heater.

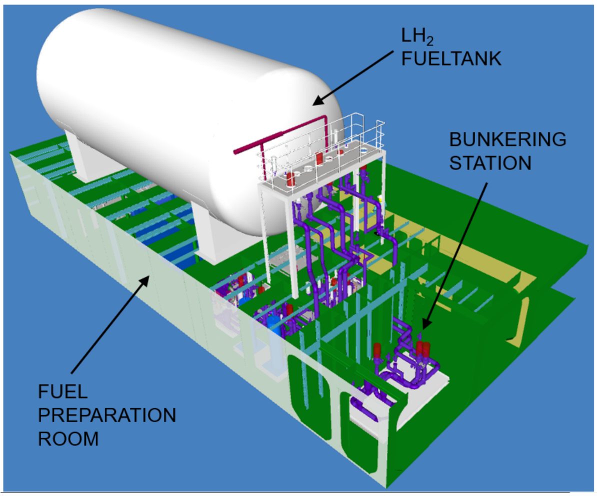


Figure 9. Arrangement of MHFS-HP on board

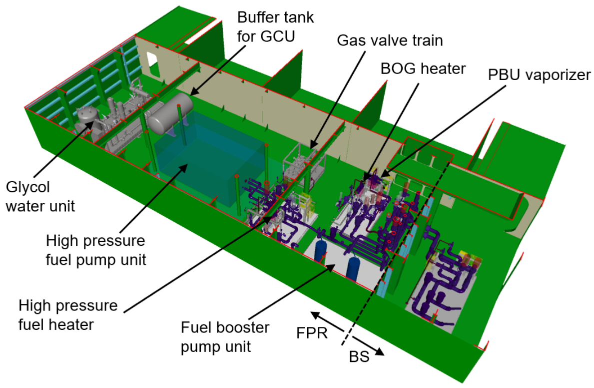


Figure 10. Arrangement in FPR

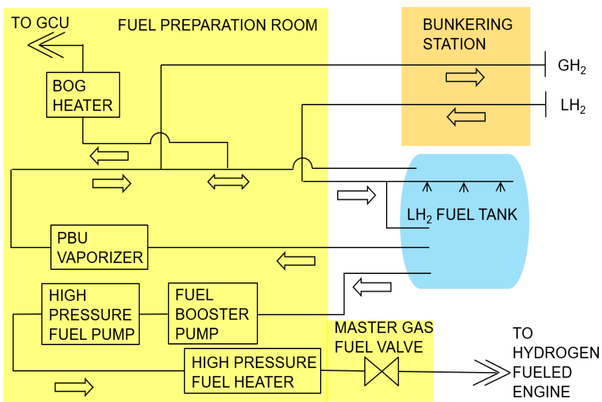


Figure 11. Schematic diagram of MHFS-HP

### 2.2.5 PARTICULARS OF EQUIPMENT

The particulars of main components of MHFS-HP are summarized as below:

- PBU vaporizer
  - Type:

    Diffusion-bonded, micro channel heat exchanger
  - Hydrogen flow: max. 30 kg/h
  - Inlet temperature: 20 K (-253 °C)
  - Outlet temperature: 303 K (30 °C)
- High pressure fuel heater
  - Type:

    Diffusion-bonded, micro channel heat exchanger
  - Hydrogen flow:

    max. 200 kg/h, equivalent to the demand of hydrogen-fueled engine
  - Inlet temperature: 20 K (-253 °C)
  - Outlet temperature: 303 K (30 °C)
- BOG heater
  - Type:

    Diffusion-bonded, micro channel heat exchanger
  - Hydrogen flow:

    max. 10 kg/h, bigger than the natural boil-off amount in $LH_2$ fuel tank
  - Inlet temperature: 20 K (-253 °C)
  - Outlet temperature: 303 K (30 °C)
- Fuel booster pump
  - Type: Centrifugal multi-stage pump
  - Flow rate: more than 200 kg/h
- High pressure fuel pump
  - Type: Reciprocating pump
  - Flow rate: more than 200 kg/h
  - Discharge pressure: 33.0 MPaG
- Gas combustion unit:
  - Disposal gas:

    Pure hydrogen, hydrogen and nitrogen mixture (arbitrary ratio)
  - Disposal capacity: 10 kg/h (pure $GH_2$)
  - Inlet pressure: 0.6 MPaG or below
  - Inlet temperature: 0 to 50 °C

