World's First Zero Emission Battery-Propelled Tanker and Outlook for the Future

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1. INTRODUCTION

Reduction of emissions of greenhouse effect gases (GHG) as a measure against global warming is an urgent challenge. In ships as well, in order to reduce GHG further toward the achievement of GHG emission targets, it will be necessary not only to improve ship geometry and the efficiency of unit components such as engines and propellers, but also to change the thinking on the energy used in ships as a whole, including onboard energy use. One such approach is hybrid propulsion systems and battery propulsion systems, which are already increasingly used in automobiles.

Kawasaki Heavy Industries, Ltd. recently delivered a large-capacity battery propulsion system for coastal ships for the world's first zero-emission battery-propelled tanker, the "Asahi" (see Fig. 1), which was ordered by Asahi Tanker Co., Ltd. (hereinafter, the Owner) and completed at the end of March 2022. This ship was constructed by Koasangyo Co., Ltd. (hereinafter, the Shipyard) and is now operating as a bunkering ship (ship fuel supply vessel) sailing in Tokyo Bay. This paper introduces the background, overview and features of the battery propulsion system and the outlook for the future.

Fig. 1 Battery-propelled tanker "Asahi"

2. BACKGROUND OF DEVELOPMENT

2.1 Background of Development

In April 2018, the IMO (International Maritime Organization) adopted the Initial IMO Strategy on the reduction of GHG from ships in international shipping, and has set a target of reducing GHG emissions by 50% from the 2008 level by 2050 and further achieving zero GHG emissions by the earliest possible date in the present century. In a related development, various countries also announced their aim of achieving carbon neutrality in international shipping in 2050 at the COP26 meeting held in England in November 2021. As these moves indicate, the momentum toward GHG reduction in ships is accelerating worldwide.

In Japan, former Prime Ministry Suga announced a target of net-zero GHG emissions in 2050, with a reduction of 46% from the 2013 level to be achieved by 2030. Based on this, in August 2021 Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) raised the CO_2 reduction target for coastal ships in fiscal year 2030 from a 15% reduction to a 17% reduction against FY 2013.

To accelerate energy conservation and CO_2 emission saving in coastal ships, MLIT established an energy conservation rating system for coastal ships which evaluates the energy conservation and CO_2 emission saving performance of ships and began full-scale operation of this system in March 2020 [*1]. Thus, the momentum of GHG reduction is also increasing in the coastal shipping

[*] Kawasaki Heavy Industries, Ltd.

[*1] Ministry of Land, Infrastructure, Transport and Tourism (MLIT). For more information concerning the energy conservation rating system for coastal ships: https://www.mlit.go.jp/maritime/maritime_tk7_000021.html

sector.

2.2 Energy Use in Ships

The energy used by ships can be divided into two types, propulsion power and onboard electric power for pumps, lighting, control use, etc. Propulsion power (thrust) is supplied by the main engine, while onboard electric power is supplied by generators. As shown in Fig. 2, these two types of power are generally used in a completely separated manner. Although depending on the application and size of the ship, the main engine unit is frequently substantially larger than the generator unit and also has higher efficiency.

