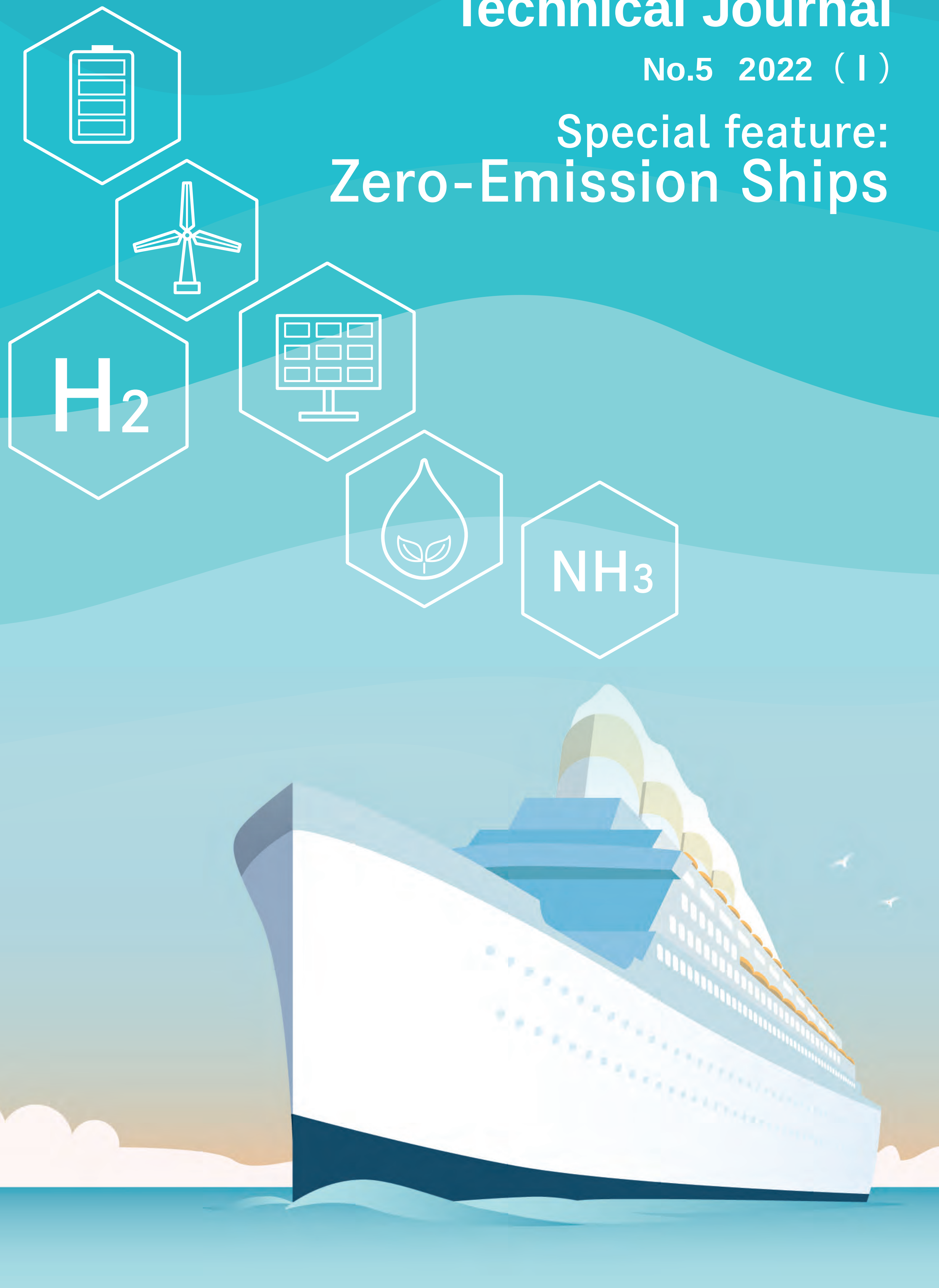
ClassNK

Technical Journal

No.5 2022 (Ⅰ)

Special feature:
Zero-Emission Ships



ClassNK Technical Journal　No.5　2022（Ⅰ）

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Since the Planning and Design Center for Greener Ships (GSC) was established in October of 2020, the GSC has promoted surveys and analyses of domestic and overseas trends, etc. with the aim of reducing GHG emissions from international maritime shipping, and also conducted a study on the ideal form of ships in the transition period leading to net-zero carbon in 2050 to promote the development of environmental ships from the viewpoint of how international shipping can achieve a smoother transition to net-zero carbon. This paper introduces representative efforts of the GSC in connection with regulatory trends and trends in new fuels related to decarbonization that will affect ship design, and the development of next-generation ships that respond to requirements for reduction of GHG emissions and zero emissions from international shipping toward the achievement of net-zero carbon.

As part of the energy transition strategy in Mitsubishi Heavy Industries Group, Mitsubishi Shipbuilding is engaged in the development of a “CO_2 capture system on the ocean” with the aim of reducing CO_2 emissions from ships. This paper introduces the CO_2 capture system of the marine demonstration project (CC-Ocean [Carbon Capture on the Ocean]), which was conducted in cooperation with Kawasaki Kisen Kaisha (“K” Line), Ltd. and ClassNK, under Japan’s Ministry of Land, Infrastructure, Transport and Tourism (MLIT), as the most recent of those efforts, and describes the future prospects for the development of this technology.

The coastal shipping industry is not only facing the longstanding challenges of both the aging of ships and seafarers and the limits to the succession of know-how, but also the issues of delayed implementation of environmental countermeasures and the resulting possibility of decreased corporate value in recent years. This paper introduces the features of the next-generation EV vessel ROBOSHIP as a realistic and practically possible solution to these problems, and its superiority and expandability in comparison with conventional ships. The paper also introduces the ship digitalization tool Marindows, which is planned to be provided as a response to delayed digitalization, which is also an issue in the coastal shipping industry.

The "EEXI regulation" and "CII fuel consumption rating system," which are intended to reduce CO_2 emissions from ships in service, are to be introduced in 2023, and moves toward zero emissions are accelerating also in the maritime shipping business. This paper introduces the outlines of the "EEXI regulation" and "CII fuel consumption rating system," ClassNK's response to these programs and the outline of the "ClassNK Zero-Emission Transition Service" being developed by ClassNK.

Technical Topics

Expanded utilization of wind energy is being promoted to realize carbon neutrality. However, as the scale and investment cost of facilities increase substantially, dramatically faster fluidics engineering calculation is necessary in order to perform more precise structural safety design and performance estimation. This paper introduces an "AI surrogate model" using a virtual particle model adopted from the lattice gas method, and explains the concepts contributing to higher computational speed through the functions of fuzzy estimation and real-time learning.

With the Paris Agreement entering into force in 2016 and the growing global momentum of decarbonization, the IMO adopted an Initial strategy on the reduction of GHG emissions at MEPC72 in 2018. Because ammonia produces zero GHG emissions, it has attracted attention as an alternative fuel, and the development of ammonia-fueled ships is being accelerated worldwide. To respond to that current situation, ClassNK issued "Guidelines for Ships Using Alternative Fuels Part C," which presents guidelines for the safety of ships using ammonia as fuel. This paper provides an overview of the current status and explains the outline of Part C of the Guidelines.

The Society established five basic strategies in the five-year medium-term management plan which started in 2017, and began a comprehensive revision of Part C of the Rules for the Survey and Construction of Steel Ships, which is an original rule for the construction of ship hulls formulated by the Society, in a manner that corresponds to one of those strategies, "Promoting research and development activities." The comprehensive revision of Part C is scheduled to be instructed around July of 2022. This paper explains the transition of the Society's structural strength rules since they were first issued in 1921 and describes the positioning of this comprehensive review from the viewpoint of the transition to date.

In the development of rules for hull structural strength, it is necessary to appropriately estimate the amount of the corrosion loss of the structural members of vessels over a period of 25 years. This paper introduces the results of estimation of corrosion loss using recent plate thickness measurement data in comparison with the probabilistic model for the process of the initiation and progress of corrosion that has been used conventionally. The corrosion additions provided in the rules were set based on the obtained corrosion loss results, and were compared with the corrosion additions provided in the Common Structural Rules of the IACS.

In recent years, the Automatic Identification System (AIS) has made it possible to assess the sea conditions actually encountered by ships by linking the location and time information obtained by AIS and the oceanographic data calculated by wave hindcasting. Based on the actual sea conditions encountered by general merchant ships in the North Atlantic, in this paper, a quantitative assessment of the effect of actual sea conditions on ship operation was carried out based on the Table of Wave Occurrence Frequencies in the North Atlantic Areas in Recommendation No. 34 of the International Association of Classification Societies (IACS Rec. No. 34) for the ship motions, vertical wave bending moment and wave hydrodynamic pressure of the ships concerned.

This study is joint research conducted for the purpose of “understanding bearing damage by monitoring the main bearing lubrication oil (LO) outlet temperature”. The study consisted of an actual ship onboard monitoring test and a simulation test. In the actual ship test, an analysis method that enables easier monitoring was also studied in addition of data monitoring, and damage items that cannot be measured on an actual ship were examined in the simulation test.

This article introduces recent topics discussed at International Maritime Organization (IMO). At this issue, a summary of the decisions taken at 77th Marine Environment Protection Committee (MEPC 77) and 104th Maritime Safety Committee (MSC 104) is provided.

Introduction to the Special Feature on “Zero-Emissions Ships”

Corporate Officer, Director of Research Institute, ClassNK
Yukihito FUJINAMI

I would like to take this opportunity to welcome our readers to this Special Feature of ClassNK Technical Journal No. 5 on “Zero-Emissions Ships.”

Globally, moves toward decarbonization are gaining momentum. Japan also announced a policy targeting net-zero emissions of greenhouse gases (GHG) by 2050, and at the United Nations Climate Change Summit in April 2021, the Prime Minister declared that Japan will accelerate its efforts by developing policies to achieve a 46% reduction in GHG in FY 2030 from the level in 2013.

In oceangoing shipping, study and introduction of regulations are underway based on the GHG reduction targets set under the leadership of the IMO, but since April 2021, various countries have proposed raising those targets.

In response to these circumstances, ClassNK carried out a reorganization in October 2021, and created the “Zero-Emissions Transition Center,” which is responsible for overall management such as drafting business strategies for GHG-related work, and the “Marine GHG Certification Department,” which responds to customer needs for GHG reduction in maritime shipping in an integrated manner, beginning with the response to international treaties.

By unifying the organization centering on these two new units, we intend to support carbon neutrality and contribute to expanding the businesses of all concerned.

On the other hand, we are also steadily promoting technical research and development, demonstration studies and related activities in order to expand and improve our technical services. During this fiscal year, we established a new R&D roadmap and proactively planned and implemented joint research with companies in maritime industries, specialized research organizations, universities and others, with society, the environment and safety as top priority research areas.

The ClassNK Technical Journal carries articles on the technical research activities of ClassNK, trends in international treaties, etc., beginning with the outcomes of technology research and development and the new knowledge developed through these kinds of partnerships.

In the previous issue, Class NK Technical Journal No. 4, we received contributions on risk evaluation of autonomous ship systems, the development of a comprehensive simulation system for autonomous ships, etc. from our joint research partners as a Special Feature on “Autonomous Operation.”

For the present Technical Journal No. 5, we have received contributions on the initiatives of the Planning and Design Center for Greener Ships (GSC), joint technology development for achieving carbon neutrality, etc. as a Special Feature on “Zero-Emissions Ships.”

In the future, ClassNK will continue its efforts to realize global social contributions through proactive efforts in technology development responding to the needs of society and maritime (shipping and shipbuilding) industries, the development of technical tools that support the solution of problems related to the environment and safety, and publication of the results of research and development.

We sincerely request the further guidance and support of all those concerned in the future, as in the past.

Efforts of the Planning and Design Center for Greener Ships (GSC)

Ryutaro KAKIUCHI*

1. INTRODUCTION

Initiatives to achieve the SDGs (Sustainable Development Goals) and the ESG (Environmental, Social and Governance) investment associated with those efforts are now part of the code of conduct of most of the companies. In particular, moves to reduce greenhouse gas (GHG) emissions have brought about a substantial transformation in the sense of values in corporate activities and products, and efforts to implement global warming countermeasures are accelerating at an increasing pace worldwide.

In international maritime shipping, the International Maritime Organization (IMO) adopted the Initial IMO Strategy on the Reduction of GHG emissions from Ships (hereinafter, GHG Reduction Strategy) in April 2018 with an interim target of reducing total GHG emissions by at least 50% compared to 2008 by 2050 and a long-term target of zero to be achieved as early as possible in this century. However, international shipping has already entered an era where efforts are premised on “2050 net-zero,” as can be seen in announcements of 2050 net-zero strategies by leading shippers in both Japan and other countries. In these circumstances, environmental performance, beginning with reduction of GHG emissions and the related technologies, now have an increasingly large value for ships.

Because Japan is surrounded by the sea, maritime industries, and particularly shipping and shipbuilding, are indispensable industries for this country, but in order to survive in the face of fierce international competition, it is necessary to accelerate efforts to realize competitive ships by integrating various environment-related technologies ahead of global competitors.

Against the backdrop of this social and industrial transformation, the Planning and Design Center for Greener Ships (hereinafter GSC) was established in October of 2020 by a group of volunteering companies that supported its purposes as the core organization for mobilizing the capabilities accumulated by the Japanese shipbuilding industry to date, integrating environment-related technologies that already exist and will be developed in the future, and continuously planning and proposing state-of-the-art ships. As of March 2022, the member companies were (in alphabetical order) Imabari Shipbuilding Co., Ltd., Japan Marine United Corporation, Mitsubishi Shipbuilding Co., Ltd., Mitsui E&S Machinery Co., Ltd., Naikai Zosen Corporation, Namura Shipbuilding Co., Ltd., Nippon Kaiji Kyokai (ClassNK), Onomichi Dockyard Co., Ltd., Oshima Shipbuilding Co., Ltd., Shin Kurushima Dockyard Co., Ltd., Shin Kurushima Sanoyas Shipbuilding Co., Ltd., and Sumitomo Heavy Industries Marine & Engineering Co., Ltd.

The GSC conducts wide-ranging information collection and technology development which extends beyond the framework of individual companies, and promotes the planning, development and commercialization of advanced environmental ships integrating diverse environment-related technologies in response to strengthening of environmental regulations in the medium- to long-term with the aim of contributing to the development of the Japanese shipbuilding industry.

2. TRENDS IN REGULATIONS AND FUELS RELATED TO DECARBONIZATION AFFECTING SHIP DESIGN

2.1 Trends in Regulations for Reduction of GHG Emissions in International Shipping

Due to the difficulty of assigning emissions to specific countries when ships operate under flags of convenience and third-party transportation is common, and due to a single global market of international shipping, reduction of GHG emissions in international shipping is being promoted in the form of uniform worldwide efforts and regulations through discussions in the IMO. Fig. 1 presents an overview of the technical and operational GHG emission reduction measures established by the IMO.

The international regulatory framework begins with two measures approved for introduction in 2011: the Energy Efficiency

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Design Index (EEDI) which mandates ship energy saving performance in the design stage of new ships; and the Ship Energy Efficiency Management Plan (SEEMP), an operational measure which requires that a plan showing the most efficient operational methods for CO_2 emission reduction be carried on board ships. Introduction of the EEDI system promoted reduction of GHG emissions through improvement of ship types and improved propulsion efficiency by the employment of energy-saving equipment. However, in spite of ongoing increases in the number of low-carbon LNG-fueled ships, the transition to zero-carbon fuels has not been achieved.

As operational measures for GHG emission reduction, efforts to achieve efficient ship operation have been made through SEEMP up to the present, but there were still no regulations that directly required reduction of CO_2 emissions in ships. However, based on the above-mentioned GHG Emission Reduction Strategy of the IMO, revisions of Annex VI of the MARPOL Convention for introduction of EEXI (Energy Efficiency Existing Ship Index) and CII (Carbon Intensity Index) regulations were adopted at the 76th session of the Marine Environment Protection Committee (EMPC 76) held in June 2021. Under the EEXI regulation, ship energy efficiency performance regulations are applied retroactively to certain types of existing ships, while CII is a new regulation based on CO_2 emission results, as a data collection system for rating fuel economy performance. The EEXI and CII regulations are scheduled to be introduced from 2023.

The EEXI regulation is a technical GHG reduction measure which is intended to reduce the amount of CO_2 emissions from ships in service by providing standard values for the fuel economy (fuel oil consumption) performance of those ships. This regulation is applicable to all ships of 400 GT or larger engaged in international maritime shipping, irrespective of the date when ship construction was completed. It should be noted that this is not intended to be a stepwise strengthening of the regulatory values, but rather, is set to be a constant value equivalent to the level of Phase 2 of EEDI (EEDI-II). By introducing EEXI, fuel economy performance similar to the level of newly built ships at this time is also required to ships in service.

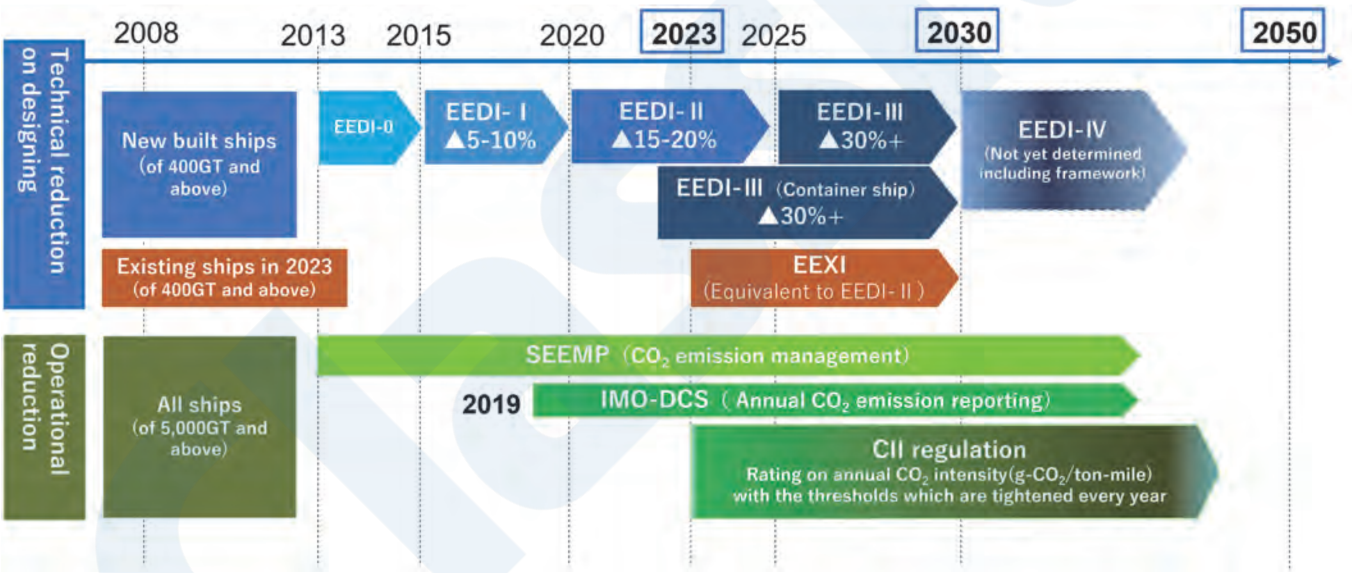

Fig. 1 Overview of technical and operational GHG emission reduction measures

The CII (Carbon Intensity Index) rating system for GHG emission intensity performance is a regulation with a large potential impact on the design of ships in the future. Until now, the core of regulations in ship design was the EEDI regulation, which is currently in the Phase 2 stage. Although Phase 3 is also scheduled for the future, the EEDI regulation is nevertheless a traditional approach to regulation of ship design by the IMO. That is, if a ship conforms to the EEDI requirements at the time of commissioning, a certificate is issued, and in principle, operation can continue for the life of the ship so long as the same condition is maintained.