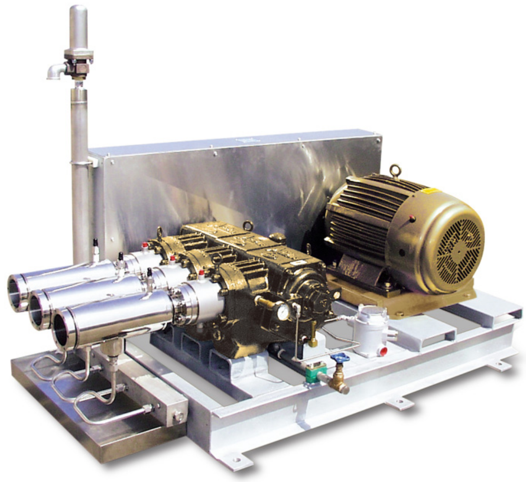

Figure 12. High pressure fuel pump for $LH_2$ (Courtesy of NIKKISO ACD, LLC)

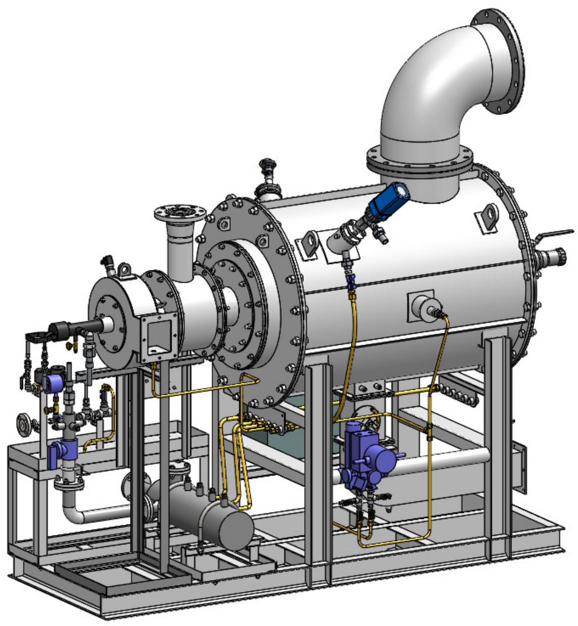

Figure 13. Gas combustion unit (Courtesy of Volcano Co., Ltd.)

### 2.2.6 $LH_2$ FUEL TANK

The design concept of $LH_2$ fuel tank of MHFS-HP is similar to that of MHFS-LP.

The main specifications of $LH_2$ fuel tank are as below:

- Volume: 200 $m^3$ (100%)
- Type:

  Vacuum and multi-layer insulated,Type-C
- Material: Stainless steel, 304L
- Loading limit: 10,750 kg ($LH_2$)
- MARVS: 0.6 MPaG

## 3 DEVELOPMENT ISSUES ABOUT HYDROGEN FUELED SHIP AND MHFS

Since hydrogen fueled ships are not yet prevalent in the world, regulations relating to such ships are not gotten in place. Therefore, the hazard identification study, so-called HAZID was carried out by all parties as an initial risk assessment in order to extract potential hazards and risks to hydrogen fueled ships that are not covered by the existing regulations. As the result of HAZID, several potential risks have been identified, KHI faced various challenges. However, since KHI has a wide range of hydrogen-related technologies, achievements and experiences as a shipyard, a marine equipment manufacturer including reciprocating engines and a plant engineering, as an example KHI can perform quantitative CFD analysis and can take advantage of such strength to address them. KHI is now developing MHFS in preparation for demonstrations by the actual ships, with a view to achieving decarbonization in the future maritime industry.

### 3.1 HYDROGEN CHARACTERISTICS

Hydrogen has physical characteristics like extreme cryogenic liquefied temperature, very light weight, wide flammability range, high heating value, low energy density, low minimum ignition energy and high diffusivity in air. Some differences in physical characteristics between hydrogen and methane (the main component of LNG) are shown in Table 5. It is obvious that hydrogen needs to be handled and treated differently from LNG.