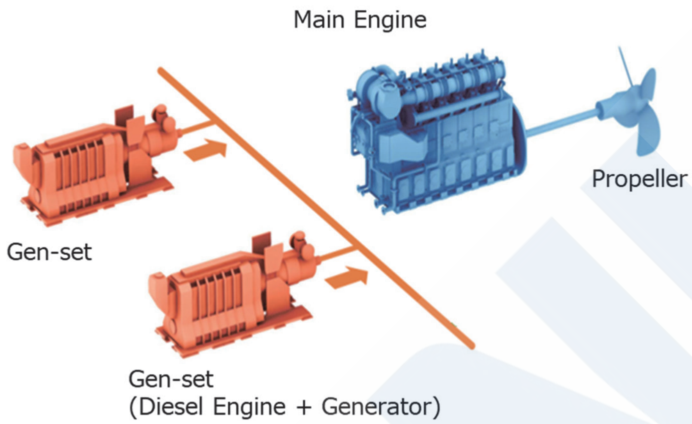

Fig. 2 General energy system of ship

Since the cost of the fuels consumed by the main engine and generators occupy a large part of the cost of ship operation, reduction of fuel costs has attracted great interest. Ongoing research and development on ship propulsion performance is being carried out, including ship geometries that reduce propulsion resistance, improvement of the performance and efficiency of the main engine and propeller, and accessory items to improve above performances. However, in some cases different companies are responsible for the hull (shipyard), the main engine (main engine maker) and the propeller (propeller maker), and as a general practice, improvement activities for each are only carried out for the simple unit component.

2.3 Energy Use in Ships

In these circumstances, the Kyoto Protocol of 1997 led to heightened awareness of the environment, and the price of crude oil rose sharply from around 2005 and has remained high since that time. Against this background, efforts were made to reduce fuel costs and conserve energy in the total ship, rather than in the individual component parts. There were attempts to couple the two energy sources, that is, the main engine for ship propulsion and the generators for onboard power, from an electrical view point and optimize the operation of the main engine and generators considering the power required in the total ship. This system configuration is called a hybrid propulsion system because propulsion power is supplied by two power sources, that is, the main engine and the generators (Fig. 3).

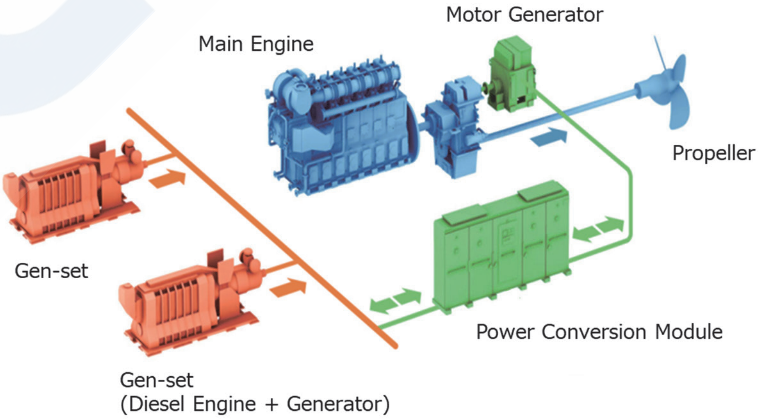

Fig. 3 Hybrid propulsion system

2.4 Trend toward Environment-Friendly Systems Incorporating Batteries

In addition to the hybrid propulsion system described above, lithium-ion batteries (LiBs), which are widely used in industrial applications and electric vehicles (EVs), are now also available for ship use. A battery hybrid propulsion system (Fig. 4) is a system that combines a marine LiB and a conventional hybrid propulsion system.

While a ship is navigating with energy supplied by the battery, it discharges zero exhaust gas, enabling local "zero emission navigation," for example, in ports and harbors.