In contrast, under the CII regulation, the annual GHG emission performance of ships are rated in 5 levels from A to E, and ships with a low rating (defined as the D rank for 3 consecutive years or E rank for 1 year) are given guidance on improvement by the supervising agency. As a system, the CII regulation is classified as an operational regulation for promoting improvement of environmental impacts, but because CII requirements can also affect the ship's loading capacity, the CII system also affects ship design. Among a noteworthy feature of this system, because threshold value (reduction factor) for ratings is automatically tightened each year, a ship's rating evaluation will gradually decrease even if that ship maintains the same fuel consumption performance as when newly constructed. Threshold values have been decided up to 2026, and while it has been decided that the values will also be tightened in 2027 and thereafter, the actual values are still undecided. This point, that is, the annual tightening of values, is completely different from the traditional EEDI approach mentioned above. Moreover, because this evaluation is based on actual emission results, this system may also have a large effect on ship design in cases where it is not possible to meet the requirement by operational measures alone, for example, by sailing at a slower speed. Depending on future CII threshold values aiming at achievement of 2050 net-zero emissions, a situation in which ships with a product life exceeding 20 years must switch to a zero-carbon fuel at some point during a voyage are also assumed.

Fig. 2 shows the results of a trial calculation of the CII reduction factor for achieving the 2050 net-zero target, when the target is the threshold value for the C rank (median value) of the CII rating.

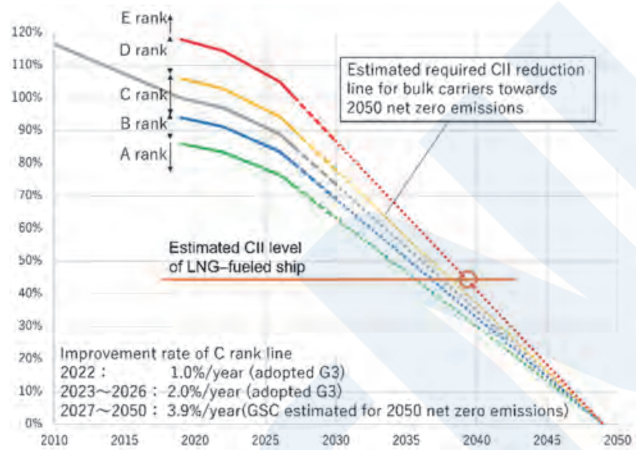

Fig. 2 Future reduction ratio (improvement rate) of CII rating (assumed by GSC)

As shown in this figure, in order to achieve the 2050 net-zero target, efforts to reduce CO_2 emissions by nearly 4% per year are required. Even assuming a ship reduces CO_2 emissions to CII performance of around 50% by energy saving measures and switching to LNG fuel, its rating will fall to the E rank in the second half of the 2030s, which means that conversion to a zero-carbon fuel will be necessary, as shown in Fig. 3. Moreover, at the present point, the only regulatory penalty is guidance on improvement, but there are also moves, particularly among major shippers and financial institutions, to evaluate the CO_2 emissions of chartered ships and ships financed by loans. Specifically, Sea Cargo Charter is a framework which was established by shippers, and the Poseidon Principles are an agreement among financial institutions for evaluating "climate alignment." The purpose of these two initiatives is to encourage reduction of CO_2 emissions in line with the reduction targets of the IMO. Since the IMO's fuel efficiency indexes are used in those evaluation indexes, it appears that this will heighten the business pressure on ships with low CII ratings in chartering and procuring financing in the future.

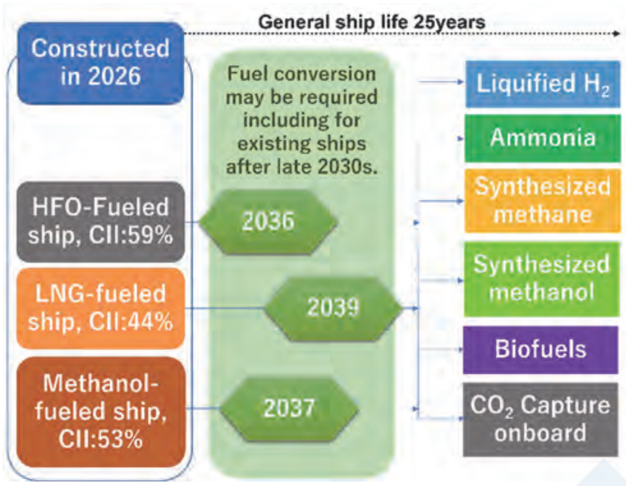

Fig. 3 Fuel conversion scenarios considered by the GSC

2.2 Trends in Low-Carbon and Zero-Carbon Fuels

Various zero-carbon fuels are possible, including hydrogen, ammonia, synthetic methanol and biofuels, among others. The GSC has made trial calculations of fuel costs based on trends in the production technology for these fuels, and has collected and analyzed information on the current status of the fuel supply infrastructure. Based on survey results, the properties and future supply potential of various alternative fuels are summarized in Appendix. While it is not possible to determine the future selection of fuels at present, when examining the diffusion of alternative fuels in international maritime shipping, it is especially important to consider stable combustion, storability on ships, handling on ships (i.e., safety and environmental impacts), cost, availability and other related factors. Referring to materials prepared by the IEA, NEDO, etc., Fig. 4 shows the assumed production costs of the alternative fuels targeted for the period from 2030 to 2050.

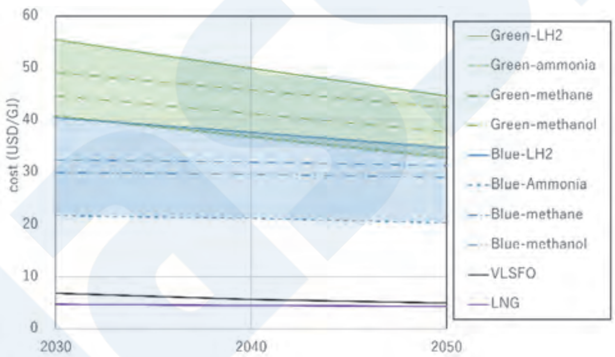

Fig. 4 Assumed production costs of alternative fuels (trial calculation by GSC)

A trial calculation and comparison from the viewpoint of fuel production costs was carried out for “green” fuels (liquid hydrogen, ammonia, synthetic methane, synthetic methanol), which are produced using a hydrogen feedstocks obtained from renewable electric power, and “blue” fuels, which are derived from natural gas + CCS (liquid hydrogen, ammonia, synthetic methane, synthetic methanol). Here, the trial calculations for the feedstock CO_2 for synthetic methanol were made for DAC (direct air capture)-derived and bio-byproduct-derived CO_2. The assumed production and supply process was production and storage of the alternative fuel in Australia → transportation to Japan → storage and secondary transportation in Japan → bunkering to ships. However, the cost of bunkering was not included in the calculations.

Approaching 2050, the cost of green fuels is expected to decline as the cost of renewable electric power decreases, but overall, blue fuels are more economical, and the most inexpensive is blue ammonia. Per unit of heating value (GJ), the cost differential between blue ammonia and heavy oil and LNG is around US$15, and by CO_2 conversion, the difference is approximately US$ 250 to 300/t-CO_2, while liquefied hydrogen incurs very high costs for liquefaction, storage and transport. It goes without saying that changes in these prices are possible, depending on future innovations in production technology, but based on the technologies assumed at present, the cost outlook is as outlined above.

2.3 Outlook for Zero-Carbon Fuels for Ocean-Going Ships

As alternative fuels for ocean-going vessels, at present, the GSC considers the leading scenario is to be expanded use of LNG as a low-carbon fuel for the time being until the 2030s, followed by conversion to blue ammonia. The reasons for this are as follows.

- From the viewpoints of the available supply amount and supply bases, LNG must inevitably be considered a realistic solution as a fuel for promoting low carbon for the time being. However, greater attention must be given to measures to prevent methane slip (unburned fuel that is not fully combusted in ships).
- In terms of the assumed fuel production cost for zero-carbon fuels (both green and blue), blue ammonia is the most advantageous. Diffusion of liquefied hydrogen is expected to be difficult for various reasons, including not only the high cost of liquefaction, storage and transportation, but also the difficulty of shipboard storage and handling. While ammonia is a toxic substance and N_2O is a concern, engine makers and ship classification societies are promoting equipment development and preparation of guidelines assuming measures to cope with those issues, and it is thought that these problems will not be significant obstacles to diffusion.
- In the case of carbon-neutral synthetic methane and synthetic methanol, the cost and supply capability of DAC-derived and bio-derived CO_2 are unknown, and the handling of emission rights for CO_2 derived from exhaust gas capture is also an issue.
- With biofuels, there are issues in terms of production scale, and competing demand for biooil for use as an aviation fuel has also been pointed out, suggesting that it will be difficult to secure the necessary amount of fuel for ships (although use as a pilot fuel for certain types of engines is expected).

Although blue ammonia is predicted to be relatively inexpensive among the various zero-carbon fuels, it is assumed that the prices will still be significantly higher than that of the current ship fuels. Therefore, in realizing the conversion to zero-carbon fuels, backing in the business aspect by promotion of investment in decarburization and the establishment of an international regulatory system by the IMO will be indispensable.

From the viewpoint of ensuring a smooth energy transition, there are also strong opinions in favor of synthetic fuels (methane and methanol) because these fuels can use the existing infrastructure. Moreover, on short-distance routes, the total amount of energy required is small, suggesting the possibility of using hydrogen or electric power (fuel cells, batteries, etc.). Thus, various types of fuels are expected to be used in the future, depending on the route and type of ship.

3. DEVELOPMENT OF NEXT-GENERATION ENVIRONMENTAL SHIPS FOR REDUCTION OF GHG EMISSIONS AND ZERO EMISSIONS IN INTERNATIONAL SHIPPING

3.1 Directions in Next-Generation Ships Based on Regulatory and Fuel Trends

Based on trends in the regulation of GHG emissions, technologies related to zero-carbon fuels and trends in construction and improvement of infrastructure for international maritime shipping, since its inception, the GSC has carried out a study of the form of ships in the transition period of the shipping industry leading to 2050 net-zero carbon, while conducting various surveys and analysis on regulatory trends, trends in alternative fuels and trends in related technologies. There are large elements of uncertainty in regulatory trends, trends in the development of technologies related to alternative fuels and trends in the construction of bunkering infrastructure, and the future image is still opaque. However, based on the assumption that fuel conversion during the transition period will progress from LNG to ammonia, the GSC is carrying out the conceptual design and basic plan for next-generation ships as a concrete solution under the situational awareness and policies described below.

- An actual fuel consumption rating system (CII regulation) will be introduced by the IMO, heightening the importance of the environmental evaluation and product life of ships in product evaluations.
- The threshold values for ratings under the CII regulatory system become stricter each year.
- Assuming introduction of a “2050 net-zero” target by the IMO, the target ships should have competitiveness through the transition period from 2025 to 2050 (assuming introduction in the market around 2025).
- Ammonia is judged to be a strong candidate for a zero-carbon fuel for international maritime shipping.
- As the assumed scenario, use of LNG as a low-carbon fuel expands until the 2030s, followed by conversion to ammonia for zero emissions. However, the possibility of synthetic methane is also considered.
- Considering the product portfolio of the Japanese shipbuilding industry, the main target ship types for development to achieve

zero carbon in the large ship field and the development of next-generation mainstay products for the Japanese shipbuilding industry are bulkers, tankers and container carriers. General applicability of designs will also be secured by development which targets medium- and small-scale ships with a high degree of design difficulty.

As the concrete concept of fuels targeted for development, pros and cons were evaluated considering the lifetime cost of the ship, the outlook for fuels, and flexibility in responding to an external environment filled with uncertainties. As a result, four fuel concepts were selected as development targets from among the various candidate concepts. These were LNG-DF (Dual Fuel) (CII improved type), LNG-DF (ammonia-DF conversion-ready type), HFO-mono-fuel (ammonia-DF conversion-ready type) and ammonia-DF. Fig. 5 shows the image of the transition of these concept ships.

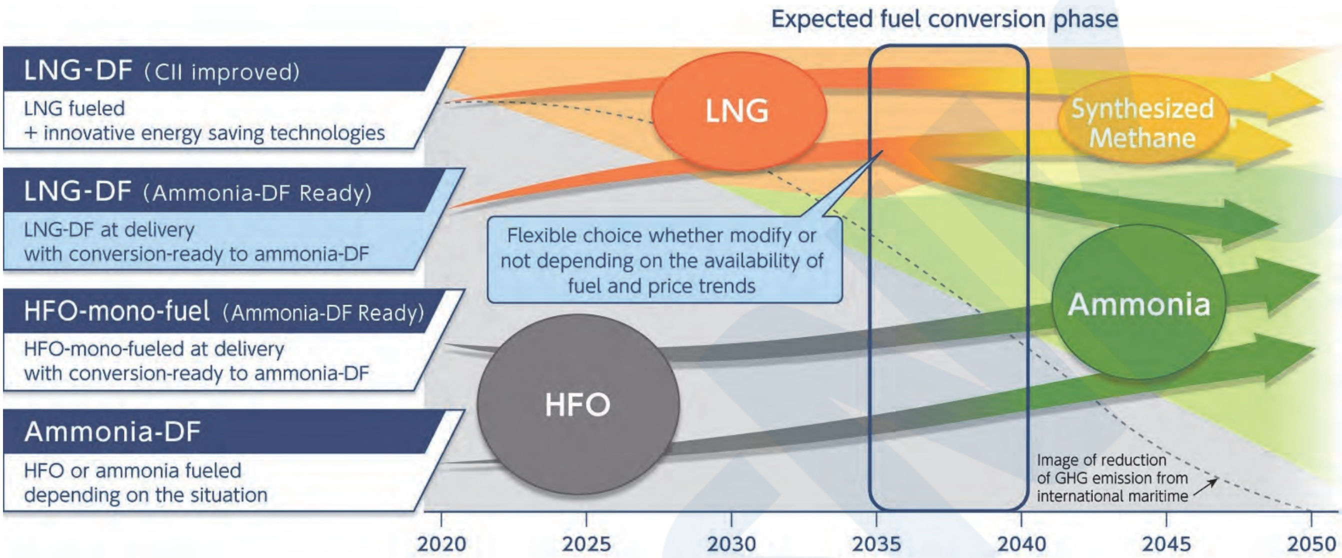

Fig. 5 Image of solutions (ship concepts) in transition period

As the main design issue when studying ships that use low environmental load LNG or ammonia fuel, the energy density of the fuel has a large influence on the design of the fuel tank capacity and form. Fig. 6 shows the relationship of the energy density per unit of volume and energy density per unit of weight for various alternative fuels and the assumed (possible) tank forms.

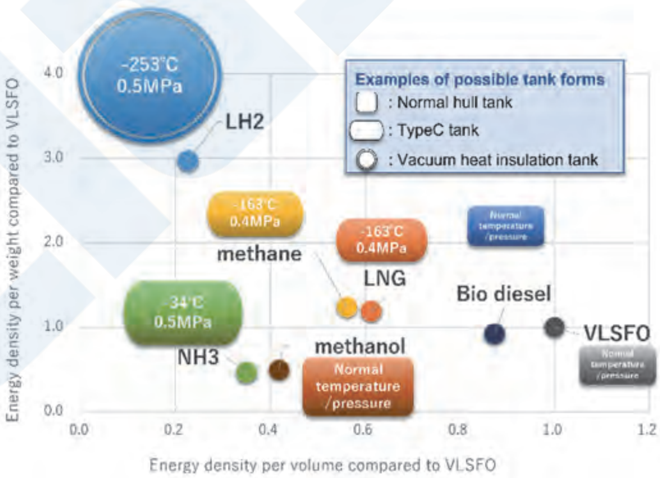

Fig. 6 Image of energy density of fuels and possible tank forms

Based on the relationship between the heating value and volume of the fuels, in order to securing a cruising range of 20 000 SM, which is equivalent to that of a ship using heavy fuel oil (HFO), it is necessary to secure a volume about 1.7 larger than that of HFO when using LNG and about 2.7 larger when using ammonia. Therefore, in this ship, ingenuity will be required in order to arrange the fuel tanks without greatly affecting the cargo carrying capacity of the ship, within the range of the dimensional limits allowed by terminals at ports where the ship is expected to call.

Since it is necessary to handle fuels with properties that are completely different from those of conventional HFO, that is, fuels that have the properties of a low temperature at atmospheric pressure, gasification by penetrating heat, high inflammability, toxicity and combustibility different from that of HFO, the fuel supply system will differ greatly from the types used to date. It is also important to consider safety, including the arrangement of the fuel tanks, fuel supply equipment, living quarters and so on, as well as fire prevention, fire extinguishing system and securing evacuation routes. In addition, while GHG emissions must be reduced more than in the past in order to achieve zero emissions, the cost of zero-carbon fuels is predicted to be far higher than that of conventional fuels. Therefore, in addition to study of the arrangement of the equipment, the GSC is also conducting an evaluation of energy-saving equipment for reducing the consumption of expensive zero-carbon fuels in order to improve economy to determine whether those equipment should be adopted or not. Moreover, the evaluation of energy-saving equipment is not limited simply to the direct merit of fuel consumption improvement, as in the past. That is, it is also necessary to evaluate equipment that will be employed in the ship from new viewpoints, since improvement of the CII rating can also be expected to have the effect of extending the product life of the ship.

3.2 Example of Design of Greener Ships

As part of the development described above, the GSC developed Japan’s first design for an ammonia-fueled Panamax bulk carrier in cooperation with its member shipbuilding companies and received Approval in Principle (AiP) from the ship classification society Nihon Kaiji Kyokai (ClassNK) on January 20 of this year. Fig. 7 shows the general arrangement (GA) plan of the ship which received AiP.

In the design that received AiP, various items were studied in accordance with the ClassNK Guidelines for alternative-fueled ships (in this case, ammonia-fueled), including the general arrangement, fuel supply concept, fire prevention, fire extinguishing and evacuation routes, the concept of hazardous areas, ammonia treatment countermeasures, the emergency evacuation procedure during bunkering, trim and restoring force calculations, etc., and the necessary safety measures were implemented. A study was also carried out considering the arrangement and capacity of the ammonia fuel tanks, which have a much larger volume than HFO tanks, in order to design a safe, easy-to-use ship, for example, by minimizing the effect of the larger tanks on the ship’s cargo carrying capacity and cruising range. The design was also prepared considering development to larger-scale ships, such as Capesize vessels, and “ammonia-ready” LNG-fueled bulk carriers, etc., assuming retrofitting for ammonia after the vessel is commissioned.

The main features of this ship are as follows.

- Arranging the living quarters in the stern enables an efficient layout of the large-volume ammonia fuel tanks while maintaining the same main dimensions as a conventional ship.
- The lifeboats are separated from the ammonia fuel tanks, securing a safer evacuation route so that crew members do not have to pass through the area near the ammonia fuel tanks during an emergency.
- The ammonia fuel tank capacity secures an sufficient cruising range assuming the Far East-Australia round trip and South America-South Asia routes, which are main routes for bulk carriers.
- A HFO capacity equivalent to that of conventional ships is secured to cope with uncertainty about the supply of ammonia fuel during the fuel transition period.
- A cargo hold capacity equivalent to that of a conventional HFO-fueled Panamax bulk carrier is secured.
- Safety measures are taken referring not only to the ClassNK guidelines, but also the guidelines of other main ship classification societies.
- Development to “ammonia-ready” LNG bulk carriers supposing retrofitting after vessels are commissioned is also considered by adopting a common layout and structure with LNG ships in the basic arrangement, such as the tank layout, etc.