Table 5.
Characteristics of hydrogen vs methane [1]

| Physical characteristics | | **Hydrogen** | Methane |
|---|---|---|---|
| Boiling point | K | **20.3** | 110 |
| Liquid density | kg/$m^3$ | **70.8** | 423 |
| Vapor density | kg/$Nm^3$ | **0.084** | 0.717 |
| Flammable range | % | **4 - 77** | 5.3 - 17 |
| Lower heating value | MJ/kg | **120** | 50 |
| Liquid energy density | GJ/$m^3$ | **8.5** | 21.2 |
| Minimum ignition energy | mJ | **0.017** | 0.274 |
| Air diffusion coefficient | $cm^2/s$ | **0.61** | 0.16 |
| Critical pressure | MPa | **1.315** | 4.595 |

The following liquefied and gaseous hydrogen-specific hazards have to be considered [1]:

- Low temperature hazard
- Hydrogen embrittlement
- Permeability
- Low density and high diffusivity
- Ignitability
- Fire hazard
- High pressure hazard
- Health hazard
- Wide range of flammability limits
- Prevention of dangerous purging operation

### 3.2 COUNTERMEASURE FOR HAZARDS AND RISKS

To cope with hazards and risks of hydrogen, a variety of investigations and studies has been implemented. Based on them, various countermeasures have already been involved in the developments of MHFS.

#### 3.2.1 HIGH-QUALITY THERMAL INSULATION

Especially for cryogenic temperature of hydrogen, high-quality thermal insulation for piping and $LH_2$

fuel tank is indispensable to meet the following two hydrogen-related hazards and risks.

One is an extremely low boiling temperature of 20 K (-253 °C) at the atmospheric pressure. Only the high performance thermal insulation can suppress generation of boil-off hydrogen to a quite low level. If a large amount of boil-off hydrogen generates, pressure in the pipe reaches much higher pressure than the working pressure. That results in operating safety relief valves and also leads to gas lock, then hydrogen cannot send to the hydrogen fueled engine.

The other is a risk of generation of liquid air. If the insulation is lack of enough performance, outside surfaces on cryogenic pipes and $LH_2$ fuel tank become extremely cold below the liquefied temperature of surrounding air. It has to be counter-measured so as to prevent air from being liquefied because it causes damage to ship's crews and ships' structures.

In order to take countermeasures against these risks, vacuum insulation is applied as high-quality insulation to both cryogenic pipes and $LH_2$ fuel tank. Vacuum insulation has the highest insulation performance, but those applications to extreme cryogenic temperature around 20 K (-253 °C) are not prevalent in the marine industry so far, new considerations are required as listed below:

- Complete airtightness must be achieved so as to maintain a high degree of vacuum for a prolonged period.
- Radiant heat ingress passing through vacuum insulation must be minimized with multi-layered sheets.
- Outgassing from steel structures of vacuum insulated pipes and tank must be previously discharged out and evacuated as far as possible at the manufacturing stage and before use of them.

### 3.2.2 GAS DIFFUSION ANALYSIS (MHFS-LP)

Since hydrogen has high diffusivity, risks associated with hydrogen gas vented from the vent mast may exist.

In case a large amount of hydrogen is released into the atmosphere, it may be assumed that high concentration plume of hydrogen and air mixture reaches to safe areas such as the accommodation area on the ship.

In order to confirm possibilities of such risks thoroughly, several cases of hydrogen gas diffusion analysis have been simulated for both types of MHFS. As one of crucial scenarios, a situation where $LH_2$ fuel tank is wholly enveloped by fire on the ship and the largest amount of cold gaseous hydrogen is released into the air from the vent mast via the tank's pressure relief valves was assessed.

As an example, Figure 14 shows the results of the studies for MHFS-LP under different wind conditions. It was confirmed that high concentration over 100% LEL (contour line in red) even in high wind speed does not cover the accommodation area. The appropriate location of the vent mast and the distance between the accommodation area and the vent mast was reviewed, considering such a crucial situation in an initial design phase.