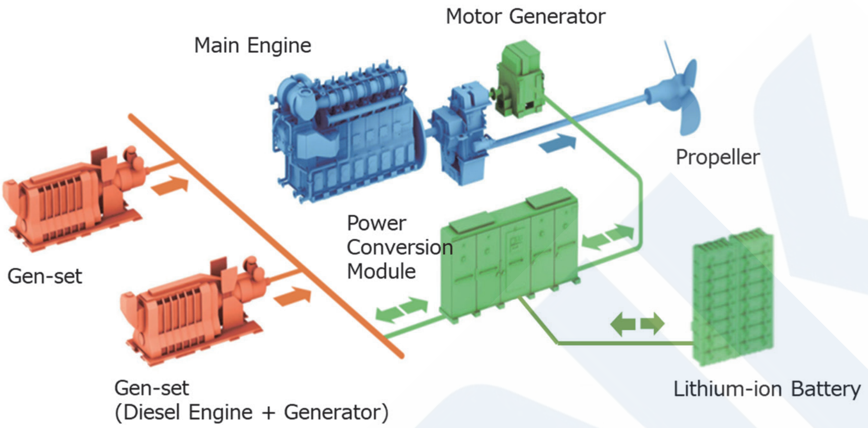

Fig. 4 Battery hybrid propulsion system

In a pure battery propulsion system (Fig. 5), the main engine and main generators are eliminated from the equipment configuration in Fig. 4. Because a pure battery propulsion system does not use internal combustion engines, it is an extremely environment-friendly system which makes it possible to realize zero emissions in all operations.

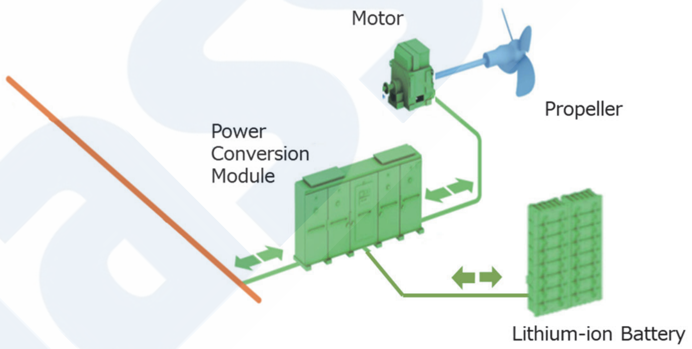

Fig. 5 Battery propulsion system

2.5 Initiatives of Kawasaki Heavy Industries

Kawasaki Heavy Industries has designed and manufactured various types of marine propulsion equipment, such as engines for use as main engines and generator engines, variable pitch propellers, and a fully azimuth-steerable 360° rotating-type thruster called the Kawasaki Rexpeller®, which can generate thrust in any desired direction. Although the company contributed to ship energy conservation and CO_2 emission saving by increasing the performance and improving those equipment, it also developed and commercialized the Kawasaki Hybrid Propulsion System beginning in 2014. Development was carried out prioritizing the power management technology, which optimally controls multiple energy sources, including the main engine, generators, batteries, etc., and battery management technology, which is currently indispensable for zero emission operation, and a system package that achieves economic effects and exhaust gas reduction while also securing the necessary power and power source quality is proposed.

Environment-friendly propulsion systems are available in multiple patterns, as outlined above. Since the most suitable system will differ depending on the vessel size and operation, it is important to take a comprehensive view of the ship as a whole, including its role and operation, the effects that the owner hopes to achieve, etc. Kawasaki Heavy Industries communicates fully with the ship's owner in order to optimize the concept at an early stage.

3. OVERVIEW AND FEATURES OF THE ZERO-EMISSION BATTERY-PROPELLED TANKER "ASAHI"

3.1 Features of Battery Propulsion System

As benefits of battery propulsion systems, both GHG emissions such as carbon dioxide (CO_2) and pollutants such as nitrogen compounds (NOx), sulfur compounds (SOx) and soot and smoke (particulate matter: PM) can be substantially reduced. Other benefits of battery propulsion systems include improvement of the living environment for the crew by reduction of noise and vibration because the ship does not have a main engine, and improvement of the environment around the port.

On the other hand, because the batteries employed in battery propulsion systems have a much smaller energy density than the heavy oil used as a general marine fuel, the cruising distance (range) is an issue. In terms of the system configuration, a battery propulsion system appears simple, but actual operation is a challenging endeavor. In fact, system configurations that supply all of the energy required for ship operation using only batteries have only been adopted in some limited types of ships, such as short distance ferries serving regular routes.

3.2 Study of Specifications of the "Asahi"

Operation of a bunkering ship broadly consists of four types of operation: ① Cargo handling work (taking on fuel oil on the bunkering ship, supplying the fuel oil to other ships), ② Voyaging to fuel oil loading and bunkering locations (navigation), ③ Entering/leaving port, berthing/deberthing, coming alongside/leaving the ship being fueled and ④ Anchorage (waiting while in service, mooring). The main equipment used in these respective operations is as follows.