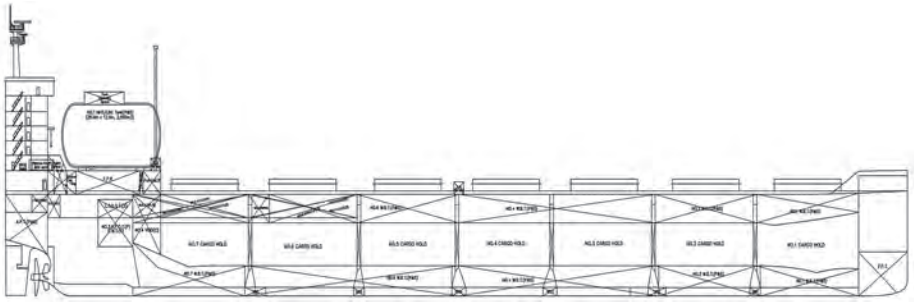

Fig. 7　General arrangement (GA) plan of AiP-approved ship

Table 1 shows principal particulars and Figs. 8 and 9 show appearances.

Table 1　Principal particulars of AiP-approved ship

Principal particulars	
LENGTH(O.A.)	abt. 228.9　M
LENGTH(B.P.)	225.45　M
BREADTH(MLD)	32.26　M
DEPTH(MLD)	20.10　M
DEADWEIGHT	abt. 80,400　MT
MAIN ENGINE	MCR　8,000 kW
SERVICE SPEED	abt. 14.2 KNOTS
NH_3 FUEL TANKS	2,500m^3 x 2sets

Fig. 8　Appearance of AiP-approved ship (from bow)

Fig. 9　Appearance of AiP-approved ship (from stern)

4. CONCLUSION

Dizzying changes in world trends targeting the achievement of 2050 zero emissions, including regulatory moves, are expected in the future, and heightened awareness of the environmental value of decarbonization increases the pressure to adopt evaluation standards that are contrary to economic efficiency. It is also possible that the introduction of the CII rating system will have a serious impact that limits the product life of ships, even though a long operating life of more than 20 years after construction has been taken for granted until now. Based on these kinds of global trends, users who operate and manage ships must now make more difficult decisions than in the past regarding the business risks associated with the decarbonization of ships, and the types of ships which they should purchase during the transition period to zero carbon.

In order to respond to these circumstances, the GSC is examining what types of ships should be supplied during the transition period based on ongoing information collection and analysis, and is carrying out development, in recognition of the fact that providing rational solutions for the shipping and shipbuilding industries is a critical issue.

In the development of actual next-generation environmental ships, the GSC is developing its study of the current proposed solutions to a more detailed design in cooperation with its member companies, and will deepen its study so as to make it possible to offer actual proposals to customers. In parallel with this, we are also conducting a study of indispensable common issues for realizing solutions, which include the technologies and systems, safety, environmental performance, the response to use of multiple fuels assuming fuel switching, and further improvement of fuel economy necessary when using new fuels in collaborative work with marine equipment manufacturers, and hope to reflect this work in future design.

Through these activities, the Planning and Design Center for Greener Ships (GSC) is aiming to contribute to the decarbonization of Japanese maritime industries and the development of the Japanese shipbuilding industry.

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APPENDIX

Properties and Future Supply Potential of Various Alternative Fuels Based on the Results of Survey by the GSC

APPENDIX

The following table shows the properties and future supply potential of various alternative fuels based on the results of survey by the GSC.

	VLSFO	LNG	Liquefied hydrogen (LH_2)	Ammonia	Carbon recycled (CR) synthetic methane	CR synthetic methanol	Biodiesel (FAME)
Lower heating value (GJ/t)	40.4 (39.8～41.7)	48.0 (46.5～50.4)	120.0	18.8	50.0	19.9	37.1
Liquid density (t/m^3)	0.93	0.48	0.0708	0.7	0.422	0.79	0.885
CO_2 conversion factor (CO_2-t/fuel-t)	3.126	2.693	0	0	(0＊)	(0＊)	0
Volume ratio per unit heating value (VLSFO ratio, in liquefied state)	1.00	1.63	4.42	2.86	1.78	2.39	1.14
CO_2 emission per unit heating value (CO_2-g/GJ)	77.38	56.10	0	0	(0＊)	(0＊)	0
Byproduct GHGs and global warming potential (GWP; according to IPCC AR5)		Methane (methane slip) GWP: 28		N_2O, GWP: 265	Methane (methane slip) GWP: 28		
Boiling point (°C)	200～400	abt.-161	-253	-33	-161	65	345～354
Shipboard storage method (liquid state)	Normal temperature/normal pressure Hull tanks	Type C (low temperature or pressurized), or independent rectangular tanks/membrane	Vacuum heat-proof tanks	Type C (low temperature or pressurized), or independent rectangular tanks/membrane	Type C (low temperature or pressurized), or independent rectangular tanks/membrane	Normal temperature, normal pressure Hull tanks	Normal temperature, normal pressure Hull tanks
Properties during shipboard storage (liquid state)	Normal temperature, normal pressure	-160～-140°C, 0.07～0.5MPa	app.-250°C, 0.5MPa	-30～-10°C, 0.07～0.5MPa	-160～-140°C, 0.07～0.5MPa	Normal temperature, normal pressure	Normal temperature, normal pressure
Ignition point (°C)	abt.407	abt.537	560	630	537	440	256～266
Cycle of low speed ship engine	Diesel	Diesel/Otto	Diesel/Otto	Diesel/Otto	Diesel/Otto	Diesel/Otto	Diesel
Pilot fuel	Not necessary	Necessary	Necessary	Necessary	Necessary	Necessary	Blend with FO

Future potential for supply expansion (global/land use) Points to note and influencing factors	▲～△ Decreasing investment in petroleum	△ Decreasing investment in gas	◎ Hydrogen as a whole (gas and liquid) is expanding, but liquefaction for hydrogen carriers is extremely limited.	○ Land-side demand is expanding (entry of energy industry, scaling up and cost reduction).	△～○ Carbon neutrality (CN) of feedstock CO_2 gas, long-term assurance	△～○ Future outlook of expanded use of methanol fuel on land (automobiles, thermal power plants, etc.) is unknown.	○ In the 1st generation, conversion of land use is a problem. In the 2nd generation, depends on increased crops and conversion technologies.
Future potential for supply expansion (ship use) Points to note and influencing factors	▲～△ Decreasing on-land demand	○ Criticism of methane slip	▲～△ (Liquefied hydrogen)	○	△～○	△～○	△ Competition with pilot fuel use or aviation fuel use
Bunkering infrastructure	◎	△～○ Currently expanding	None	Possible to use import/export infrastructure?	△～○ Possible to use LNG infrastructure		Possible to use FO infrastructure?

Development of onboard CO_2 Capture System

— "CC-Ocean Project" for verification testing of onboard CO_2 capture system —

Shinichi KAWAMATA*, Yusuke WATANABE*, Takashi UNSEKI*

1. INTRODUCTION

With the increasing global momentum of decarbonization, the IMO adopted a "GHG reduction strategy" aimed at halving GHG emissions from the international shipping sector by 2050 and reducing those emissions to zero at an early period within this century, and even faster reduction has also been discussed in many quarters. As measures to reduce GHG, conversion from fossil fuels to alternative fuels such as synfuels, hydrogen and ammonium has been studied. On the other hand, utilization of the captured CO_2 or semi-permanent storage in CO_2 storage sites, are also regarded as one candidate for GHG reduction.

As part of Mitsubishi Heavy Industries (MHI) Group's energy transition strategy, Mitsubishi Shipbuilding Co., Ltd. is also engaged in the development of onboard CO_2 capture system with the aim of reducing CO_2 emissions from ships. This paper introduces "Carbon Capture on the Ocean" (CC-Ocean) project for verification testing of onboard CO_2 capture system, which was conducted in cooperation with Kawasaki Kisen Kaisha, Ltd. ("K" Line) and Nippon Kaiji Kyokai (ClassNK), with support from Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT), as the most recent of this company's efforts.

2. OUTLINE OF CC-OCEAN PROJECT

In this project, a small-scale CO_2 capture demonstration plant (hereinafter, "demo plant") was installed on a coal carrier "CORONA UTILITY" (hereinafter, "the ship") operated by "K" Line, and the world's first demonstration test under commercial operation conditions was carried out in order to verify the CO_2 capture technology on the ocean and organize marinization requirements.

The project was carried out over a period of two years. After HAZID (HAZard IDentification: identification of inherent hazards and assumed accidents) of the demo plant by ClassNK, the demo plant was fabricated and installed on the ship, and the demonstration test started in August 2021, and measurements to confirm performance of the demo plant on the ocean were conducted for approximately six months.

The demo plant installed on the ship was fabricated with measures against ship motion/vibration, which are unique to ships, based on a CO_2 capture system designed for onshore plants which use the chemical absorption method. Fig. 1 shows an illustration of the demo plant.

Fig. 1 Illustration of demo plant

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3. OUTLINE OF CO_2 CAPTURE SYSTEM

Fig. 2 shows the process flow of CO_2 capture from the exhaust gas of a marine engine. The demo plant consists mainly of four towers: exhaust gas quencher, absorption tower, exhaust gas cleaning tower and regeneration tower. The exhaust gas discharged from the marine engine is absorbed by a blower from a pipe branching partly from the exhaust gas pipe installed at the outlet of the funnel and is supplied to the demo plant. The exhaust gas supplied to the demo plant is first delivered to the exhaust gas quencher and cooled to almost normal temperature with fresh water spayed from above in the tower. The fresh water circulates in the system and removes heat from the exhaust gas by heat exchange with seawater.

The exhaust gas discharged from the exhaust gas quencher is delivered to the absorption tower, where it comes into contact with an absorbent sprayed from above in the tower, and the CO_2 in the exhaust gas is absorbed by the absorbent.

Next, the exhaust gas discharged from the absorption tower is delivered to the exhaust gas cleaning tower, and the CO_2 absorbing liquid contained in the exhaust gas is washed away by fresh water sprayed from above in the cleaning tower.

The clean exhaust gas discharged from the exhaust gas cleaning tower is then vented to atmosphere through a pipe leading to the area of the funnel.

The absorbent which has absorbed the CO_2 is delivered to the regeneration tower from the bottom of the absorption tower, and is heated with steam to release CO_2, after which the regenerated absorbent returns to the absorption tower and is reused.

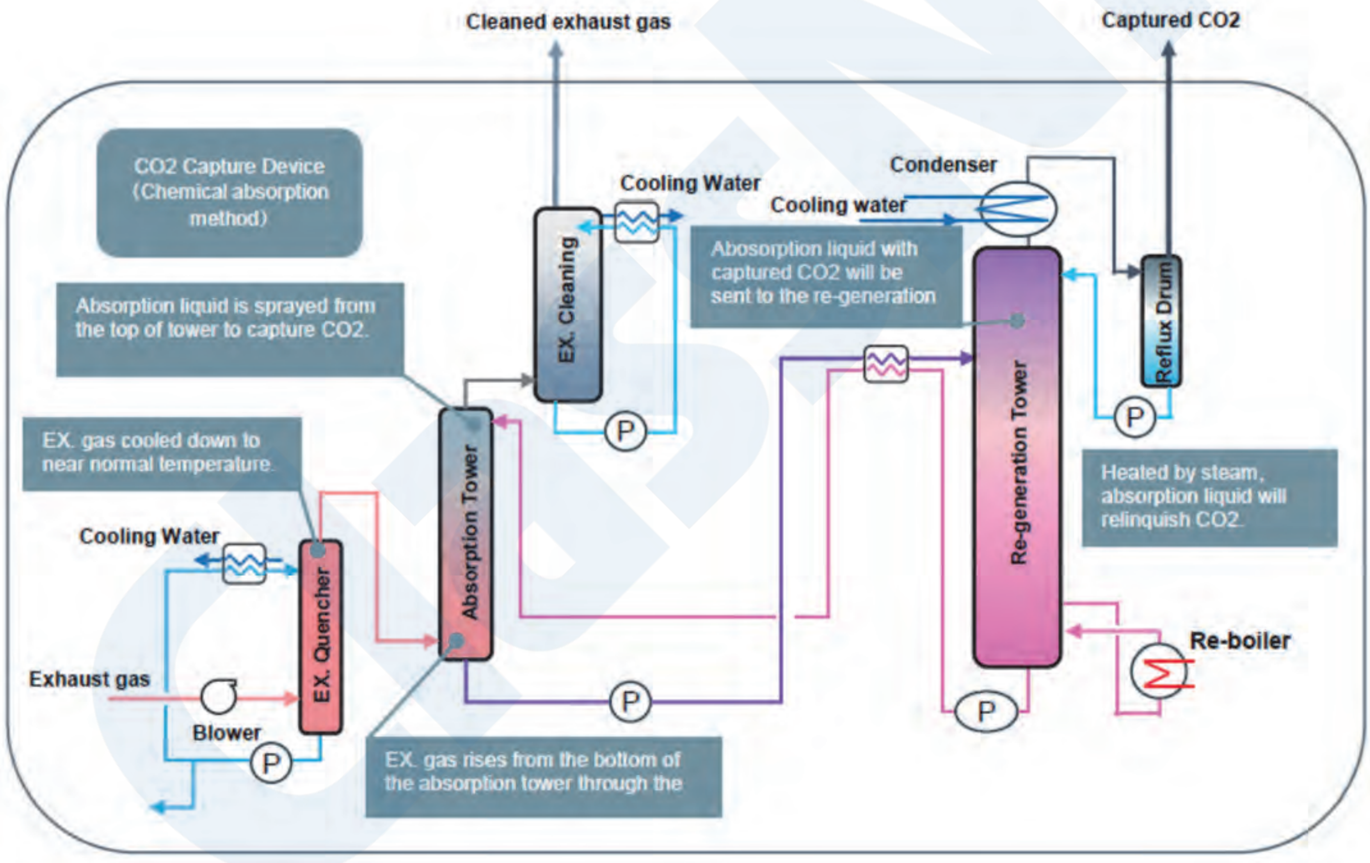

Fig. 2　Process flow of CO_2 capture

Because the purpose of this project was to verify the CO_2 capture technology on the ocean, as mentioned above, CO_2 liquefaction system or CO_2 storage tank were not equipped. The CO_2 captured in the regeneration tower was released into the atmosphere after analysis of its properties.

4. HAZID OF DEMO PLANT

4.1 Procedure for HAZID

The following shows the procedure of the HAZID conducted with the demo plant.

①In order to identify risks, ClassNK mainly conducts a review of the safety of the CO_2 capture system, and “K” Line mainly reviews the operation of the demo plant.

②For the risks identified in ①, the system failure modes and causes and the influence from failures (local influence, consequential influence on entire system) are analyzed.

③The risks are evaluated by quantifying, as indexes, the severe influence and failure frequency of effect on human beings and ships in the event that the risks actually occur.

④Measures to reduce the risks are formulated and reflected in the design/manufacture and operation manual of the demo plant and the instruction manual for CO_2 absorbing liquid.

⑤The risks after risk reduction measures are implemented are reevaluated to confirm whether the risks are on an acceptable level.

4.2 Risks and Risk Reduction Measures

Table 1 shows the major risks identified in the HAZID and measures to reduce those risks.

Table 1 Major risks and risk reduction measures

Risk	Risk reduction measures
Leakage of CO_2 absorbing liquid	• Take measures to prevent scattering at pipe joints of the CO_2 absorbing liquid. • Visually check that no leakage of the CO_2 absorbing liquid is observed before the startup of the demo plant, during operation and after shutdown. • Provide a caution plate (“Check that there is no chemical leaks or other abnormalities when entering the room”) at the entrance of the demo plant room. • Take measures to prevent the CO_2 absorbing liquid from leaking outside the ship in case of leakage from the demo plant. • In the operation manual, add procedures for checking for leakage of the CO_2 absorbing liquid when entering the room and the action to be taken in the event of leakage.
Erroneous handling of CO_2 absorbing liquid	• Wear protective equipment when handling the CO_2 absorbing liquid. • While replenishing the CO_2 absorbing liquid, visually check the liquid level of the makeup tank. • If it is difficult to replenish the CO_2 absorbing liquid due to vibration caused by the emergency generator located under the demo plant or ship motion, do not replenish the liquid.
Leakage of exhaust gas or CO_2	• When entering the demo plant room and before starting the demo plant, run the exhaust fan. • The exhaust fan start/stop switch must be installed outside the demo plant room. • Provide a caution plate (“Run the exhaust fan when entering the demo plant room and before starting the demo plant”) at the entrance of the demo plant room. • In the operation manual, add procedures for operating the exhaust fan.

5. INSTALLATION WORK

5.1 Outline of Demo Plant Ship

The following is an outline of the ship on which the demo plant was installed.

Ship name: CORONA UTILITY

Ship type: 88 000-ton coal carrier

Dimensions of ship: Length 229.98 m, Breadth 38 m, Depth 19.9 m

Completion: January 2016

Ship registration: Japan

5.2 Outline of Installation Work

The installation work was conducted at the quay of Yokohama Dockyard & Machinery Woks of MHI. Fig. 3 shows the image of the installation work. An additional overhanging deck was installed beside the engine casing, and the demo plant was installed in an independent room (hereinafter, “demo plant room”) built on the deck.

Since the ship is engaged in transportation of coal for electric power generation, it was necessary to carry out the installation work at a point on the route to the loading port after unloading. Therefore, the timing for the work was determined while checking the vacancy of the quay of the Yokohama Dockyard & Machinery Works and carefully adjusting the ship operation schedule.

To shorten the work period, the following preparations were made before the installation work at Yokohama Dockyard & Machinery Works, and the installation work was completed in a short period as planned.

- Work such as piping and wiring to the demo plant and hull reinforcement associated with the installation of the demo plant room were conducted at this company’s dock in China.
- The demo plant room, including the internal fittings, was fabricated onshore in advance, and the entire room was installed as a unit after the ship was docked.
- Inspections such as resurveying due to revisions of the classification certificate and JG certificate, which were required when the demo plant room was installed, were conducted onshore before the installation of the room.

Figs. 4 to 6 show the condition of demo plant room installation.

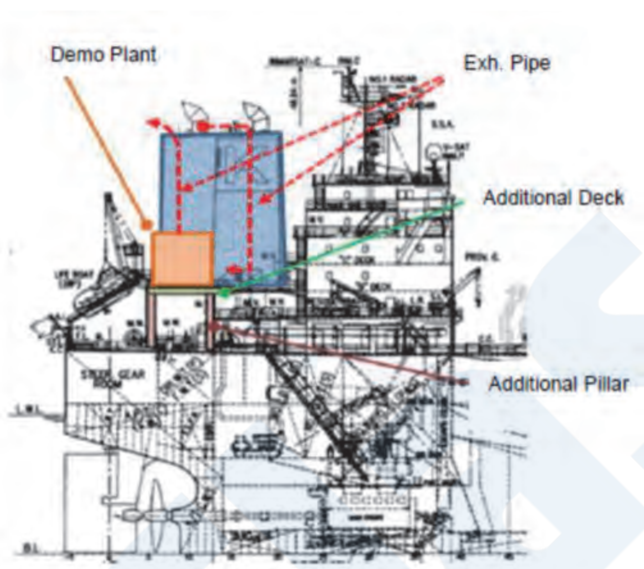

Fig. 3 Image of installation work

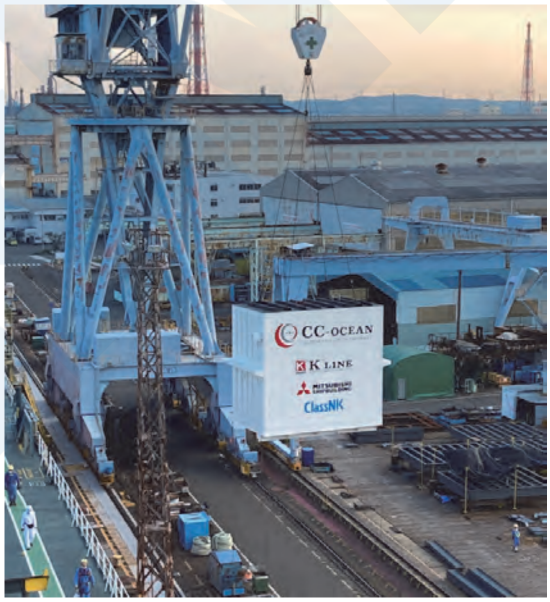

Fig. 4 Condition of demo plant room installation

Fig. 5 Condition of demo plant room installation

Fig. 6 Demo plant room after completion of installation on the ship

6. DEMONSTRATION TEST

6.1 Outline of Test

The demonstration test was conducted on the ship's route between Japan, Australia, Canada and Russia. After the demo plant was installed on the ship, engineers of Mitsubishi Shipbuilding were on board the ship for approximately one month to perform tasks such as plant operation and maintenance, instructions on the plant operation to crew and measurement of the exhaust gas and the separated/captured CO_2.