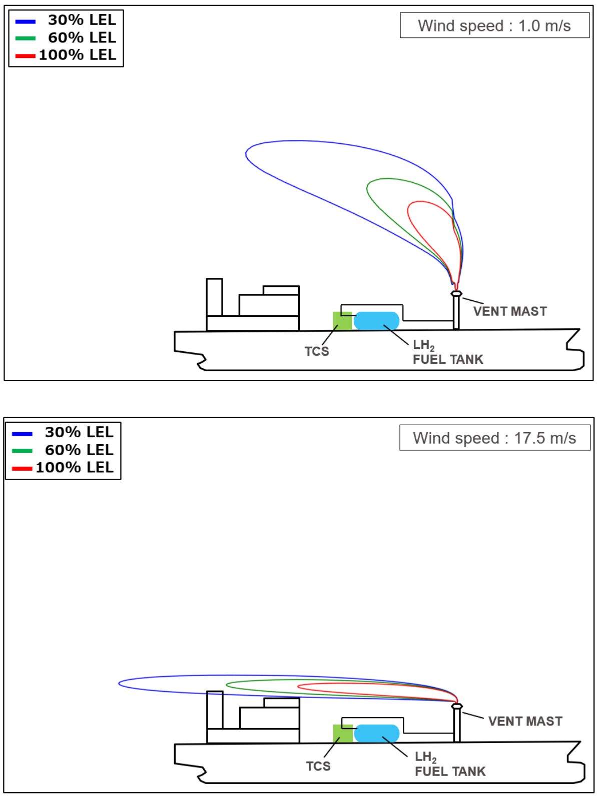


Figure 14.
Result of diffusion analysis from vent mast

### 3.2.3 STUDY OF THERMAL RADIATION IN VENTED GAS FIRE (MHFS-LP)

Since hydrogen has properties of a wide range of flammability and low ignition energy, potential risks of ignition and fire of hydrogen gas vented from the vent mast may exist.

In case that large fire around $LH_2$ fuel tank continues, continuous hydrogen gas discharge from the vent mast via the tank's pressure relief valves cannot be avoided. Therefore, the effects of heat radiation by vented gas fire is considered to be necessary. The largest vent amount of hydrogen is equivalent to the capacity of the pressure relief valves.

The effects of heat radiation by vented gas fire have been calculated in various conditions to assess safety issues for both types of MHFS. Regarding the estimation of the effects of vented gas fire, references are made to API Standard 521 [2]. As an example, Figure 15 shows the calculation result of radiation heat flux by the largest vented hydrogen fire for MHFS-LP on board. The evaluation criteria of 2.5 kW/m$^2$ is the maximum radiant heat flux, one of the life safety performance criteria in IMO MSC.1 / Circ.1552 [3].

Even in the event of the severest situation considered, it was confirmed that the accommodation area and escape routes around the area will not be exposed to radiant heat flux greater than 2.5 kW/m$^2$. As a different case from the above, vent fire where natural boil-off hydrogen gas is discharged and then ignited was also evaluated. Discharge of natural boil-off gas would happen a little more frequently than the above-mentioned severest situation. It was also confirmed that the effect of vent fire of natural boil-off gas is very limited and negligible to the ship.

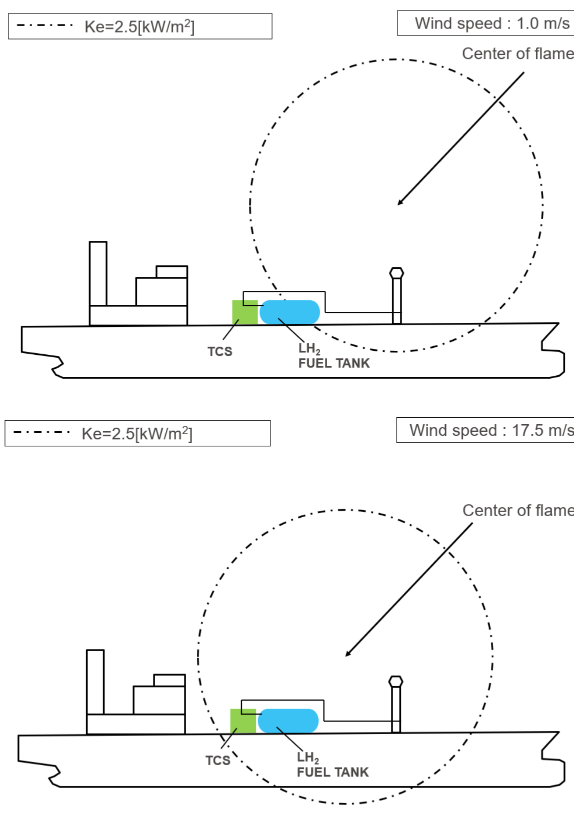


Figure 15. Result of radiant heat area calculation for MHFS-LP

### 3.2.4 SIMULATION OF GAS DISPERSION IN ENCLOSED SPACE (MHFS-HP)

Most hydrogen-fueled ships will have enclosed hydrogen hazardous spaces, such as FPR in which fuel supply machinery and equipment are arranged. In case that a hydrogen leak occurs in the enclosed space, inflammable hydrogen gas can spread and disperse throughout the space. IGF Code specifies a ventilation capacity of 30 times air changes per hour for such a space, however the requirement is applicable to natural gas. Therefore, the safety equivalence of the design and arrangement for hydrogen fueled ships should be verified comparing hydrogen gas with natural gas. In addition, hydrogen gas which is lower density than air collects below the ceiling, so it is necessary to prevent hydrogen gas from stagnating in pockets in back of structural frames and in corners.