Table 1 Main equipment in each operation

① Cargo handling	Cargo pump (when fueling other ships), controllers and other onboard equipment
② Navigation	Thrust (propeller), onboard equipment
③ Entering/leaving port, berthing/deberthing, coming alongside/leaving	Thrust (propeller), side thrusters, deck machinery
④ Anchorage	(when waiting) Pumps and other onboard equipment, (mooring) cooking equipment and other everyday life devices

The battery capacity, which is the largest factor in a battery propulsion system, was determined by conducting a simulation of energy use. The factors related to battery capacity are the operating time of each of the above operations and the energy consumption of the operation. Because the cargo handling locations are distributed in Tokyo Bay and the number of cargo handling operations in one day differs, various operational patterns must be considered. Therefore, the operational data for an existing ship, navigation distances and other information were obtained from the ship's Owner, updated for the specifications of the new ship, and used as the input data for the simulation. The propulsion performance and a knowledge of batteries are also important elements for determining the battery capacity. In conducting the simulation, we took advantage of the strengths of Kawasaki Heavy Industries as a general heavy industrial manufacturer. Propulsion performance was based the experience of the company's Marine Machinery Business Division, which has delivered a large number of propellers to date, and the battery technology was based on the experience of the Battery Team in the Technology Development Division. The simulation of energy use was carried out based on this information, and the battery capacity necessary for the operation of this ship was determined. In addition, the possibility of actual operation with the calculated battery capacity was also verified.

For battery charging, a plug-in system using land-based power was adopted. In the operation of the ship, the battery is charged while the ship is moored at night after completing the day's operation and returning to port, and the ship then leaves port the next morning. The study of the charging procedure and the power supply capacity required to complete charging while the ship is moored overnight was carried out in cooperation with a land-based equipment company.

Based on the battery capacity determined as described above, the arrangement of the individual batteries in the ship was studied in consultation with the Owner and the Shipyard. Taking advantage of the flexibility of arrangement possible with a battery propulsion system, the batteries were arranged in two layers on the bow sides, realizing a shipboard layout that can secure the necessary load capacity of fuel for bunkering while also keeping a large living area for the crew.

Since high maneuverability is demanded in a bunkering ship, which frequently performs the operations of entering/leaving port, berthing/deberthing and coming alongside/leaving ships being fueled, a design with 2 azimuth thrusters and 2 side thrusters was proposed for the propulsion equipment. The power of the propulsion equipment was decided considering its arrangement on a vessel with a gross tonnage of 499 tons while maintaining the necessary speed.

Based on the study described above, the following specifications were adopted for the ship.

Table 2 Specifications of "Asahi"

Dimensions	Length overall: 62 m / Beam: 10.3 m Draft: 4.15 m
Speed	10 knots (approx.)
Tank capacity	1,277 m^3
Propulsion equipment	Azimuth thruster: 300 kW x 2 Side thruster: 68 kW x 2
Battery capacity	3,480 kWh

3.3 Large-Capacity Battery Propulsion System

Kawasaki Heavy Industries was responsible for the large-capacity battery propulsion system, which comprises the large-capacity LiBs, main switch board, power management system, power conversion module, main electric motor, azimuth thrusters (Kawasaki Rexpeller®), propulsion control system, side thrusters and other equipment (Fig. 6).