After the completion of the test by the engineers of Mitsubishi Shipbuilding, the crew continued tasks such as plant operation, measurement and maintenance for approximately five months. During this demonstration test, the operation manual for the demo plant continued to be updated by the crew and was optimized as a valuable manual filled with field know-how, becoming a "bible" for reliable operation of the plant. In this way, the world's first attempt in which a ship's crew captured CO_2 during commercial ship operation was successfully completed.

The measurements in the demonstration test were started after operation of the demo plant had reached a steady state, and the composition of the inlet exhaust gas, outlet exhaust gas and captured CO_2 gas were measured. For items that could not be analyzed on the ship, only sampling of the substances was conducted, and the sampled substances were brought back ashore and analyzed.

During the test, the operational data acquired on the ship were promptly transferred to an onshore facility and various analyses were conducted by Mitsubishi Shipbuilding, which then provided advice to the ship on adjustment of the demo plant and additional replenishment of the CO_2 absorbing liquid in order to support the demonstration test. The fact that procedures for this kind of communication between the ship and the onshore facility, confirmation of the operational data and the crew support were established between "K" Line and the ship before the demonstration test began is also considered one important factor in the success of the demonstration test.

Figs. 7 to 10 show the condition of the demonstration test.

Fig. 7 Condition of demo plant operation

Fig. 8 Instructions on demo plant operation to ship's crew

Fig. 9 Measurement of exhaust gas discharged from the marine engine

Fig. 10 Operation of demo plant by ship's crew

6.2 Verification Items

The following were the major verification items in the demonstration test. The results for each are summarized below in section 6.3.

①CO_2 capture performance of demo plant

②Effect of fluctuations in engine load and ship motion on CO_2 capture performance

6.3 Test Results

6.3.1 CO_2 Capture Performance of Demo Plant

In the demonstration test, Mitsubishi Shipbuilding confirmed the amount of captured CO_2, CO_2 capture rate and purity of the captured CO_2 were achieved as planned and verified the proven onshore CO_2 capture technology could be also applied to marine use. The purity of the captured CO_2 was more than 99.9%. When an onshore plant captures CO_2 with a purity of more than 99.9%, the captured CO_2 can be used in a wide range of applications, including chemical processes to enhance production of fertilizer or methanol, general use such as dry ice for cooling, and enhanced oil recovery (EOR) to increase crude oil production. In this demonstration test, CO_2 with comparable high purity was also successfully captured.

6.3.2 Effect of Fluctuations in Engine Load and Ship Motion on CO_2 Capture Performance

During the demonstration test, the load on the main engine fluctuated between approximately 40% and 70% and since there was no change in the CO_2 concentration in the exhaust gas at the demo plant inlet, these fluctuations had no significant effect on CO_2 capture performance. Similarly, almost no effect of ship motion during the demonstration test period on CO_2 capture performance was observed.

7. CONCLUSION AND FUTURE PROSPECT

This paper introduced an outline of the CC-Ocean Project as a technological approach to the capture of CO_2 from ships, the verification items and the result of the demonstration test.

Based on the knowledge and technological issues obtained thorough the demonstration test, in the future, Mitsubishi Shipbuilding intend to proceed with the development of a total system including CO_2 liquefication and onboard CO_2 storage, which have not been considered in the demonstration test, and pursue efforts to commercialize the system by achieving marinization, downsizing and cost reduction.

As described above, MHI Group is pursuing a range of strategic measures to strengthen businesses related to energy transition, and establishing a CO_2 ecosystem is a key part of this effort. Carbon dioxide capture, utilization, and storage (CCUS) is attracting attention as an effective means to achieve a carbon neutral society. Mitsubishi Shipbuilding, in response to these demands, is continuing its efforts to reduce greenhouse gas (GHG) emissions from ships and other types of marine equipment, in order to contribute to environmental conservation, and the realization of a carbon neutral society on a global scale.

ACKNOWLEDGMENTS

This demonstration test was conducted with support from the Maritime Bureau of Japan’s Ministry of Land, Infrastructure, Transport and Tourism (MLIT), as part of its assistance project for research and development of technological advancements in marine resource development. Mitsubishi Shipbuilding would like to express our gratitude to all concerned for providing the opportunity to conduct this demonstration test, and also extend our thanks to ClassNK, which provided advice mainly on HAZID, “K” Line, which led the demonstration test, “K” Line RoRo Bulk Ship Management Co., Ltd. and the crew members of “CORONA UTILITY.”

Prospects for Widespread Adoption of Next-Generation Standard EV Vessel ROBOSHIP

― Can we change the world? ―

Yuri JINNAI*, Takehiko TSUCHIYA*

1. ORIGIN OF THE NAME ROBOSHIP

"ROBOSHIP" is a newly coined word of "Robot" and "Ship."

In the period when one of the present authors was a child (1960s), the 21st century was still the distant future. That future was imagined as a world where mankind would be free from calamities such as war and disease and would enjoy peace, where the everyday life of humankind would progress thanks to science and technology, and "robots" would be ubiquitous. "Robots" were envisioned as a "tender-hearted child of science,"[*1] who would not only help people in the workplace, but would also do housework, sometimes discipline children, and become their friends.

The word "ship," of course, means "watercraft," but the suffix "-ship" means "state, condition of being [such-and-such]" or "[such-and-such] to be created" as used in "friendship" or "partnership."

Today, we live in the 21st century that science and technology have advanced, and humankind enjoys their blessings. However, as in the 20th century, the fear of war and disease is still with us, and we also face the new challenges such as climate change, an aging population and low birthrate.

The challenges which confront the coastal shipping industry are described in the following Chapter 2 "CURRENT CONDITIONS SURROUNDING THE COASTAL SHIPPING INDUSTRY." We named our Next-Generation Standard Electric Vessel as "ROBOSHIP" with the wish she will be a "ship to assist seafarers" and "ship to shape what the costal shipping industry should be" and hope she will provide solutions to those challenges.

2. CURRENT CONDITIONS SURROUNDING THE COASTAL SHIPPING INDUSTRY

2.1 Two Kinds of Aging (Ships and Seafarers)

The number of seafarers in the Japanese coastal shipping industry was 21,374 as of October 2020. Although the total number increased by about 260 from the previous year, the shortage of seafarers still continues, and looking at the age composition, the number of seafarers over 50 years old exceeds 50% and the aging advances. (Numbers as of October 1st, 2020. Source: Website of the Japan Federation of Coastal Shipping Associations)

Similarly, although the breakdown of coastal vessels by age shows that less than seven years old vessels account for only 16% of the total number and 29% of the total tonnage, overage vessels aged 14 years or more account for 68% of the total number and 45% of the total tonnage. In terms of average vessel size by age, the average gross tonnage (GT) for aged 14 years or more is 509 GT, whereas the average for vessels under 14 years old is more than 1,000 GT. Thus, aging is more advanced in smaller ships.

Since vessels less than 500 GT account for 77.9% of the total number of vessels, it is clear that taking measures to address these two kinds of aging have become pressing issues for the industry. (Numbers are on the fiscal 2020 year-end basis. Source: Website of the Japan Federation of Coastal Shipping Associations)

2.2 Limits to Succession of Know-How

A study[*2] conducted in 2017 pointed out that while hiring of new graduates (2.9%) exceeded the number of seafarers retiring on reaching retirement age (1.5%), seafarer shortages are nevertheless a problem due to the extremely high rate of turnover in the workforce (ranging from 14.7 to 17.1%).

* e5 Lab Inc.

*1 From the Japanese lyrics of the theme song of the Astro Boy animated television series (lyrics by Shuntaro TANIKAWA).

*2 Toshihiko MATSUO: "Trends in Hiring and Retiring Seafarers in Domestic Shipping Industry," NAVIGATION, No. 203, submitted in October 2017.

The problem here is whether these unskilled newly-hired seafarers can be assigned quickly to actual service while the veterans who are responsible for training them are retiring rapidly. I do not mean to belittle the current seafarers' training efforts in various positions, but rather, ask whether the necessary software and hardware to assign unskilled seafarers to actual service are being prepared systematically. An aversion to change and a tendency of change-resistant and making incremental improvements without fundamental reform is one of the typical features of the use of organizations and IT systems in government agencies and companies in Japan. In the former Imperial Japanese Forces, an extreme pursuit of personal proficiency, combined with a belief in the superiority of "spiritual" virtues, later led to the relative neglect of military technologies and strategy, which contributed to the eventual defeat in the World War II. If we keep ignoring the transformation of technology which is currently in progress and attempt to overcome difficulties by applying the conventional business model, it means we have learned nothing from history.

During the World War II, Japan suffered a huge death toll the Japanese government and Imperial Forces clung to wishful thinking, unworkable paper theories, and ideas based on how they wished the situation was. Groundless optimism is to be avoided. As the American novelist Mark Twain commented, "The past does not repeat itself, but it rhymes." This maxim must not be forgotten.

2.3 Delay in Digitalization

The Japanese coastal shipping industry is lagging behind in digitalization. There are two causes for this: a delay in implementing the necessary communication environment and a strong tendency to maintain traditional practices.

It is rare for coastal vessels not to enter a port for several days, as is the case with ocean-going vessels, and the availability of cellular radio channels when they get close to land has delayed the introduction of communication equipment. The difficulty of making additional investments in the equipment of operating vessels due to low profitability has also invited delays in the introduction.

Changing traditional practices is difficult for anyone. Particularly in industries with a long history, such as shipping industry, business models and business customs tend to be fixed. As a result, daily operations are also routinized and have been streamlined over many years. In such cases, it is difficult to take the risk of introducing the new tool of digital technology. Since ship operators and seafarers do not see the merit of introducing new technology in an operation which they've already felt efficient enough, the disadvantages of introduction, such as the cost and the time required to master a new system, tend to be more obvious than the potential advantages.

Structurally, with the exception of common carriers such as passenger ships and RORO ships, the shipper-operator-shipowner hierarchy in the coastal shipping industry (industrial carriers) is also considered to be an impediment to digitalization. In addition to this characteristic hierarchical relationship among three parties, various enterprises and organizations, such as agencies, shipyards and government agencies, are also involved in each vessel's operation. As a result, it is more difficult to achieve the effects of digitalization, since what each company can get digitalized and systematized is only a part of this entire structure.

In the meanwhile, the COVID-19 pandemic has given rise to new changes in coastal vessels which have been left behind in digitalization. As one example, before the pandemic, many shipping operators had relied mainly on fax messages to exchange vessel operation information between vessels and shore, and had not begun digitalization, even assuming they were interested. However, during the pandemic, those operators have been forced to handle information transmitted electronically due to the increase in work from home and it resulted in a sharp drop in information communications by fax. In other words, there are cases where most of the information that was formerly faxed has successfully been replaced with digital information by using tools that were already available.

This means that information that was formerly sent and received via fax is now being communicated by email or SNS. The next step is to apply software to this data, which will enable data storage in a well-organized form. Analysis of this accumulated data will then make us possible to utilize this data for various purposes in the future, for example, to improve safety in vessel operation or reduce fuel consumption.

These types of analyses will not only be useful for understanding individual conditions (e.g., the status of operational management and seafarer management) but will also be integrated into a core system that can be utilized in managerial decision-making. It has been noted that face-to-face work has been limited by the COVID-19 pandemic, but this assumed disadvantage also reflects the fact that the coastal shipping industry has relied entirely on face-to-face work until now. As an advantage of this situation, the introduction of business chat tools has made it possible for seafarers and other employees, who had hesitated to speak or been unable to express opinions in face-to-face situations, to speak and express their opinions frankly.

Moreover, there is no foreseeable future in conventional personalized systems that depend on the skills of individual seafarers and employees. From this viewpoint, digitalization is a good opportunity for companies to envision their future and reconsider their survival strategies.

2.4 Delay in Environmental Protection Measures (Coastal Vessels Lagging Behind in Implementation)

The Sixth Strategic Energy Plan established in 2019 by the Japanese government declares that “Japan aims to achieve carbon neutrality by 2050, intends to cut GHG emissions by 46% relative to FY 2013 level as the newly set GHG emissions reduction target for FY 2030, and will keep tackling the challenge toward the lofty goal of 50%.” For the coastal shipping sector, the Plan states that “Japan will promote the development, demonstration, and implementation of ship technologies contributory to the modernization and operational efficiency enhancement of coastal vessels, based on innovative energy-saving technologies which include LNG fueled vessels, hydrogen fuel cell-powered vessels, and electric vessels, digital technologies and so on.”

Based on these commitments, subsidies have been made available as financial support for technological development of hydrogen- and ammonia-fueled vessels and for further enhancement of transportation efficiency using AI, IoT and other digital technologies. However, due to new technologies such as hydrogen and ammonia to be developed from now on, commercial penetration will require a long-term timeframe. On the other hand, since subsidies for enhanced transportation efficiency and other improvements focus mainly on novelty and innovativeness, therefore implementation of mass-produced products is excluded from the scope of eligibility, and as is the case of subsidies in general, the work involved in the subsidy application procedure itself places a considerable workload on applicants. These subsidies are not easily accessible, particularly for small-scale shipping operators such as coastal shipping operators. It is difficult to secure the time to achieve the target set in the Sixth Strategic Energy Plan, and support for environmental measures toward the social implementation are urgently needed.

Moreover, as explained in 2.3, the shipper-operator-shipowner hierarchy in the coastal shipping industry has also been an impediment of environmental protection measures.

2.5 Possibility of Decreased Corporate Evaluation

On March 1st, 2022, the Japanese government made a Cabinet Decision on the Bill for the Act on the Partial Revision of the Rational Energy Utilization Act. The Revision Bill adds non-fossil energy sources to the scope of energy use rationalization and requires factories to switch from fossil energy to non-fossil energy. Since it requires specified business operators, etc.to prepare mid-to-long-term plans for conversion to non-fossil energy, they must further accelerate their countermeasures.

Some of the companies listed on the new Prime market of the Tokyo Stock Exchange are substantially required to disclose their climate risk information from the spring of 2022. This requirement mandates the disclosure of information such as losses incurred from GHG emissions and is based on the concept of the Task Force on Climate-Related Financial Disclosure (TCFD) established by major countries. The TCFD requires the disclosure of climate risk information regarding Governance (e.g., the organization’s internal assessment of risks related to climate change), Strategy (e.g., increased profit due to increased demand for climate change countermeasures, for example, in EV-related fields), Risk Management (e.g., quantitative and qualitative assessment of risks specific to the company’s operations), and Index and Targets (e.g., GHG emission reduction indexing, also including the supply chain). The TCFD recommends that enterprises disclose not only their own GHG emissions, but also the total GHG emissions of their whole transaction network. Since these emissions data are supposed to cover the transportation departments of the listed companies mentioned above, their effects are naturally presumed to extend to the coastal shipping industry. Thus, how the companies address GHG emissions reduction will become an important part of corporate evaluations in the future, and companies that are unable to follow this trend may not only suffer a decrease in their corporate values, but may also find themselves in the “stranded assets” management group.

3. FEATURES OF ROBOSHIP

3.1 Features of Hull (Twin-Skeg Hull Form)

ROBOSHIP is intended to standardize coastal 499 GT cargo ships. The mainstream hull form for ships of this type is the single-screw hull. It is thought that twin-screw ships generally underperform single-screw ones of the same hull form in terms of efficiency.

However, there is the other point to consider in the case of coastal 499 GT cargo ships. While it goes without saying that large-diameter low-speed propellers offer better efficiency, the propeller diameter of coastal vessels is limited by their draft due to external factors (water depth in ports to call, etc.). This means there are limits to optimization of the propeller design, which inevitably results the higher propeller load than expected. As the ROBOSHIP is a twin-screw ship, it is possible to reduce the propeller load under these limited conditions and enable high efficiency in the propellers.

The propellers and shafts of twin-screw ships are generally supported by shaft brackets, and these hull appendages increase water resistance. For this reason, twin-screw ships are considered inferior to single-screw ships in terms of hull efficiency. However, in the twin-skeg hull form of ROBOSHIP, the shaft portions of the twin-screw are covered (skegged) with the outer shell plating. As a result, a twin-skeg ship has a smoother water flow to the propellers than conventional twin-screw ships with shaft bracket supports, and thus has the advantage of improving propulsion efficiency. Although this ship has a larger wetted surface area than single-screw ships, the design was optimized to minimize the increase in hull resistance. Fig. 1 below shows a GA image, and Fig. 2 shows the image of a twin skeg.

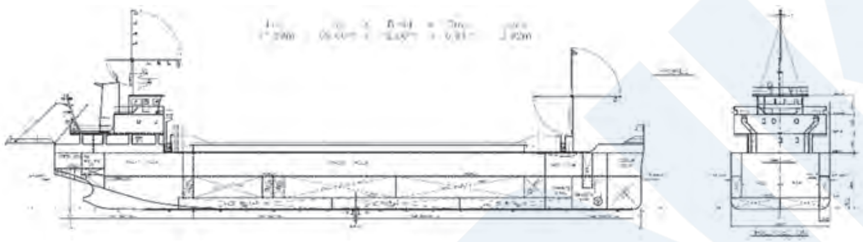

Fig. 1　GA image

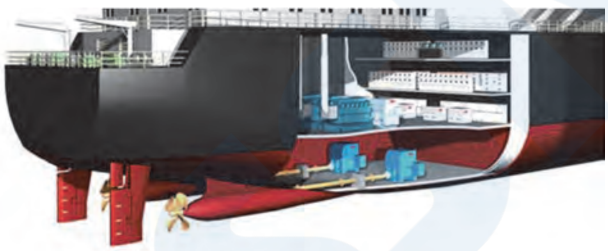

Fig. 2　Image of twin skeg

To clarify the effects of these twin-screw skeg hull forms, the Japan Railway Construction, Transport and Technology Agency (hereinafter “JRTT”), an incorporated administrative agency under the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), carried out an investigative study project titled “Hull Form Study on Twin-Screw Super Eco-Ships (SES). ”[*3] In this study, three type hull forms were developed and subjected to water tank tests. As a result, it was reported that this new design achieved 20 to 25% improvement on a shaft horsepower basis.

3.2　Features of Power Plant

The power plant of ROBOSHIP is configured by two forms of efficiency enhancement, electrical efficiency improvement through optimal power management based on the combined use of generators and batteries, and transmission efficiency improvement by use of a microgrid (DC grid + high-efficiency water-cooled inverter + PM motor).

Generators and batteries have been used in combination in previous electric propulsion systems. In conventional systems, however, only the generator or the batteries could be used at one time, and a blackout is inevitable to switch over from one mode to the other, which imposed an additional operational burden on the seafarers. ROBOSHIP allows the simultaneous use of the batteries and generators, thereby enabling active power control.