Figure 16 shows an example simulating ventilation efficiency of FPR with a software for computational fluid dynamics. It was checked how long it takes to completely exchange air in the room and whether or not stagnant pockets are formed. Figure 17 shows a simulation result of hydrogen gas dispersion. A scenario with the most amount of leakage was identified among the possible leakage troubles on pipes and valves in the room, and the simulation shows that the ventilation is efficient and does not leave a widespread explosion atmosphere exceeding the lower explosion limit.

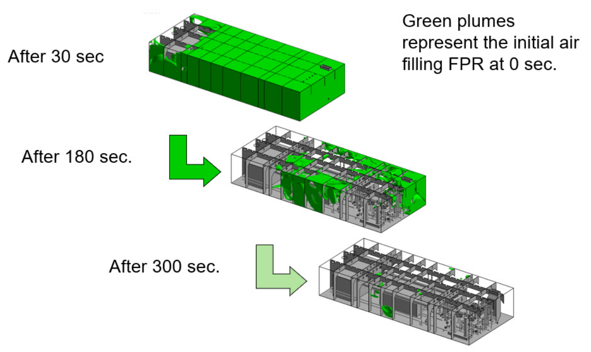


Figure 16.
Simulation of ventilation efficiency in FPR

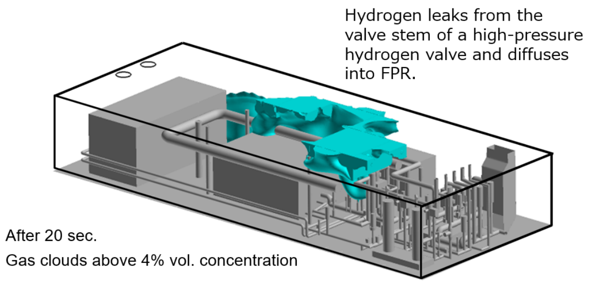


Figure 17. Simulation of gas dispersion in FPR

### 3.2.5 SIMULATION OF GAS EXPLOSION IN ENCLOSED SPACE (MHFS-HP)

Following the simulation of gas dispersion in FPR, a simulation of gas explosion in the room was carried out with an explosion, fire, dispersion modelling software.

FPR is classified as a hydrogen gas hazardous area Zone 1, so it must be forcedly and continuously ventilated and equipped with certified electrical equipment. However, hydrogen has properties of a wide flammability range and low ignition energy, so the risk of explosion should be anticipated just in case.

In order to study this risk, an explosion simulation for the enclosed space was carried out taking into account several strict conditions, including a large amount of hydrogen leakage, the time lag until the leaked hydrogen reaches a hydrogen detector, the detection delay by the detector, and the activation time of the MHFS-HP emergency shutdown devices. Based on this hypothetical scenario, the total amount of hydrogen remaining in the room was calculated and used as the amount of hydrogen to be ignited in the explosion simulation.

Figure 18 shows the distribution of explosion peak pressure just after the hydrogen explosion in FPR. Figure 19 is an example of the time variation of an explosion pressure wave at a point.

KHI is currently working with the shipyard to design the structure of FPR to tolerate these peak pressures.

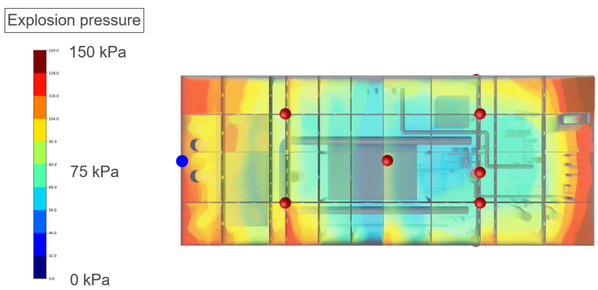


Figure 18. Result of explosion analysis (1), Peak pressure distribution in FPR

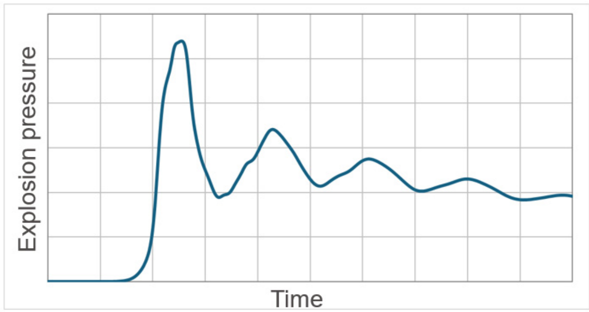


Figure 19. Result of explosion analysis (2), Time variation of explosion pressure (at blue point of Figure 18)