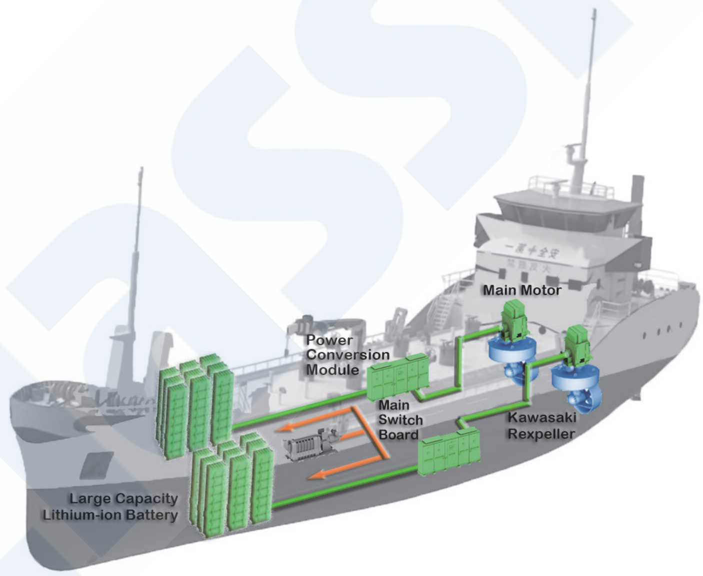

Fig. 6 Large-capacity battery propulsion system

As shown in Fig. 6, the lithium-ion batteries are coupled with the power conversion module, which distributes the power from the LiBs to the main motor and the main switch board for use as propulsion power and onboard power, respectively. As discussed in Section 3.2, this ship has four types of operation, ① Cargo handling, ② Navigation, ③ Entering/leaving port, etc. and ④ Anchorage. The following mode setting is performed for these four operations.

Table 3 Definitions of operational modes

Cargo handling mode	Mode in which fuel is supplied to the ship being fueled by using the cargo pump.
Navigation mode	Mode in which the ship navigates by using the azimuth thrusters.
Entering/leaving port mode	Mode in which the ship enters/leaves port, performs berthing/deberthing and comes alongside/leaves the object ship by using the azimuth thrusters and side thrusters.
Anchorage mode	Mode in which the ship stops the azimuth thrusters and side thrusters and moors.

Smoothly utilizing each of these operations as appropriate is extremely important for the operating efficiency of the ship. Furthermore, it is also necessary to consider the safety aspect so as to ensure that there are no mistakes in the start of operation of the propulsion equipment during cargo handling work. Considering both the operational aspect and the safety aspect, mode switching sequence is set as navigation mode and entering/leaving port mode, in which the propulsion equipment is used, and cargo handling mode, in which mode switching is performed once via the anchorage mode.

The devices used in the four operational modes are different, and large propulsion power is required in the navigation mode, while large onboard power is required in the cargo handling mode and entering/leaving mode. This means it is important to switch the necessary propulsion power and onboard power smoothly based on the operational mode. Since it is a burden to the ship's operator for switching the operating equipment and changing the allocation of power with an awareness of this, the system for this ship is equipped with a function that automatically judges the operational mode and switches the energy distribution automatically. This function is materialized by optimal management of the energy/power flow in the propulsion control system. In the anchorage mode at the mooring point, the batteries are charged by receiving power from an onshore power supply facility.

In addition to operational mode switching and management of propulsion power and onboard power, the propulsion control system also performs integrated control of battery charge/discharge management.

3.4 System Safety

At present, no ClassNK rules have been established for battery-propelled ships at present. Therefore, the battery room and the batteries themselves were designed based on "Guidelines for Large-Capacity Storage Batteries," which has been published by ClassNK. Because Chapter 4.9 of the Guidelines requires a risk assessment for safety, the safety of the system was verified by using HAZID (Hazard Identification). HAZID is one assessment technique for determining how the target system may affect human life and the environment by identifying assumed events (hazards) and studying the safety of the system based on the combination of their frequency of occurrence and degree of effect. In HAZID, the risks in the ship operation condition during normal operation and under abnormal conditions such as fire, etc. is verified, and safety measures are studied. In the HAZID for this ship, the risk assessment was conducted with the participation of the Owner, the basic design company and Kawasaki Heavy Industries, and for a safety assessment from the third-party viewpoint, ClassNK and NK Consulting Service Co., Ltd., which is also a risk assessment facilitator, were also asked to participate.