As energy conversion efficiency varies significantly depending on the power management between the batteries and generators, the control software has been improved through data collection, accumulation, and analysis, making it possible to improve energy efficiency. Energy efficiency improvements are available from the following three functions:

[*3] Joint Construction of Ship Assistance Department, Japan Railway Construction, Transport and Technology Agency: Report on the “Hull Form Study on Twin-Screw Super Eco-Ships (SES),” March 2012.

[Spinning reserve function]

In case of load fluctuations large enough to control the number of operating generators, batteries absorbs (charges and discharges) the load fluctuations and optimizes generator operation to improve energy efficiency.

In the case of generator-only electric propulsion systems, when the number of in-operation units is changed (increased) to cover load fluctuations, the load fluctuations themselves may be an obstacle to putting a standby unit into operation. An electric propulsion system with a spinning reserve function can cope with this problem. (See Fig. 3 "Conceptual image of spinning reserve.")

Fig. 3　Conceptual image of spinning reserve

[Peak shaving function]

For generator load-leveling, this function cuts the upper and lower energy (power) demand peaks (the upper peak is cut for power discharging while the lower peak is cut for power charging), and as a result, energy loss is improved. (See Fig. 4 "Conceptual image of peak shaving.")

Fig. 4　Conceptual image of peak shaving

[Active engine load control function]

When the generator goes under load, this function provides a battery power assist (power discharging and charging) to allow the generator engine to run in its fuel-efficient range so as to moderate load fluctuations and optimize the engine load in order to improve energy loss. (See Fig. 5 "Conceptual image of active engine load control.")

Fig. 5　Conceptual image of active engine load control

Adoption of the microgrid made it possible to reduce the weight of the power plant as well as the footprint and volume of the associated equipment. A further improvement in energy efficiency is also expected by combined use of the microgrid and a variable speed generator.

3.3　Superiority over Conventional Ships and Conventional Electric Propulsion Ships

The propulsion system of almost all conventional ships is, of course, a medium-to-low-speed diesel engine, which is subject to load fluctuations every time the operational mode changes. Operation and maintenance of this type of system place a heavy workload on the ships' engineers.

In contrast, electric propulsion ships in coastal service fall into three types, depending on the type of propulsion machinery, as follows:

Type 1: Generator-only systems

Type 2: Generator and diesel main engine hybrids

Type 3: Dual-mode systems switchable between the generator- and battery-powered modes

Types 1 and 2 are considered to have an energy-saving effect of 10% to 30% (on a fuel consumption basis or a cargo volume (ton-mile) basis), while also reducing the engineers' workload, which is a burden on conventional ships. However, these types rely entirely on generators to absorb load fluctuations. ROBOSHIP features the generator/battery combination described in 3.2 so that the batteries absorb load fluctuations, thereby producing an additional energy-saving effect (improvement of energy loss).

As for even Type 3, ROBOSHIP has an advantage in terms of the exclusive relationship between the generator- and battery-powered modes explained in 3.2 (i.e., only the generators or the batteries can be used at one time).

As an additional advantage of ROBOSHIP, since the power supply aboard a conventional ship relies entirely on an AC grid, enhancing electric conversion efficiency is a critical point. However, ROBOSHIP uses power plant based on a DC grid (and further, a combination of PM motors for propulsion motors and variable speed generators, as necessary), resulting in an energy efficiency improvement of up to 10% compared with a power plant based on an existing AC grid.

Figs. 6 and 7 below show examples of a conventional AC grid and a DC grid for the ROBOSHIP, respectively.

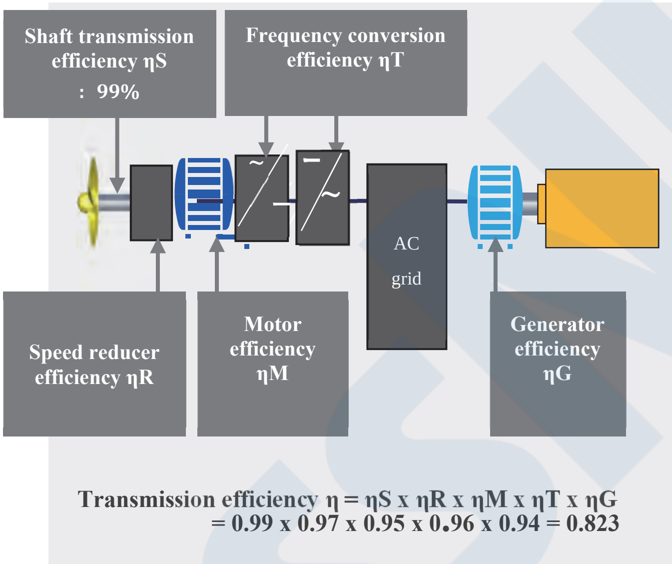

Fig. 6 Example of conventional AC grid

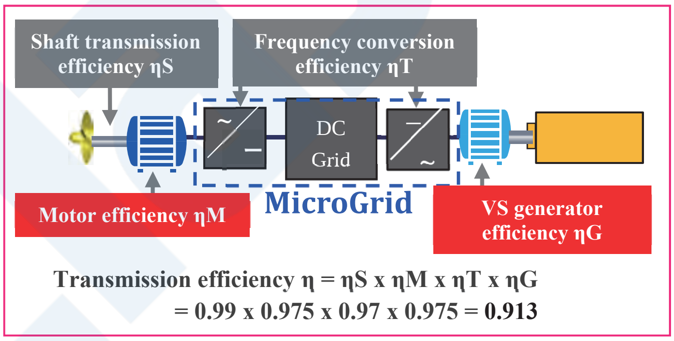

Fig. 7 Example of DC grid of ROBOSHIP

Moreover, thoroughgoing standardization and modularization provide the following advantages:

○ Cutting-edge technology usable without specialist knowledge
○ Pursuit of labor-savings in installation and maintenance
○ Simplified seafarer training
○ Reasonable battery pricing

The battery-only operation mode enables zero emissions, for example, during departure, arrival and anchorage, and is a feature not found in conventional electric propulsion ships. Since ROBOSHIP can sail on power supplied from the generators while underway, there are no particular restrictions on operational conditions, and its cruising range and speed are also comparable to those of conventional ships, operation is essentially no different from that of conventional ships.

3.4 Construction Scheme

The actual construction of the ROBOSHIP will be carried out by shipyards that build coastal vessels. To support these shipyards, Mitsubishi Shipbuilding Co., Ltd. will not only undertake the total engineering and conceptual design of the power plant, including on-shore power supplies, but will also provide engineering support in the basic design, construction and after-sales service stages.

The microgrid and associated components of the power plant will be manufactured by ABB, with IHI Power Systems Co., Ltd. who participate as the system integrator and supplier of the power plant in order to provide engineering support.

We at e5 Lab will coordinate the aspects of the actual construction work in cooperation with Mitsubishi Shipbuilding, IHI Power Systems and the shipyards that build coastal vessels.

3.5 Purpose of Introducing Marindows

As explained in Chapter 1, ROBOSHIP is an attempt to fuse a "robot" as a friend of humankind with a "ship." To achieve this, not only the hardware, but also the software is an extremely important element. Marindows is the platform software program for this purpose and provides the marine DX (digital transformation) infrastructure to solve facing hard-to-solve problems of the maritime industry, which include climate change, energy transition, a late start in DX and a decreasing workforce due to Japan's aging population and low birthrate.

The functions of software are digitalization, data creation and DX. The advantages of digitalization include flexible implementation conditions and the short time required for implementation, and low technical hurdles to implementation of digital tools, particularly mobile applications ("apps") not only in new ships, but also in existing ships. Provided digital devices (PCs, smartphones, tablet terminals) that run apps, the power to charge them and a communication environment are available, an app can be used as soon as it is installed on a device. Depending on the setting of the terminal and application, apps can also be used without an always-on communication connection.

Marindows is a digitalization tool designed for ships which makes full use of these advantages of digital technology. The aim of its introduction is to promote the digitalization of coastal vessels, enable safer and more efficient vessel operation, reduce seafarers' workloads and improve the quality-of-life aboard ships.

3.6 Functions and Superiority of Marindows

The initial version of Marindows, which is to be released in the near future, includes labor management and healthcare services of seafarers which pursued the thorough efficiency improvement by the digitization based on the legal amendments made this year (2022). Dedicated Marindows devices will be provided with preinstalled with these apps. Seafarers will use these devices to input their own data, which will then be compiled and shared to captains, onshore managers and partner companies supporting the apps, enabling easy digital handling of communications which are currently performed nondigitally and information that has not been managed until now.

The superiority of Marindows is its updateability. The functions of Marindows will be expanded successively. This point can be understood easily by analogy with mobile phone operating systems. Even state-of-the-art operating systems undergo constant research and development and repeated updating to add new functions, improve convenience and strengthen security. Marindows will also continue to evolve in the same way. In addition to labor management and healthcare services, new services to suit the needs of the worksite, such as navigation support and entertainment content for seafarers, can be introduced easily via dedicated devices and can be used immediately.

Considering the instability of telecommunication conditions at sea, the apps necessary for duties during voyages and the apps used at irregular times will be designed with specifications that allow offline use of some functions.

4. EXPANDABILITY OF ROBOSHIP

4.1 Positioning of 499 GT Standard Ship in Coastal Shipping Industry and Expandability to Other Hull Forms

The replacement of conventional coastal ships with ROBOSHIPs will have a large ripple effect because the 499 GT cargo ship, which is the target of the ROBOSHIP project, has a share of 20.6% in the coastal shipping industry (vessel count basis for 400 GT to 499 GT ships as of March 31st, 2021. Source: Website of the Japan Federation of Coastal Shipping Associations). Moreover, ROBOSHIP is also a highly versatile system, since its design can be applied to other hull forms and other types of ships by reviewing the capacity and the number of generators and the capacity of the batteries.

4.2 Expandability as a Realistic Solution

In the Prime Minister's Policy Speech to the Diet in October 2020, then-Prime Minister Suga declared that "by 2050 Japan will aim to reduce greenhouse gas emissions to net-zero, that is, to achieve 2050 carbon-neutral, decarbonized society." In line with this declaration, the transportation sector's midterm CO_2 emissions reduction target has been accelerated to a 35% reduction from 27% in FY 2030 relative to FY 2013. The FY 2030 CO_2 emissions reduction target of the coastal shipping industry, which is part of the transportation sector, has also been revised upward from a reduction of 1.57 million t-CO_2 (approx. 15% reduction) compared to FY 2013 to approximately 1.81 million t-CO_2 (approx. 17% reduction).

Since a transition to non-fossil fuels, namely, hydrogen and ammonia, is also required as an effective means of responding to Japan's "2050 Carbon Neutral" target, industrial, governmental, and academic circles have steered in unison to technological development and supply networks for this purpose.

Nevertheless, fossil fuels will inevitably still be the main energy source at the interim milestone year of 2030. Assuming the use of fossil fuels, GHG emissions reduction must be promoted using existing technologies for the time being. In this sense, the introduction of ROBOSHIP can be considered as a realistic choice for CO_2 emissions reduction at present.

4.3 Future-Oriented Expandability

The current power plant of ROBOSHIP consists of lithium-ion batteries combined with diesel generators (heavy fuel oil), and as explained in 3.3, zero-emission operation of this power plant is inevitably limited. However, the range of zero-emission operation can be expanded by increasing the battery capacity, use of LNG as a diesel generator fuel and concurrent use with hydrogen fuel cells. With progress in practical application of all-solid-state batteries on a commercial basis and development of technologies and supply networks for introducing the non-fossil fuels (hydrogen and ammonia) mentioned in 4.2, it will become possible to replace diesel generator fuels with these alternative energy sources, and in this case, complete zero emissions will become possible. Thus, it can be said that this system has expandability to allow version upgrades in line with future trends.

5. CONCLUSION

As we mentioned in section 2.1 above, the labor environment in the coastal shipping industry faces difficult situation. The 2020 National Census Results published by the Ministry of Internal Affairs and Communications last year revealed that the productive-age population (15 to 64 years old), which is the driving force of economic activity, has decreased by 13.9% from its peak in 1995. In addition, Japan also ranks low in productivity and our added value per hour of work in 2020 was US$48.10, which was the lowest among the G7 countries and was also below the average of the OECD members (US$54.00). Although companies have been striving the employment expansion for elderly people and women, the effects of those efforts alone have limit. It cannot compensate for the decrease in productive-age population unless productivity is improved.

In the global context, we are now facing with two crises, which are the COVID-19 pandemic and climate change. However, these two crises differ in that climate change has already been existed danger and its future is also scientifically predictable.

In a report released by UNPD (United Nations Development Programme) on February 8, 2022, it was stated that as of 2020, approximately 2.4 billion people were suffering food shortages, and 82.4 million people had been forced to relocate. It also predicts that a cumulative total of 40 million people mainly from developing countries, would die by 2100.

At the same time, the IPCC (United Nations Intergovernmental Panel on Climate Change) issued 6th Assessment Report on February 28, 2022 stating that "approximately 3.3 to 3.6 billion people live under conditions of extremely vulnerable to climate change." Regarding the current adaptation and its effects, the IPCC AR6 adds: "Many initiatives prioritize immediate and short-term climate risk reduction which reduces the opportunity for transformative adaptation. Long-term planning and rapid implementation over the next 10 years is required."

Failing to take action in spite of these circumstances is simply a groundless optimism, a betrayal of future generations and negligence. We must not forget that the anger of Generation Z is directed at us, our generation. We hope that the ROBOSHIP which we are promoting will contribute to solving these problems.

ClassNK's Efforts to Reduce GHG Emissions from Ships

Planning Division, Zero-Emission Transition Center, ClassNK
Plan Approval and Technical Solution Division, Marine GHG Certification Department, ClassNK

1. INTRODUCTION

The International Maritime Organization (IMO) adopted its initial strategy on reduction of GHG emissions from international shipping in 2018. This IMO strategy lays out a goal of achieving zero GHG emissions as early as possible within this century as the final non-binding target for GHG emissions reduction, and improving CO_2 emissions per transport work by at least 40% by 2030 and at least 70% by 2050 (both from 2008), with the goal of reducing total GHG emissions by at least 50% by 2050 in comparison with 2008.

Based on this strategy, at the 76th session of the Marine Environment Protection Committee held in June 2021 (MEPC 76), the Committee adopted amendments to Annex VI of the MARPOL Convention for introducing an "EEXI regulation" and a "CII rating" intended to reduce CO_2 emissions from ships in service in order to ensure that international shipping as a whole will achieve a target of reducing the CO_2 emission per transport work by at least 40% by 2030 from 2008 (2030 target) [1]. These regulations will be introduced in 2023.

Broadening our perspective from international shipping to the entire world, because more than 120 countries and regions, including Japan, have now declared their intentions to achieve "carbon neutrality in 2050," efforts to reduce GHG emissions are expected to be strengthened in many countries. Together with these regulations, similar efforts led by the private sector are also underway in the maritime transportation business, suggesting that movements toward zero emissions will be accelerated.

This paper introduces the outlines of the "EEXI regulation" and the "CII rating" which will be introduced in 2023, ClassNK's response to those programs and the outline of "ClassNK Zero-Emission Transition Support Services" being developed by ClassNK.

2. OUTLINE OF EEXI REGULATION AND RESPONSE OF CLASSNK

2.1 Outline of EEXI Regulation

The EEXI regulation is a framework for reducing CO_2 emissions from ships in service by setting a certain standard for the energy efficiency of those ships. The ship's energy efficiency is evaluated by the Energy Efficiency Existing Ship Index (EEXI), which is similar to the Energy Efficiency Design Index (EEDI). The regulation requires that the attained EEXI value of each individual ship must satisfy the required EEXI value (Fig. 1). If the attained EEXI value of an individual ship does not satisfy the required EEXI value, action such as limiting the engine power of the ship or installing additional energy-saving devices must be taken.

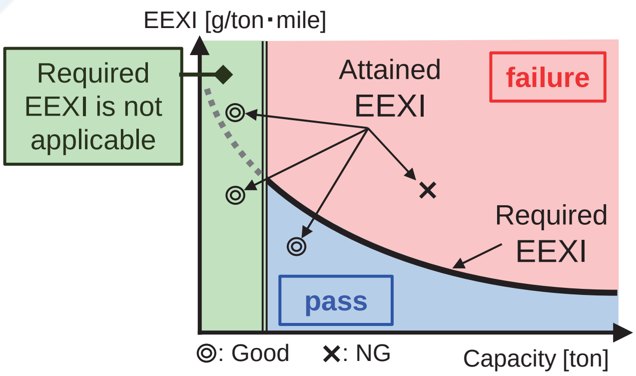

Fig. 1 Relationship between attained EEXI and required EEXI

2.1.1 Ships Subject to EEXI Regulation

The EEXI regulation applies to all ships of 400 GT and above that are engaged in international voyages regardless of the delivery date of the ship. However, as with the EEDI regulation, this regulation will not apply to ships not propelled by mechanical means.

2.1.2 Attained EEXI and Required EEXI

The EEXI is calculated by using a formula similar to that of the EEDI [2]. As its basic concept, EEXI is calculated by dividing the product obtained by multiplying "engine output" by "fuel consumption" and a "CO_2 conversion factor," by the "carrying capacity" and "ship speed," and represents the estimated CO_2 emissions when 1 ton of cargo is transported 1 nautical mile.

The EEXI values of ships to which EEDI is applied are calculated by using the vessel speed, which is obtained from the power curve used in EEDI certification. In the EEXI calculation for a ship which is not subject to the EEDI regulation, the ship speed is determined based on the result of a tank test, numerical computation of CFD, etc. or a speed trial in the full loaded condition, if any of those has been conducted, and if none of those has been conducted, the ship speed is calculated by using a simplified formula.

While the EEXI regulation applies to ships of 400 GT and above engaged in international voyages, the ships required to meet the required EEXI vary by ship type and size. For example, for bulk carriers, the EEXI calculation is required for vessels of 400 GT and above, and vessels of 10,000 DWT and above are required to comply with the required EEXI. For tankers, the EEXI calculation is required for those of 400 GT and above, and those of 4,000 DWT and above are required to comply with the required EEXI. The Required EEXI is determined by an "EEDI reference line," which is the baseline of the EEDI, and a "reduction factor (X)" (Fig. 2).

$$Required\ EEXI = \left(1 - \frac{X}{100}\right) \times EEDI\ Reference\ Line$$

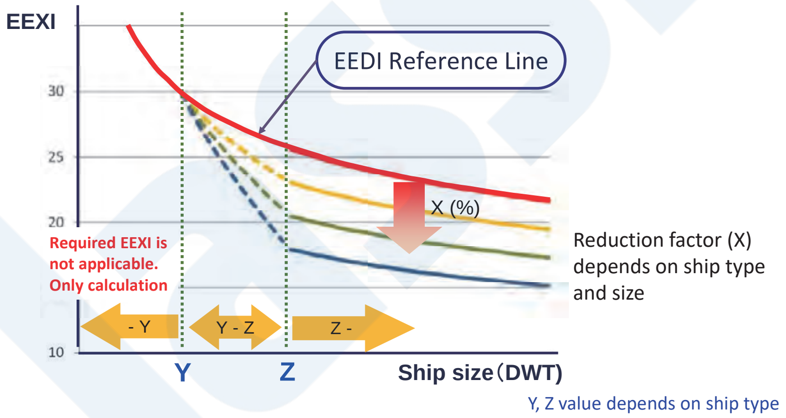

Fig. 2 Relationship between Required EEXI, EEDI reference line and reduction factor

Under the EEDI regulation, required values begin with Phase 0 according to the "contract date" and "delivery date," and are set so as to become stricter in stages from Phase 1 to Phase 2 and Phase 3. By contrast, the EEXI regulation requires a certain value with no stepwise strengthening of the required value. This required value is basically set at the same level as the required EEDI value as of 2023 (when the EEXI regulation takes effect). Ships such as bulk carriers, tankers and vehicle carriers are required to meet a required value equivalent to Phase 2 of EEDI, while ships such as containerships, general cargo ships, LNG carriers and gas carriers are required to meet a required value equivalent to Phase 3 of EEDI (Fig. 3). However, the required values are slightly relaxed for bulk carriers of 200,000 DWT and above, tankers of 200,000 DWT and above and containerships of less than 120,000 DWT, ro-ro cargo ships and ro-ro passenger ships, as it is assumed that it would be technically difficult to achieve a substantial improvement in the energy efficiency of ships in service.