### 3.2.6 BUNKERING OF $LH_2$ TO THE SHIP

In addition to development of MHFS, the bunkering facility and procedures for $LH_2$ fuel bunkering needs to be developed. There are several development issues to be considered for liquefied hydrogen bunkering, including the fact that nitrogen gas utilized as inert gas can condense due to the higher boiling temperature than liquefied hydrogen, and the fact that hydrogen is prone to leaking, and use vacuum insulation technology for bunkering equipment such as bunkering hoses, bunkering manifold connections and emergency release couplings.

KHI is planning to complete the facility and operating procedures in time of the demonstration of the hydrogen fuelled ships. See Figure 20 as an image.

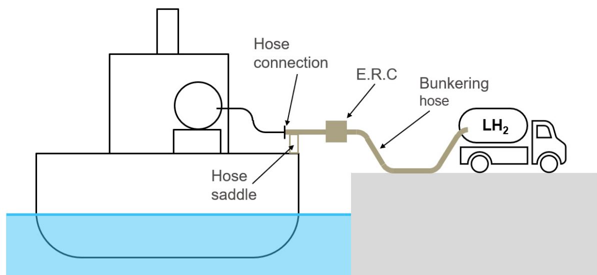


Figure 20. Bunkering operation image of MHFS

## 4 CONCLUSION

Since the Paris Agreement came into force, public concerns about the global environment are shifting from low-carbon to decarbonization. In the marine sector, LNG fueled ships have already become prevalent as one of ways to low-carbon, and technical standards, fundamental regimes and systems are almost gotten in place. However, any kinds of zero-emission ships are not yet prevailing, and further efforts toward decarbonization are still required. In order to develop zero-emission ships such as hydrogen fueled ships, it must be carefully considered what points should be paid attention to and what measures should be taken in unknown and limited historical fields.

Since the physical characteristics of hydrogen are significantly different from those of LNG, a wide range of considerations and reviews are essential for developing hydrogen fueled ships and hydrogen fuel supply systems. In particular, hazards and risks related to hydrogen, such as cryogenic, ignition, explosion, diffusion, etc. need to be assessed and addressed at the early stages of concept and design to mitigate them as much as possible.

KHI will continue developing MHFS and addressing a variety of challenges associated with the developments, focusing on the potential of liquefied hydrogen as a fuel for advanced ships. Through the developments, KHI aims to complete its first MHFS-LP and MHFS-HP as FGSS for hydrogen fueled ships within the next few years.

## 5 ABBREVIATIONS

| | |
|---|---|
| BS | Bunkering Station |
| ERC | Emergency Release Coupling |
| FPR | Fuel preparation room |
| FGSS | Fuel Gas Supply System |
| GCU | Gas Combustion Unit |
| $GH_2$ | Gaseous Hydrogen |
| GI FUND | Green Innovation Fund |
| HAZID | Hazard Identification Study |
| IGF Code | International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels |
| IMO | International Maritime Organization |
| KHI | Kawasaki Heavy Industries, Ltd. |
| LEL | Lower Explosion Limit |
| $LH_2$ | Liquefied Hydrogen |
| MARVS | Maximum Allowable Relief Valve Setting |
| MHFS | Marine Hydrogen Fuel System |
| MHFS-LP | MHFS for Low Pressure supply |
| MHFS-HP | MHFS for High Pressure supply |
| PBU | Pressure Build-up |
| TCS | Tank Connection Space |
| VIP | Vacuum Insulated Pipe |

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## 7 REFFERENCE

[1] MSC.565(108)-Revised interim recommendations for carriage of liquefied hydrogen in bulk

[2] API STANDARD 521, SEVENTH EDITION, JUNE 2020

[3] MSC. 1/Circ.1552-AMENDMENTS TO THE GUIDELINES ON ALTERNATIVE DESIGN AND ARRANGEMENTS FOR FIRE SAFETY (MSC/CIRC.1002)