In the HAZID, hazards related to the ship were identified by the cause of the hazard, which included items related to the lithium-ion storage battery system itself and electrical, thermal and other hazards. The following are examples of representative hazards.

① Overcharging of batteries
② Thermal runaway of batteries [*2]
③ Abnormality of control devices

The validity of the design in the stage prior to the HAZID was evaluated for these hazards, and the necessity of additional safety measures was discussed. As a result, it was confirmed the risk of all hazards could be suppressed to the tolerable range by executing the design at the time of the HAZID with additional safety measures, and the design in which these safety features were confirmed was implemented in the ship.

[*2] Thermal runaway refers to a condition in which a designated internal component in a battery generates heat for some reason, that heat generation triggers heat generation in other components, and the temperature of the battery continues to rise. The main causes are internal short circuit, external short circuit, overcharging, heating from an external source, etc.

3.5 Handling of Batteries and Points to Note

Even in familiar electronic devices such as cellphones, it is known that batteries have a useful life, as they deteriorate with use and their performance gradually declines. Although fewer in recent years, in the past, examples of accidents in which mobile batteries exploded had been reported on television and in other media. The following are points to note when using large-capacity batteries on a ship.

① Temperature management

Proper temperature management of the ambient environment for battery use is important. If proper temperature management is not introduced, early deterioration of the battery is possible, and this may be fatal for the battery propulsion system, which depends on the battery as its main source of electric power. Therefore, we consulted with the Shipyard, air-conditioner manufacturers and others and selected an air-conditioner considering the heat generation from the battery itself and external heat inputs to the battery room.

② Application of the Fire Services Act

Lithium-ion batteries contain a flammable liquid electrolyte that falls under Class IV hazardous materials, Class II petroleum of Japan's Fire Services Act. Appropriate handling in accordance with the Act or local government ordinances must be noted, including handling during storage and ship outfitting work in the shipyard.

③ Fire-extinguishing devices in the battery room

A CO_2 fire extinguishing system was adopted as the fire-extinguishing device in the battery room. To enable sure fire-extinguishing in case a fire occurs, the control location and fire-extinguishing agent storage location were also discussed in the HAZID.

3.6 Features of the "Asahi"

In this ship, we adopted the KICS (Kawasaki Integrated Control System), which enables integrated control of multiple ship-handling elements. The improved ship maneuverability and shorter time required for berthing and deberthing, etc. reduce the energy necessary in ship operation, which in turn makes it possible to reduce the battery capacity in the battery propulsion system. In conventional ship handling, the ship operator must simultaneously operate multiple thrusters in order to move the ship in the intended direction. In response to operation of a joystick and dial, KICS moves the ship in the direction that the joystick is moved and turn the ship in the direction that the dial is turned (Fig. 7). KICS can also calculate the size and direction of the thrust that should be output by multiple thrusters corresponding to the operation of the joystick and dial by the operator and give appropriate commands to the various thrusters. This allows the operator to steer that ship only by intuitive operation, even in operations that are difficult and require care, such as berthing and deberthing.