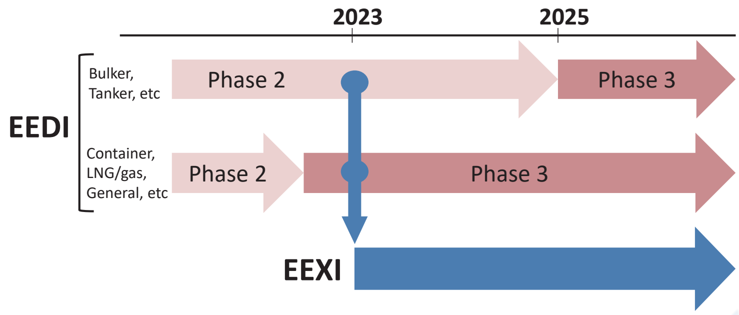

Fig. 3 Relationship between Required EEDI and Required EEXI

2.1.3 Timeline of EEXI Regulation

Application of the EEXI regulation will start on 1 January 2023. Ships delivered before 1 January 2023 must comply with the EEXI regulation at the first annual, intermediate or renewal survey of IAPP Certificate on or after 1 January 2023. Ships delivered on or after 1 January 2023 are required to comply with the EEXI regulation at the initial survey of the IEE Certificate, that is, before the ship's delivery.

2.2 Status of Compliance with EEXI Regulation and Response of ClassNK

2.2.1 Status of Compliance with EEXI Regulation

Among the ships registered in the ClassNK, approximately 7,200 are subject to the EEXI regulation, consisting of approximately 5,300 ships to which the EEDI is not applied, approximately 750 ships to which the EEDI is applied but which do not comply to the required EEXI and approximately 1,150 ships that already comply with the required EEXI. Thus, approximately 6,050 ships must respond to the EEXI regulation, which is equivalent to about 84% of ships subject to the EEXI regulation (Table 1). Among the ships which need to take action to meet the EEXI regulation, bulk carriers account for approximately 86%, tankers approximately 73%, containerships approximately 80% and gas carriers approximately 90%, indicating that an extremely large number of ships must take action to satisfy the EEXI regulation (Fig. 4).

Table 1 Status of EEXI compliance of ships registered in ClassNK

<table>
<tr><td>Ships subject to EEXI regulation</td><td colspan="2">7,200</td></tr>
<tr><td>Ships not subject to EEDI</td><td>5,300</td><td rowspan="2">Action needed 6,050 (84%)</td></tr>
<tr><td>Ships subject to EEDI (ships not subject to EEXI regulation)</td><td>750</td></tr>
<tr><td>Ships subject to EEDI (ships subject to EEXI regulation)</td><td>1,150</td><td>No action needed 1,150 (16%)</td></tr>
</table>

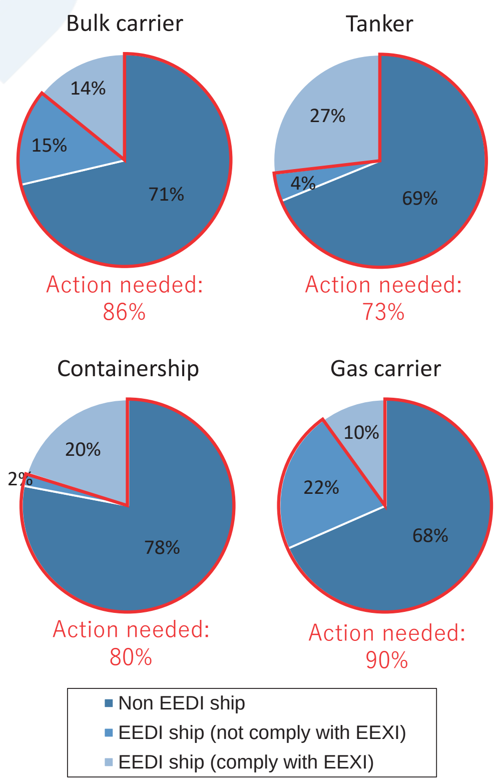

Fig. 4 Status of EEXI compliance of ships in ClassNK registry by ship type

2.2.2 Response to EEXI Regulation

Fig. 5 shows the flowchart for ship owners / management companies to judge whether any kind of action is needed or not in order to comply with the EEXI regulation.

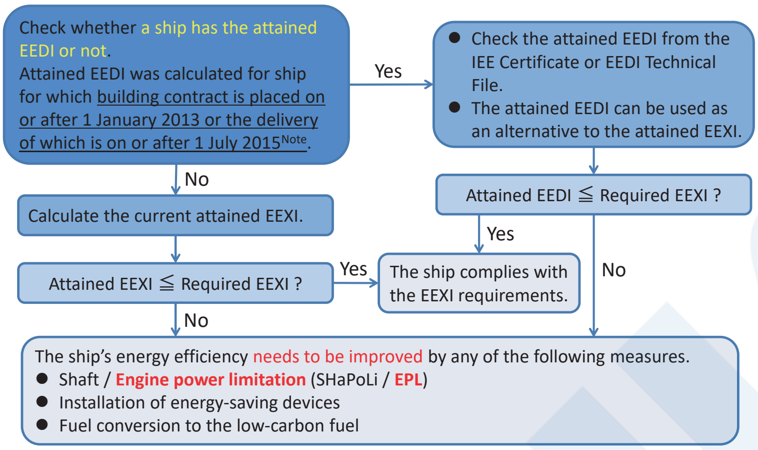

Fig. 5 Flowchart of response to EEXI regulation

If the ship is subject to the EEDI regulation, it is necessary to check the attained EEDI value indicated in the ship's IEE certificate or EEDI technical file to confirm whether or not the value satisfies the required EEXI. If the value satisfies the required EEXI, the attained EEDI value can be used as the attained EEXI value.

If the ship's EEDI value does not exceed the required EEXI, the ship can be considered as already satisfying the EEXI regulation, and it is unnecessary to be taken any particular action to improve the ship's energy efficiency. If the EEDI value is larger than the required EEXI, it is necessary to improve the energy efficiency of the ship by taking measures such as limiting the main engine power [3], adding or improving energy-saving devices, improving propulsion efficiency through measures such as the optimization of the propeller and/or bow shape, conversion to low-carbon fuel, etc.

For ships to which the EEDI regulation has not been applied, it is necessary to first calculate the ship's current EEXI value in order to determine whether or not it satisfies the required EEXI. If the value satisfies the required EEXI, it is not necessary to take any special action to improve the ship's energy efficiency. However, if the value does not satisfy the required EEXI, it is necessary to take some form of measures that will contribute to improving the ship's energy efficiency.

2.3 Response of ClassNK to EEXI Regulation

ClassNK has prepared a simplified EEXI assessment tool called "EEXI Simplified Planner," which enables shipping companies to determine whether or not their own ships comply with the EEXI regulation in a simplified manner. This tool is available on the ClassNK website (Fig. 6).

This assessment tool makes it possible to estimate the limit value of the main engine output for meeting the EEXI regulation, and to estimate the amount of reduction in vessel speed in case the main engine power is limited. It should be noted that this assessment tool is intended solely to enable ship companies to perform simplified calculations, and is different from actual certification.

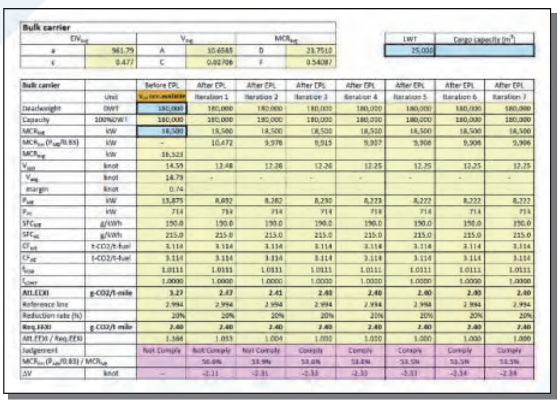

Fig. 6 Simplified EEXI assessment tool "EEXI Simplified Planner"

3. OUTLINE OF CII RATING AND RESPONSE OF CLASSNK

3.1 Outline of CII Rating

The CII rating is a framework for promoting fuel efficiency improvement in international shipping as a whole by checking the annual fuel consumption of each ship and rating the ship according to the results. Specifically, the fuel consumption (CII: Carbon Intensity Indicator) of individual ships is calculated every year based on the IMO's Data Collection System (IMO-DCS), which was implemented in 2019, and ships are rated in five levels (A, B, C, D and E) based on their deviation from a required value set for each ship type (Fig. 7). For low-rated ships with a rating result of E in any year or a rating of D for 3 consecutive years, it is necessary to formulate a fuel efficiency improvement plan which includes navigation at reduced speed (slow steaming), selection of optimum routes and appropriate maintenance, fill out a Ship Energy Efficiency Management Plan (SEEMP) and obtain the approval of the Administration or the ship classification society. For high-rated ships with ratings of A or B, it is recommended that the Administrations or the port authorities provide incentives.

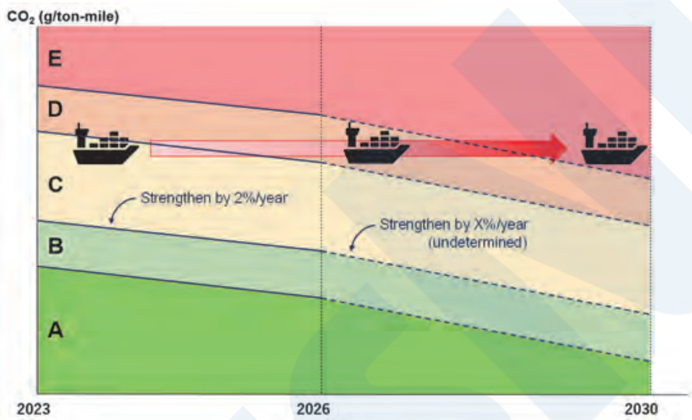

Fig. 7 CII rating

3.1.1 Ships Subject to CII Rating

As in the case of the IMO-DCS, the CII rating is applied to all ships of 5,000 GT and above (bulk carriers, gas carriers, tankers, containerships, general cargo ships, refrigerated cargo carriers, combination carriers, vehicle carriers, ro-ro cargo ships, ro-ro passenger ships, LNG carriers and cruise passenger ships) that are engaged in international voyages.

3.1.2 Attained CII and Required CII

The attained CII value of each ship is the CO_2 emission per deadweight tonnage-mile (gross tonnage-mile for vehicle carriers, ro-ro passenger ships and cruise passenger ships) based on the actual results of fuel consumption in the previous year [4]. The formula is as follows, where CO_2 emissions are calculated by multiplying the ship's fuel consumption by a CO_2 conversion factor. Because emissions can be calculated using only the data collected under the IMO-DCS system, it is not necessary to collect additional data.

$$Attained\ CII = \frac{CO_2\ emissions}{(DWT\ or\ GT) \times Distance\ travelled}$$

In addition, the required CII value will be strengthened every year based on the CII reference value (CII reference line) [5] calculated by each ship type in 2019. The required CII in 2023, when the system begins, will be a reduction of 5% from 2019, after which the reduction factor will be strengthened by 2% every year until 2026 [6]. The yearly reduction factors from 2027 to 2030 will be determined by 2025 based on the condition of GHG reductions in the future (Table 2).

$$Required\ CII = \frac{100 - Z}{100} \times CII\ reference\ value$$

Table 2　Reduction factor (Z) for the CII relative to 2019

Year	Reduction factor (Z)
2023	5%
2024	7%
2025	9%
2026	11%
2027	(to be decided)
2028	(to be decided)
2029	(to be decided)
2030	(to be decided)

The correction factors for ship types in the CII calculation and the requirements for exclusion of voyages are under continuing deliberation in the IMO.

3.1.3　Timeline of CII Rating

The CII rating will be started on 1 January 2023, and fuel consumption and other data in 2023 will be subject to the rating. The rating for 2023 will be conducted in 2024.

Ships subject to this rating system must enter “CII calculation method,” “Required CII value for the coming 3 years,” “implementation plan for achieving the required CII value” and “procedures for self-evaluation and improvement” in the ship’s SEEMP and obtain the approval of the Administration or the ship classification society by 1 January 2023.

3.1.4　Evaluation Method for CII Rating

In the CII rating, the CII value for each ship is calculated, and ships are evaluated in the five levels of A, B, C, D and E according to their deviation from the required CII value in that year [7]. It should be noted that this rating is not based on a relative evaluation, but on an absolute evaluation against the required CII, which will be strengthened every year (Fig. 8). Therefore, if a ship’s fuel consumption results are similar for each year, its rating will be downgraded at some point in time.

This CII rating system is not intended to impose a penalty such as suspension of operation even if a ship’s rating result is low. However, if the rating result is E in any year or D for 3 consecutive years, it is necessary to prepare a fuel efficiency improvement plan for the next fiscal year and beyond, make the required entries in the SEEMP and obtain the approval of the Administration or the ship classification society. The IMO guidelines on matters such as the specific method of entering this improvement plan in the SEEMP are to be finalized at MEPC 78 in June 2022.

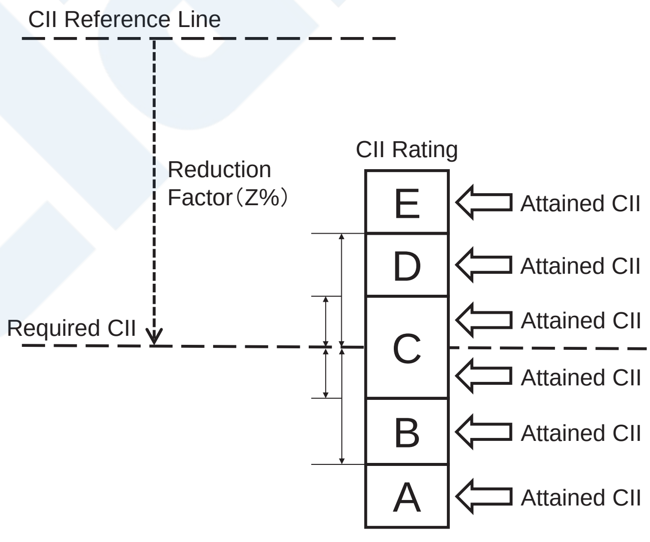

Fig. 8　Required CII and CII rating

3.2 Response of ClassNK to CII Rating

The following introduces the improvement of the ClassNK MRV Portal and the CII simple assessment tool as ClassNK's response to the CII rating.

3.2.1 ClassNK MRV Portal

ClassNK has provided the ClassNK MRV Portal since 2017 so that ship companies can respond efficiently to IMO-DCS and EU-MRV regulations. This data collection and management system makes it possible to receive fuel consumption and other data from the ship or third-party software, prepare and submit annual reports (EU MRV Emission Report and IMO DCS Annual Report) managed on the website and acquire certification by ClassNK.

ClassNK is conducting work to improve the ClassNK MRV Portal by adding the functions described below toward the start of the CII rating.

3.2.1.1 Preparation of Annual Report and Improvement Plan

To reduce additional work of ship companies related to data reporting and verification associated with the CII rating, ClassNK will add information on CII in IMO DCS Annual Report which are prepared automatically on the ClassNK MRV Portal. Since it is necessary to prepare a plan of corrective actions for the next fiscal year and beyond if the rating result is E for any year or D for 3 consecutive years, ClassNK will also add a function to support preparation of improvement plan documents by selecting the improvement measures to be implemented in the next fiscal year and thereafter from a list of options such as the weather routing, just in time, propeller cleaning, etc. on the portal.

3.2.2 Simplified CII assessment Tool

ClassNK has created a simplified CII assessment tool and made it available on the ClassNK website (Fig. 9). This assessment tool is capable of automatically calculating the ship's CII rating when the user enters a ship type, DWT and the annual values of fuel consumption and distance travelled. It should be noted that this is an assessment tool that allows ship companies to perform calculation voluntarily, and is different from actual verification.

CII Calculation

Please input blue cells

ClassNK

Version 0.2 June 2021

Ship Particular	IMO Number	1111111
	Ship Name	NK bulker
	Ship Type	Bulk carrier
	Deadweight	61338
	Gross Tonnage	
Fuel Consumption (ton)	Diesel/Gas Oil	563
	LFO	
	HFO	3580
	LPG(Propane)	
	LPG(Butane)	
	LNG	
	Methanol	
	Ethanol	
Distance Travelled (nm)		54289
CO2 Emission		12953
Attained CII		3.89
CII ref		4.99
Rating Year		2023
Required CII		4.74
Attained CII / Required CII		0.820
CII Rating		A

Fig. 9 CII simple assessment tool

4. CLASSNK ZERO-EMISSION TRANSITION SUPPORT SERVICES

ClassNK has developed "ClassNK Zero-Emission Transition Support Services" so that customers involved in the maritime transportation business can pursue zero emissions while carrying out planning and management of GHG emissions in their everyday business operation.

As the actual menu of services, ClassNK has arranged and provides a comprehensive range of support services that includes the GHG emissions management systems development & certification, GHG emissions management tools, GHG emissions verification & assessment and GHG emissions reduction support (Fig. 10). This chapter introduces the outline of these support services.

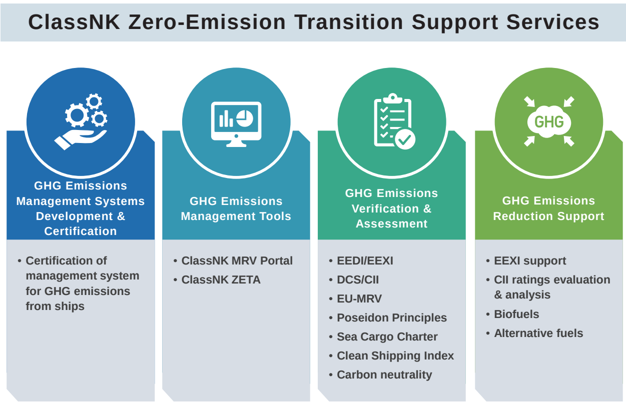

Fig. 10　ClassNK zero-emission transition support services

4.1　GHG Emissions Management Systems Development & Certification

ClassNK certifies the proactive efforts of concerned parties that set a clear target for reduction of GHG emissions from ships, develop appropriate management systems for its achievement and operate the management system.

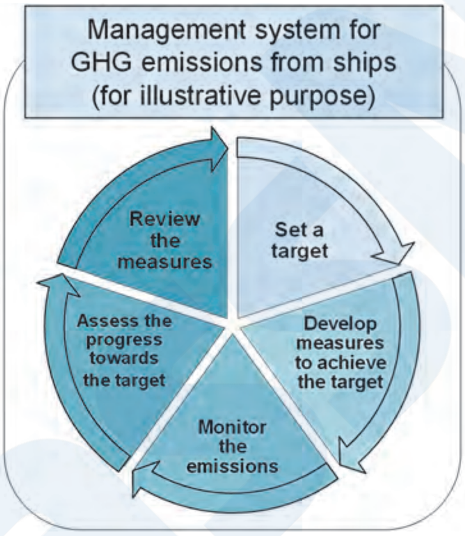

Fig. 11　Management system for GHG emissions from ships (image)

To manage GHG emissions from ships in a planned manner, it is considered necessary to continue the cycle of setting a clear target for the reduction of GHG emissions from the ship, studying measures for achievement of that target, determining the actual GHG emissions and evaluating the target achievement level and reviewing measures (Fig. 11).