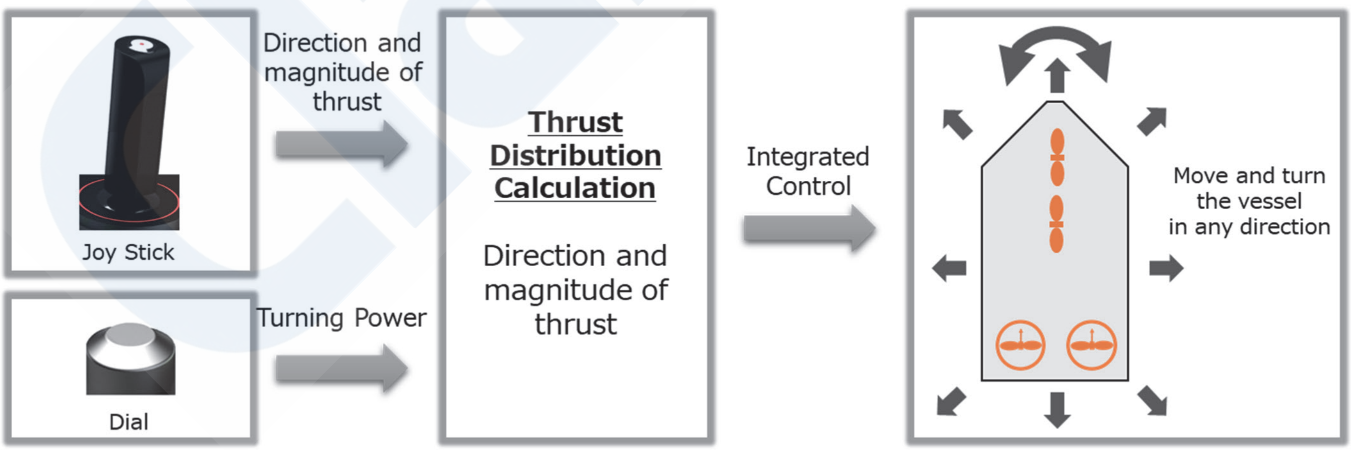

Fig. 7 Overview of KICS

As one more noteworthy feature, the ship's batteries can also be used as an emergency power source during large-scale natural disasters, which was an idea proposed by the owner and e5 Lab. By utilizing the electricity stored in the LiBs on the ship as an emergency power source on land, it is possible to contribute to the business continuity plans (BCP) and life continuity plans (LCP) of regional society. Moreover, because a ship can access locations where electric power is required from the sea under conditions where the land transportation network is not functioning due to traffic congestion or damaged roadways, this capability will expand the possibilities for responding to states of emergency.

4. OUTLOOK FOR THE FUTURE

4.1 Optimum System Configuration Corresponding to the Ship

Although higher energy densities have been achieved in batteries through technical innovation, the energy density of batteries is still far lower than that of the heavy oil used as a marine fuel. This means there is a limit to the cruising distance of a ship using only batteries, considering the balance with space on the ship. From this viewpoint, hybrid propulsion using a combination of batteries and an internal combustion engine is realistic in certain cases, for example, in ships with comparatively long continuous cruising distances and large ships, in which battery propulsion would only be used when entering and leaving port. In addition to the problems of shipboard space and cruising distance, there are also other elements that should be considered, such as the availability of charging points (or charging interval) and the time required for charging. Thus, it is necessary to study a total solution that includes not only the aspects of ship layout and operation, but also charging facilities on the land side.

Moreover, the types of operations such as cargo handling, work at sea, etc. vary depending on the type of ship, and the optimum size of the main engine, battery capacity and system configuration of each type will also differ. We, Kawasaki Heavy Industries, propose the optimum system for all ship sizes and ship types responding to each type of ship operation and the request of the ship owner.

Battery hybrid and pure battery propulsion systems also have excellent compatibility with engines using LNG, which has been adopted progressively as a low environmental load fuel in recent years, and with engines, fuel cells and other power sources that utilize future fuels such as hydrogen and ammonia, which are expected to be used as decarbonized fuels in the future. It is possible to propose GHG reduction options that also include the future by combining those technologies with the system described here.

4.2 Gas Single-Fuel Fired Engine + Battery Hybrid Propulsion System

Kawasaki Heavy Industries has developed and received its first order for a hybrid propulsion system which combines a marine gas single-fuel fired engine (Fig. 8) and a large-capacity lithium-ion battery. The basic configuration of the hybrid propulsion system consists of the gas single-fuel fired engine and a large-capacity LiB. However, as the system integrator, Kawasaki Heavy Industries also covers the propulsion equipment, such as the gas fuel supply system, variable pitch propeller and side thrusters, as well as other equipment such as the power conversion module, propulsion control system, etc. Optimum operation for CO_2 reduction while maintaining the necessary thrust is achieved by appropriately controlling those systems and equipment corresponding to navigational conditions.