ClassNK expects that the acquisition of this certification will add further value to the future maritime transportation business of those concerned.

This certification will be conducted within the framework of Innovation Endorsement (IE), which ClassNK has operated since 2020 as a certification service to support innovative efforts by concerned parties.

4.2　GHG Emissions Management Tools

As described above, ClassNK provides the ClassNK MRV Portal to enable ship companies to respond efficiently to the IMO-DCS and EU-MRV regulations. The Society released ClassNK ZETA (Zero Emission Transition Accelerator) in April 2022 as a GHG emissions management tool linked to the ClassNK MRV Portal (Fig. 12). This tool is a comprehensive data management platform equipped with a function for monitoring the CO_2 emissions of individual ships or an entire fleet and the CII rating, which will be introduced in 2023. The Society has also constructed a framework that enables ship owners and charterers to safely use data with the permission of the data owner, namely, the ship management company providing CO_2 emissions data, by utilizing the mechanism of IoS-OP.

ClassNK ZETA is equipped with the following four functions, primarily for ship management companies, ship owners and charterers.

- A Vessel Monitoring function that displays the CO_2 emissions, result of the CII rating, etc. of individual ships in real time.
- A Fleet Monitoring function that displays the entire fleet's CO_2 emissions, result of the CII rating, etc. in real time.
- A Simulation function for simulating the changes in CO_2 emissions and the CII rating by slow steaming and other possible measures.
- A Periodical Report function that can output the CO_2 emissions for each voyage, ship or fleet.

Development is underway to also respond to requirements such as reporting of CO_2 emissions between the ship company, financial institutions and charterers, with the aim of responding to frameworks such as the Poseidon Principles and the Sea Cargo Charter, with the aim of providing a platform that enables stakeholders to check and determine the necessary CO_2 emissions of ships at the necessary time, with appropriate agreement among the stakeholders.

Fig. 12　Image of ClassNK ZETA

4.3　GHG Emissions Verification & Assessment

4.3.1　Response to IMO and EU Regulations

As a ship classification society, ClassNK conducts checks to verify compliance with IMO regulations such as EEDI and SEEMP, which were started in 2011. In addition to verification of compliance with the new EEXI regulation and CII rating described in Chapters 2 and 3, ClassNK also intends to strengthen its support related to those efforts.

In the EU, the EU-MRV regulation was started in 2018 and requires collection and reporting of fuel consumption and other data for voyages departing from and arriving in ports in areas under the jurisdiction of the EU. ClassNK has also performed certification of approximately 3,500 cases as a certification body for this regulation.

Because the United Kingdom withdrew from the EU, a regulation called UK-MRV, which is similar to EU-MRV, was introduced separately in January 2022 for voyages departing from and arriving in the UK. ClassNK is currently working to acquire certification as a certification body for UK-MRV. Since the data that must be collected for UK-MRV can be extracted from the data that ClassNK currently collects for EU-MRV, ClassNK is currently carrying out work to improve the ClassNK MRV Portal in order to respond to this function.

4.3.2　Response to Private Sector-Led Frameworks

In addition to the regulations introduced by the IMO and Europe, movements toward accelerating the reduction of GHG emissions from ships are also spreading at the private sector level.

In June 2019, the Poseidon Principles was launched as a framework for promoting the reduction of CO_2 emissions from international shipping from the standpoint of financial institutions. Financial institutions which sign the Poseidon Principles are required to evaluate to what extent the CO_2 emissions of their ship finance portfolio is aligned with the IMO's GHG target (minimum 50% reduction of total GHG emissions from international shipping from 2008 to be achieved by 2050), and disclose the results every year.

Similarly, in October 2020, the Sea Cargo Charter was launched as a framework for promoting the reduction of CO_2 emissions from international shipping from the standpoint of charterers. Charterers and shipping companies signing the Sea Cargo Charter are required to evaluate to what extent the CO_2 emissions from their cargo transportation is aligned with the IMO's GHG target (minimum 50% reduction of total GHG emissions by 2050), and disclose the results every year.

In December 2021, the Poseidon Principles for Marine Insurance was also launched as a framework for promoting the reduction of CO_2 emissions from international shipping from the standpoint of marine insurance. Insurance companies signing the principles are required to evaluate to what extent the CO_2 emissions from ships for which they undertake insurance is aligned with the IMO's GHG target (minimum 50% reduction of total GHG emissions by 2050), and disclose the results every year. However, while the above-mentioned Poseidon Principles and the Sea Cargo Charter only require evaluation for consistency with the present IMO's GHG target, the Poseidon Principles for Marine Insurance is characterized by also requiring evaluation for consistency with the 2050 zero-emissions goal.

ClassNK provides assessment services based on these frameworks.

4.3.3 Evaluation for the Achievement of Carbon Neutrality

As climate change is gaining more and more attention on a global scale, companies are increasingly setting their ambitions to achieve carbon neutrality by 2050.

For ship companies that set targets for reduction of CO_2 emissions from their ships, for example, a target of achieving carbon neutrality in 2050, ClassNK will evaluate the degree to which the CO_2 emissions from their fleets conforms to the set target. In this assessment, the CO_2 emissions to be targeted or the year of achievement can be customized according to the request of the ship company. ClassNK also plans to support lifecycle CO_2 emissions of fuels and use of the carbon offset scheme.

4.4 GHG Emissions Reduction Support

Although support by ClassNK for measures to reduce GHG emissions from ships was described in Chapters 2 and 3, the Society is also actively providing support for the introduction of alternative fuels.

Decarbonization of ships is currently in the transition phase, and it is thought that the adoption of zero-emission fuels will increase in the future. To facilitate the introduction of alternative fuels, ClassNK issued “Guidelines for Ships Using Alternative Fuels” (Edition 1.1) in September 2021. The guidelines consist of the existing “Guidelines for Ships Using Low-Flashpoint Fuels (Methyl/Ethyl/Alcohol/LPG)” and newly-added provisions for ships using ammonia as a fuel, and have a comprehensive content that includes the safety requirements for these fuels. Furthermore, ClassNK has also updated the notation for the existing “LNG Ready,” and has added provisions concerning design in preparation for the future use of these alternative fuels and “Alternative Fuel Ready” as a notation for ships with partial equipment installation.

ClassNK also provides support for the use of biofuels. Biofuels are renewable fuels that are produced from biomass, mainly plant oil, as the raw material. Although these fuels emit CO_2 during combustion, because the plants (biomass) used as the raw material absorb CO_2 in the atmosphere in their growth process, biofuels are regarded as “carbon-neutral” fuels. Some types of biofuels have the advantage of serving as “drop-in fuels” which can be used as fuels for ships without changing the specifications of existing diesel engines, and are also being used in ships on a trial basis in a growing number of cases. To assist in understanding the use of biofuels, ClassNK responds to various inquiries, and also provides explanatory materials on biofuels on ships on its website.

5. CONCLUSION

Following the adoption of the Paris Agreement in December 2015, the IMO adopted its initial strategy on the reduction of GHG emissions in April 2018, and laid out a goal of reducing total GHG emissions from international shipping by 50% from 2008 to be achieved in 2050. This strategy will be reviewed every 5 years. While the next revision will be in 2023, IMO started study toward this revision in the autumn of 2021. Among global efforts to reduce GHG emissions, currently more than 120 countries and region have declared their intentions to achieve carbon neutrality in 2050. In view of these trends, it is also possible that studies toward reduction of GHG emissions from international shipping will proceed based mainly on the opinion that the reduction target should be raised to “carbon neutrality in 2050.”

This paper introduced the outlines of the “EEXI regulation” and the “CII rating”, which will be introduced in 2023, and ClassNK’s response to those initiatives, as well as the outline of “ClassNK Zero-Emission Transition Support Services”.

We hope that this paper will be of assistance when considering further efforts toward the reduction of GHG emissions in the maritime shipping industry.

REFERENCES

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Future Fluidics Analysis and an AI Surrogate Model for Manufacturing

— Can Super Simulation Enable Real-Time Wind-Structure Coupling Analysis? —

Hiroshi MATSUOKA*

1. INTRODUCTION

More than 120 of the world's countries, including Japan, have declared their intentions to "achieve carbon neutrality by 2050." Under these circumstances, large expectations are placed on expanded utilization of wind energy, and the construction of large-scale wind farms has proceeded. However, as the plant size and investment increase, requirements for prevention of accidents and outages and improvement of operating performance become more demanding. For this reason, "multiscale and multi-physics numerical analysis," in other words, "super simulation," which is performed to achieve greater accuracy in structural safety design and performance estimation, is necessary in the design stage. In the operation stage, it is also necessary to conduct system control so as to minimize fatigue damage accumulation on a continuous basis in order to ensure stable operation over the long term, and ideally, it will be necessary to consider conducting super simulations in real time. For this reason, demand for higher speed in numerical calculations in fluidics analysis is extremely strong.

In fluidics analysis, the method of numerically solving differential equations such as the Navier-Stokes equations has long been the orthodox approach. However, some fundamentally different idea seems to be needed in order to drastically increase computation speed.

As one possible solution, this paper introduces a "lattice gas method-AI surrogate model." This approach uses a "virtual particle model of a fluid analysis method called the 'lattice gas method'" as a substitute (surrogate model) for a "differential equation" that derives the fluid behavior. Fuzzy estimation becomes possible through the particle image in this model. In addition, a learning algorithm for measurement data can be obtained by making the model compatible with the computational structure of the neural network.

The development of this model is still in progress, and a simulation technique for verifying its effectiveness and method for comparison with experimental results have not been completed at this stage. Therefore, this paper mainly organizes the thinking that led to this concept, albeit in somewhat prosaic terms.

2. EXPANSION OF WIND ENERGY UTILIZATION AND FLUID ANALYSIS IN THE FUTURE

2.1 Need for High-Resolution Prediction in Fluidics for Wind Energy

A number of large-scale projects related to the use of various forms of renewable energy are underway with the aim of achieving carbon neutrality. Particularly for wind energy, huge wind farms are being built in rapid succession, and projects such as the development of wind-assisted operating ships (e.g., Wind Challenger [1)]) and ocean energy harvesting vessels (e.g., Wind Hunter [1)]) have been started with the aim of providing next-generation systems.

In such projects, the selection of a suitable construction site or operation site where the system can safely demonstrate high performance becomes increasingly important as the plant scale and investment become larger. Therefore, a preliminary evaluation using a numerical simulation with the highest possible accuracy is required. However, from the viewpoint of general theory, in order to predict the behavior of a fluid passing around a structure with high accuracy, it is necessary to resolve the images of all the fluid vortexes of various sizes that occur around the structure. Unless the image of a vortex that actually exists at a certain time can be resolved, the prediction of the behavior of the fluid around that point at that time will be erroneous. Therefore, "lattice points," where the flow velocity is to be calculated, should preferably be arranged at intervals as fine as the diameter of the smallest vortex. If the size of the smallest vortex is much smaller relative to the size of the structure, the number of lattice points arranged around the structure will be enormous. As will be described in section 3.1, in the case of a wind farm, the range of the length scale from the "size of the smallest vortex to be resolved" to the "size of the whole structure" would

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extend to several digits or more. Therefore, **“multiscale fluid analysis”** at a very high resolution is required.

2.2 Difficulty of Multiscale Fluid Analysis

With dimensional analysis in fluid dynamics, it is known that “generally, the value of the ratio between the ‘size (representative length) of a structure’ and the ‘diameter of the smallest vortex’ must be proportional to the 3/4th power of the Reynolds number [2)] (Note: Reynolds number = representative flow velocity × representative length / coefficient of kinematic viscosity).” The value of this ratio also serves as an indication of the number of lattice points to be arranged in the one-dimensional direction in cases where the resolution must extend to the smallest vortex. Therefore, when the behavior of a fluid is to be accurately predicted, the number of lattice points to be arranged will steeply increase in proportion to the product of the number of lattice points in the three-dimensional direction, and if the Reynolds number exceeds a certain size, it will be impossible to complete the numerical calculation within a practically acceptable time. In other words, as the Reynolds number becomes larger, it becomes more difficult to perform a multiscale fluid analysis in terms of calculation time.

2.3 High-Resolution Prediction Using Present Numerical Fluid Dynamics

This section lays out the general theory for achieving a high-resolution simulation in fluidics analysis for manufacturing from the author’s point of view.

As a result of the remarkable improvement in supercomputer performance, it has now become possible to complete the necessary time evolution calculation within a practical time, even for a lattice point arrangement with very high resolution. Having said that, there is always a highest number of lattice points at which the calculation can be completed within an acceptable time. First, therefore, when attempting a high-resolution simulation, the number of lattice points to be arranged should be as close to that number as possible. In fluid analysis on an experimental or prototyping scale, the Reynolds number is not particularly large, so resolution to a level that includes the smallest vortex might be possible with the fineness of that lattice point arrangement. In this case, the extra work of considering the fluid state of further details between the lattice points is unnecessary. In other words, a direct numerical simulation (DNS) for the fluid which does not require this work would be achievable, and it would be possible to obtain an accurate simulation result. In full-scale fluid analyses, however, the Reynolds number would be excessively large. Therefore, it is still difficult to perform a simulated calculation which is capable of resolving the image of the smallest vortex only with DNS, even with the most recent supercomputers. For this reason, the turbulence model approach is adopted, in which “interpolating estimation is performed by setting a certain assumption (model)” for any part finer than the interval between lattice points, after finding the physical quantities such as the flow velocity at each lattice point. Sufficient accuracy can be secured with this approach in some cases, although this depends on the purpose of the simulation. However, this model assumption lacks physical generality in many cases, and the resulting uncertainty may have an unacceptable effect on the simulation results.

3. SETTING A DREAM TARGET AND ATTEMPTING BACK-CASTING THINKING

3.1 Ideal Resolution Is a Width of 5 to 6 Digits per Dimension

Around the end of last year, The Denki (ENERGY & ELECTRICY) Shimbun newspaper published an article entitled “On November 24, 2021, Siemens Gamesa Renewable Energy in Spain was awarded a contract for 69 windmills for Finland’s largest onshore wind farm.” According to that article, the windmill rotor diameter is approximately 170 m and the tower height is approximately 150 m. In this section, it is assumed that the resolution required for an aerodynamic calculation at each region of the windmill blade is estimated to be approximately 5 mm, which is larger than the actual smallest vortex (Kolmogorov scale). This is the result of considering factors such as the fact that the smallest scale of practical turbulence is assumed to be approximately five times the Kolmogorov scale [3)], and it is an assumption in a direction which makes the achievement of the target resolution easier. However, even in this case, the difference in the “length scale” in comparison with the blade length is a four-digit number.

As an additional problem, in a wind farm, the wake flow of a windmill is affected by the presence of a downstream windmill and the overlap with the wake flow of that windmill, resulting in a complex wake flow that also reaches windmills located further downstream. For highly accurate prediction of power generation, it is necessary to analyze the state of such wake flows for the entire wind farm, in addition to the wind prediction that considers the topography of the wind farm site. Therefore, the sparse and dense arrangement of lattice points must be adjusted while considering the size of the fluid vortices in the respective parts of a vast spatial region extending from several km to 10 km in the horizontal direction and 500 m or more in the vertical direction. This means it is necessary to arrange a huge number of lattice points in the entire wind farm, particularly if a high-resolution lattice point arrangement with an interval of 5 mm near the rotors of all the windmills is required. In the horizontal direction, the number would be 5 km ÷ 5 mm = 10^6. However, since a lattice point arrangement with super high resolution of approximately 5 mm intervals is not required for all lengths, arrangement of $10^{5\sim6}$ lattice points per dimension would give an indication of the "dream target."

This guideline is also surprisingly reasonable in other fields of fluidics analysis. For example, in a study of the air resistance of a running automobile, Tsubokura published findings indicating that if a numerical analysis (LES) in which the resolution near the boundary where the automobile comes into contact with the atmosphere is fined down to the order of 0.1 mm, the behavior can be predicted with an error of 1 to 2% from the value obtained in a wind-tunnel experiment using a full-scale automobile model [4)]. Similarly, in an investigation of the total resistance coefficient of a ship, Nishikawa found that a numerical analysis (DNS) of the state of a tank test of a towed model ship (approx. 5.5 m) at a resolution of approximately 0.05 mm with an arrangement of approximately 32 billion lattice points could predict the behavior of the ship with accuracy within 1%, which is the measurement error of the tank test [5)].

Therefore, in quantitative terms, **"realizing high-resolution multiscale analysis in which $10^{5\sim6}$ lattice points per dimension are arranged"** is considered to be an ambitious target in future fluidics analysis for manufacturing.

3.2 Requirements of Multi-Physics Hampering Target Achievement

In any of the three cases of a "wind farm," a "wind-assisted operating ship," and an "ocean energy harvesting vessel" mentioned in section 2.1, the fluid (atmosphere or seawater) interacts with an elastically deformable structure (e.g., windmill blade, ship sail). Particularly in wind farms, windmills are placed in an extremely complex wake flow, as described above, but in the analysis of the windmill structure, a strength analysis accompanying elastic deformation and a fatigue analysis for achieving stable operation over a long service life should be conducted as accurately as possible. In the cases of a "wind-assisted operating ship" and an "ocean energy harvesting vessel," a gas phase (atmosphere) and a liquid phase (seawater) coexist in the fluid, while the structure tends to rock dynamically on the boundary between those two phases. To evaluate the soundness of the structure under a condition of continuing complex motion of this type, **"multi-physics coupled analysis"** is essential. In this type of analysis, different physical equations for the fluid and the structure are continually coupled in order to perform the calculation, and in this coupled analysis, the multi-physics calculation is incorporated into the time evolution calculation, while also maintaining the high-resolution arrangement required for the multiscale analysis. Since a substantial increase in calculation time is normally unavoidable under these constraints, achievement of the numerical target in the multiscale fluid analysis mentioned in section 3.1 becomes an even more challenging goal.

3.3 Real World Requirements Hampering Target Achievement

In the natural environment of the real world, unexpected sudden changes, exemplified by changes in wind conditions, are a frequent occurrence. Therefore, in the operation stage, it is important to prevent any anomaly resulting from a sudden change in wind conditions from developing into an accident, and to extend the life of the system by preventing excessive accumulation of fatigue damage even in such cases. For that purpose, feedback control which is capable of responding promptly to sudden changes in the external environment is necessary. Conducting this control with high accuracy requires a technology for **"real-time data assimilation (real-time measurement fusion simulation)"** that enables prompt reflection of on-site measurement information in simulations. Under normal circumstances, the time required for the data assimilation calculation will unavoidably lead to an increase in calculation time, depending on the selection of the method for reflecting the simulated calculation results in feedback control.

3.4 Dream of High-Speed Super Simulation

From the viewpoint of the technologies that constitute a supercomputer, the numerical target of multiscale fluid analysis described in section 3.1 is a task of achieving massively parallel super-fast data transmission between super-large memories. While this task is in itself very difficult, achieving this target while simultaneously satisfying the "requirements of multi-physics" described in section 3.2 and the "real-world requirements" described in section 3.3 would seem to be an "impossible dream."

In a "super simulation" which combines multiscale fluid analysis with a coupled analysis of the interactions of the fluid and the structure, the orthodox approach is currently the method of proceeding with a time evolution calculation by calculating the behavior of the fluidic part by using a finite difference solution such as the Navier-Stokes equation and the structural part by using the finite element method, and constantly exchanging information on the state quantities of the two. Since approaches of this type have in fact produced meaningful results [6], it can be said that this as an extremely reasonable approach from the viewpoint of solidifying the foundations of the technology.

However, this paper pursues the dream of achieving "super simulation" in real time, and discusses the issue by back-casting thinking based on the multiscale numerical target described in section 3.1. The purpose of this effort is to discover the possibility of realizing this dream, even if only slightly. From this point of view, the first step is to explore a method for drastically reducing the burden on the computer when it performs a high-resolution multiscale analysis.