During navigation, propulsion is provided by the gas engine by way of a speed reducer. At the same time, the electric power generated by a shaft generator is used to supply onboard electric power and charge the batteries. This means the gas engine can be operated continuously in the high load region, where it is possible to maintain high thermal efficiency, and separate operation of a generator to supply onboard power, like that on conventional ships, is not necessary. In addition, high-load operation of the gas engine can also be continued during bad weather by properly controlling the balance of thrust and power generation. When entering/leaving port and when the ship is anchored or moored, the gas engine is stopped and during voyage, electrical propulsion power and onboard power are supplied by the charged batteries, thereby achieving zero emission operation.

Fig. 8　Marine gas engine

4.3　Marine Lithium-Ion Capacitor

In battery hybrid and pure battery propulsion systems, the role of power storage systems such as batteries is to supply or store energy for propulsion power and onboard electric power. However, as another role, it is also possible to absorb load fluctuations of the main engine and main generators. That is, fuel economy is improved by assisting main engine load changes, for example, in rapid acceleration, and in compensating for fluctuations in propulsion output during bad weather, etc.

In comparison with heavy oil-fired diesel engines, it is said that the above-mentioned engines that use LNG or future fuels such as hydrogen or ammonia generally have a narrower stable combustion region and are more susceptible to misfiring and knocking due to load fluctuations. For this reason, stabilizing the engine load by using these engines in combination with batteries or some other type of power storage system can contribute to expanding the range of application of these new fuel engines and their operable region.

Kawasaki Heavy Industries was the first to focus on this kind of load fluctuation absorbing application of the power storage system, and developed a power storage system using a marine lithium-ion capacitor (LiC) (Fig. 9)

The LiC is a storage device with a high power density (capable of instantaneously charging/discharging a large amount of electric power) and has an extremely long life when repeatedly charged and discharged. Table 4 shows a comparison of the representative specifications of the LiC and a lithium-ion battery (LiB), which is also a storage device. While the LiB has a high energy density and is suitable for supplying energy over a long period, the battery deteriorates due to repeated charging and discharging, and its power density is low. On the other hand, the LiC has a low energy density and thus is not suitable for supplying energy over an extended period, but it has the benefits of a high power density and extremely long life under repeated charging and discharging. Therefore, while the LiC alone cannot be used in ship propulsion and power supply applications, a large reduction in size, lower cost and long life can be expected by limiting its use to the load fluctuation absorbing function.

Fig. 9 Marine lithium-ion capacitor (LiC)

Table 4 Comparison of LiB and LiC

Item	LiB	LiC	Remarks
Temperature of use environment	15 to 25 °C	5 to 45 °C	
Cycle life	10,000 or less	500,000 or more	Differs depending on test conditions.
Float life	10 years (approx.)	20 years or more	At 25 °C
Charge/discharge rate	3 C (approx.)	100 C	1 C: 100% discharge in 1 hour

5. CONCLUSION

With the ongoing tightening of regulations on all types of exhaust gases by the IMO (International Maritime Organization), use of clean power sources as an alternative to the heavy oil which is generally used as a ship fuel has attracted large expectations and interest in the shipping industry. One of these clean power sources is battery propulsion systems, which can substantially reduce emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx) and particulate matter (PM) during ship operation. Proposing the optimum system, which differs in each ship, and wide dissemination of the system described in this paper will contribute to improvement of the global environment, and Kawasaki Heavy Industries would also like to play a role in those efforts.

In the future as well, Kawasaki Heavy Industries will focus its efforts on supplying systems with excellent environment-friendliness and economy and optimized operation in line with the requests of its customers.

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