[Panoramic Perspective] Method for Converging from the Virtual World to Reality

The approaches for computer simulations used in "fluidics analysis for manufacturing" can be roughly summarized as follows.

In general, many phenomena in the real world interact with each other and also fluctuate on an extensive spatial and temporal scale. Therefore, when attempting to reproduce real behavior faithfully by a numerical simulation, a complex and elaborate simulation model that has both a "multi-physics nature" for coupling a larger number of physical phenomena and a "multiscale nature" for capturing fluctuations in a larger spatial and temporal range will be needed.

As one example, the author was formerly a member of a project team for developing a supercomputer called the "Earth Simulator (first-generation)," and at that time, one argument exemplifying the above-mentioned point can be summarized as follows: "One of the important phenomena in prediction of global warming is 'general circulation of seawater on a global scale (oceanic general circulation).' In a simulation of this behavior, a physical model that simulates the circulation of only seawater by solving an approximation equation based on the laws of physics serves as the core. However, in order to approach the real-world phenomena more closely, it is necessary to evolve the model into one which is coupled with 'atmospheric general circulation' so as to consider the driving force due to air on the sea surface and the changes in the sea surface height due to factors such as precipitation and evaporation. Moreover, if that model can be coupled with a model which is capable of calculating factors such as the 'downward seawater flow due to icebergs' and the 'impact of changes in air composition due to the ecosystem on the atmosphere and seawater through greenhouse effect,' it would be possible to simulate the real world more faithfully."

This kind of approach, which is based on **"numerical solution of approximation equation and elaboration of the model,"** has long been the prime orthodox approach in numerical simulations (cf. Fig. 1). However, as the elaboration becomes more advanced, the complexity of the model calculation also increases, making it impossible to complete the computation within a practical time. In contrast to this, the second approach is to **"start from a more fundamental equation."** For example, one such method is an attempt to simulate a phenomenon of fluidic scale by using molecular dynamics. Because the real world which is the focus of interest in this case is molecular groups at least of the order of Avogadro numbers (10^{24}), if calculations are accumulated from the molecular size world, the extent of the multiscale digits would exceed 8 digits per dimension. Even with today's rapidly-advancing high-performance computers, the operation speed and storage capacity are still far short of the performance needed to complete this calculation within a practical time.

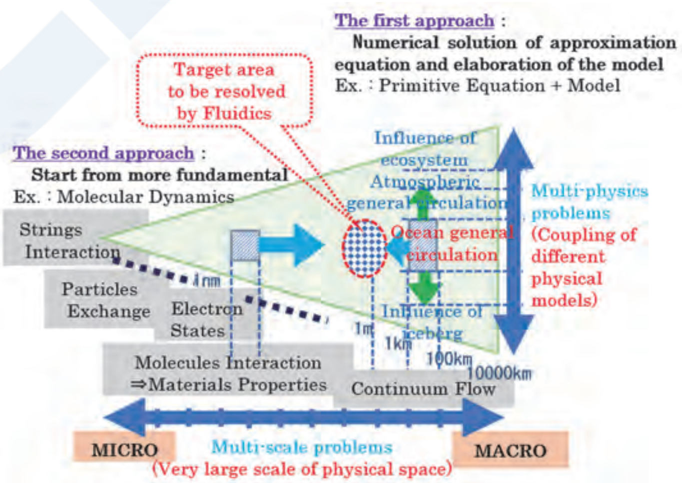


Fig. 1　Multiscale and multi-physics [7]

Under these circumstances, the third approach (cf. Fig. 2) is to "derive phenomena of the real world by imagining a virtual world with a scale one step finer than the spatial and temporal scales of the phenomenon to be analyzed, setting a simple rule that governs the temporal development of that world, solving this rule at high speed using a computer, and then averaging the behaviors of the obtained virtual world within an appropriate range of space and time." Such an approach of **"converging from the virtual world to reality"** is capable of substantially shortening computational time and is clearly advantageous from the viewpoint of real-time simulation. Specific techniques of this type include the lattice gas method and the lattice Boltzmann method.

These approaches are characterized by the fact that the behavior of a continuous fluid is simulated by the "collective behavior of virtual particles of sub-macro scale." Here, "sub-macro scale" means a scale one step finer than the temporal-spatial scale to be analyzed. This "sub-macro scale" is not intended to faithfully simulate the real world, and in fact, even when the real fluid is viewed at the sub-macro scale, it is still a "continuum," and nothing resembling a "particle" is observed. In other words, this approach assumes a "virtual particle having a size of sub-macro scale" and considers the mechanism that controls its behavior, despite knowing that it is obviously different from reality. The determination of whether or not the "sub-macro particle model" is an appropriate "surrogate model" of a "real large molecule group that appears to be a continuum" is made according to whether or not the parameter can be adjusted to match the real behavior when the model is averaged in an appropriate temporal-spatial range.

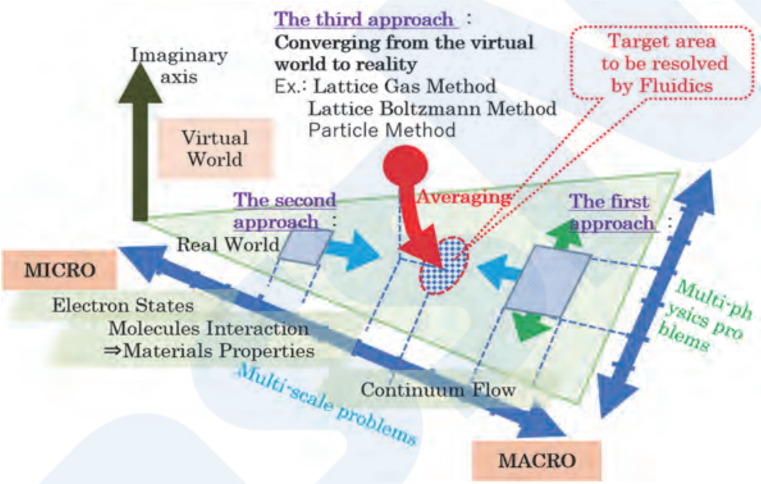


Fig. 2 Approach of "converging from the virtual world to reality" [7)]

It may be noted that there is also a powerful simulation approach called the "particle method" [8)] which can be applied to various multi-physics simulations. The "virtual particle" in the particle method is a substitute for a fluid mass or the like on the macro scale, which is created in the form of a "particle model" with the same scale. While this eliminates the need to perform the averaging (coarse graining) operation, at the stage where humans examine the calculation result in order to understand the real physical behavior, it is thought that they do in fact mentally average the "movements of individual particles" in a certain temporal-spatial range and take a general overview of the collective behavior of the particles. For this reason, the author classifies the particle method in the category of approaches called "convergence from the virtual world to reality," as in the case of the lattice gas method and the lattice Boltzmann method.

4. AIMING AT REALIZING MULTISCALE HIGH-SPEED CALCULATION (Proposal of a Simplified Model Eliminating All Real-Number Representations)

4.1 Operation with One Lattice Point and One Bit Width for Sparse and Dense Lattices

4.1.1 Selecting the "Lattice Gas Method" as the Basic Technique

Although the "lattice gas method," "lattice Boltzmann method" and "particle method" are all used to calculate the behavior of a "virtual particle," each approach has both merits and demerits from the viewpoint of calculation efficiency. This section focuses on the difference in "representation of physical quantities" which is handled when a time evolution calculation is performed. In the particle method, there is no lattice that constrains the position of the virtual particle (meshless). This means the position of a virtual particle can take a free real value. In addition, the velocity of a virtual particle is also represented by a continuously changing real value. In the lattice Boltzmann method, the position of the virtual particle is constrained on a lattice point, and only a certain discretized finite number of values can be taken for its velocity. However, the distribution of the probabilities that virtual particles will take the respective velocities is represented by a real number, and this is used in the time evolution calculation. In the lattice gas method, as in the lattice Boltzmann method, the position of the virtual particle is constrained on a lattice point, and only a certain discretized finite number of values can be taken for its velocity. The difference between these methods is that the lattice gas method causes any of the results that may be produced according to the probability distribution to be produced, without performing a calculation of the probability distribution in the time evolution calculation, so expression by a real value is completely unnecessary.

As one method for drastically increasing the saving of storage capacity and shortening of computation time in a multiscale fluid analysis, eliminating any representation of real values would be very effective, as will be explained in section 4.2 below. Accordingly, the author considers **"a model with no real-number representation that saves storage capacity and accelerates the time evolution calculation"** to be the guiding principle for substantially accelerating the multiscale fluid analysis. Because the "virtual particle model" of the "lattice gas method [9) 10)]" satisfies this condition, it was chosen as the starting point for the discussion.

There is also another approach which drastically increases storage capacity saving and shortening of computation time. That approach is to finely arrange the lattice points in regions where the diameter of the smallest vortex is small, such as the area surrounding the structure, and to coarsely arrange the lattice points in regions which are distant from the structure, where the diameter of the smallest vortex is large. While this approach makes it possible to reduce the total number of lattice points, it has the drawback that the calculation is generally more troublesome in unstructured lattices where the grid-point array is irregular in parts where the sparseness/density of the lattice point arrangement changes. Therefore, an approach of hierarchically arranging lattices that have a regular structure and differ only in sparseness/density is adopted. The "building-cube method (BCM)" is known as a typical approach of this type which is used in ordinary computational fluid dynamics (CFD).

Concerning the lattice gas method, Robert P. Bosch, Jr. had already devised a similar approach in 1993 in a dissertation entitled "A Multigrid Algorithm for Lattice Gases [11)]". In Bosch's lattice point arrangement method, a "heavy virtual particle capable of moving only a coarse grid point network" and a "light virtual particle capable of moving only a fine grid point network" are mutually converted on a lattice point located in a connection region where the coarse grid point network is linked with the fine grid point network. In this conversion, the mass and momentum of the "heavy virtual particle" must be equal to the sum of the masses and momenta of the multiple "light virtual particles" to be converted with it. However, the probability that a "heavy virtual particle" that satisfies this condition and multiple "light virtual particles" will simultaneously arrive at the same position is extremely low. Therefore, a generation and annihilation process for a virtual particle having a negative mass is introduced in the process of conversion between a "heavy virtual particle" and "light virtual particles" to ensure that the local conservation law for mass and momentum is satisfied at all times. The present paper assumes the use of this "multigrid algorithm."

4.1.2 Outline of Lattice Gas Method/Four-Dimensional FCHC Model

This section explains a specific model of the lattice gas method. In lattice gas method fluid analysis, lattice points are regularly arranged in a space where a fluid is present, and many virtual particles, each having a certain mass and momentum, move while repeating ① "collision scattering" on lattice points and ② "translational movement" between lattice points. These states are averaged in order to determine the behavior of macro fluid physical quantities (e.g., density, momentum, velocity) (cf. Fig. 3). As long as a particle collision in which the mass and momentum of the virtual particles are conserved before and after the collision scattering in this process is assumed, the behavior will be quite similar to the fluid behavior under certain conditions in nature. However, unlike fluid molecules in nature, the velocities of virtual particles cannot take continuous values. Therefore, the macro behaviors derived by the lattice gas method will be slightly different from the fluid behavior derived by general computational fluid dynamics (CFD), which assumes a continuum fluid. A calculation method for dissolving this "slight difference" was devised by Christopher M. Teixeira in 1993 [12)], and the lattice gas method has now become a fluid analysis approach which also offers accuracy equivalent to CFD in theoretical terms [13)].

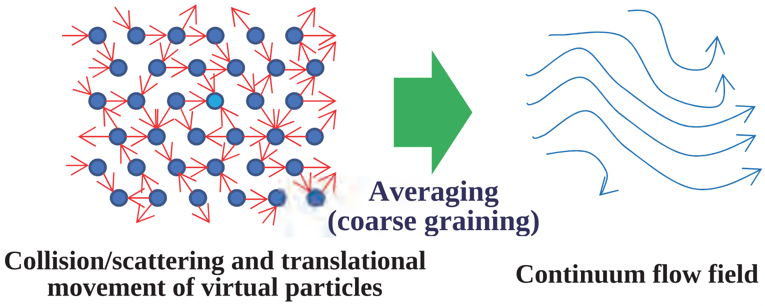


Fig. 3 Simulating of a continuum flow field by averaging the behaviors of virtual particles

Particularly in the case of Teixeira's "lattice gas method/FCHC 54-velocity model" [12], Teixeira's dissertation indicates that if the calculation result is compared with the calculation result by CFD for an incompressible fluid, the former is theoretically consistent with the latter up to the third-order accuracy for Mach numbers. In this model, one lattice point can accommodate "up to 6 stationary particles, a total of 24 slow particles consisting of one particle each in 24 different directions, and a total of 24 fast particles consisting of one particle each in 24 different directions, making a grand total of up to 54 (= 6 + 24 + 24)" virtual particles. Any lattice point arrangement where virtual particles can exist maintains the isotropy of the stress tensor. Therefore, Teixeira adopts a "four-dimensional face-centered hypercubic lattice (FCHC lattice)." The following presents the main points of the model and simulation examples (cf. Figs. 4, 5 and 6).

[Reference] Main Points of Teixeira's Lattice Gas Method/54-Velocity Model

(1) All virtual particles have the same mass (m[kg]).

(2) Each virtual particle moves in synchronization translationally on the lattice points of a "face-centered hypercubic (FCHC) lattice," where ⊿L [m] is the smallest lattice point interval that exists in the four-dimensional space, at a certain time step interval (⊿τ [s]), and has a four-dimensional velocity $\overrightarrow{C_{ji}}$[m/s] (energy: $\varepsilon_{ji} \equiv (1/2)m(\overrightarrow{C_{ji}}\cdot\overrightarrow{C_{ji}})$[J], velocity direction: i) which is necessary to realize that move.

The possible velocities of the virtual particle are as follows:

① Particles with 0 energy: number of particles that can exist d_0 = 6.
$\overrightarrow{C_{ji}}$ = (0,0,0,0) [m/sec] (← stationary particles)

② Particles with energy mc^2 [J]: possible velocities d_1 = 24 velocities
$\overrightarrow{C_{ji}}$ = (±c, ±c, 0, 0), (±c, 0, ±c, 0), (±c, 0, 0, ±c), (0, ±c, ±c, 0), (0, ±c, 0, ±c), (0, 0, ±c, ±c) [m/s]
where, c≡⊿L/⊿τ [m/sec]

③ Particles with energy $2mc^2$ [J]: possible velocities d_2 = 24 velocities
$\overrightarrow{C_{ji}}$ = (±2c, 0, 0, 0), (0, ±2c, 0, 0), (0, 0, ±2c, 0), (0, 0, 0, ±2c), (±c, ±c, ±c, ±c) [m/s]

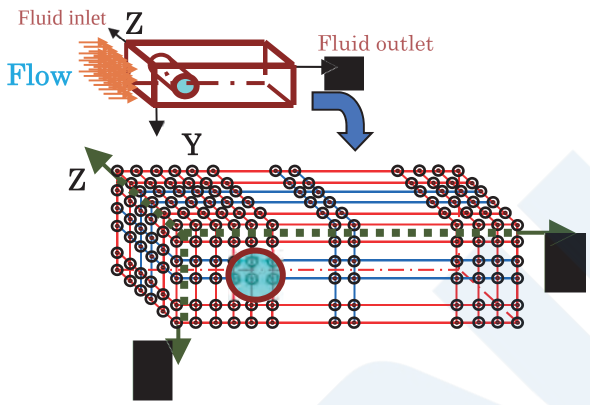
(3) No more than two virtual particles with the same velocity can be present on the same lattice point at the same time.

(4) Interaction (collision scattering) between virtual particles occurs only on a lattice point, and the collision rule under which the sum of the mass, momentum and energy of the virtual particle is conserved is probabilistically applied before and after occurrence of collision scattering.

(5) The probability of transition between the states of existence of the virtual particles that can mutually transition by collision scattering is equal in both directions.

[Example of lattice point composition when lattice gas method/54-velocity model is applied]

A large number of lattice points are arranged in directions X, Y and Z in a three-dimensional space, and a rectangular grid-point array is created. It is assumed that each grid point has the freedom to identify the positions of R = 0, 1, 2, 3 as the four-dimensional coordinates inside it. The figure below illustrates this, and shows the appearance of a four-dimensional face-centered hypercubic lattice projected in a three-dimensional space. In the numerical simulation, for example, the lattice comprises 1024 lattice points arranged in the X direction, 192 lattice points in the Y direction and 384 lattice points in the Z direction as a three-dimensional degenerate lattice.



[Example of conditions setting for transient change simulation]

At time step 0, that is, at the start of the simulated calculation, arrange virtual particles numbering 20% of the maximum number of virtual particles that can be present at each lattice point in a random direction. As a result, the macro flow velocity that can be obtained through coarse graining will be 0, and the fluid is stationary in a cubic shape. Next, at time step 1, start injecting virtual particles having a velocity in the +X direction at the X = 0 position. Then, as time progresses, the entire fluid will have a macro velocity in the +X direction. At that time, at a rectangular outlet that exists beyond the +X side, a boundary condition, under which the virtual particle arrangement on a lattice point immediately anterior to the outlet is copied to the virtual particle arrangement on a lattice point immediately posterior to the outlet, was approximately established, while in the ±Y and ±Z directions, a periodic boundary condition was adopted. An “infinitely long cylinder having a central axis in the Z direction” was placed in a position close to the inlet in this flow, and the fluid behavior occurring in the wake flow was calculated. Snapshot images are selected from the moving images of the transient changes in the momentum distribution coarsely grained on the cross section, and are represented.

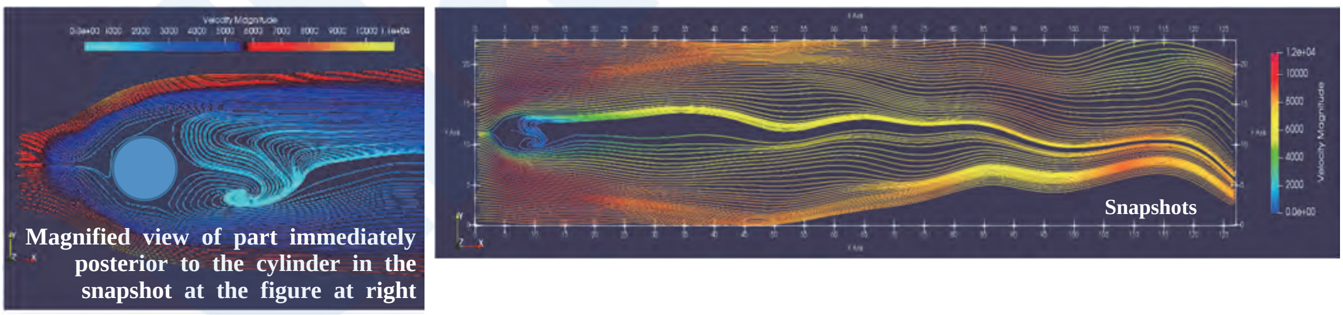
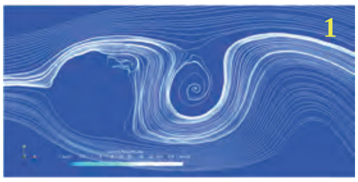
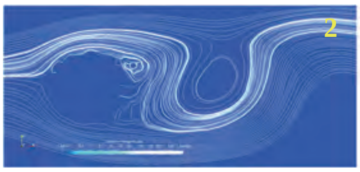


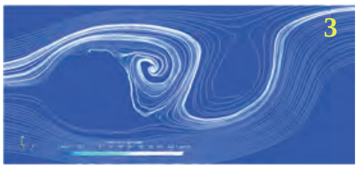
Fig. 4　Simulation of transient changes of the wake flow of a cylinder [14)]



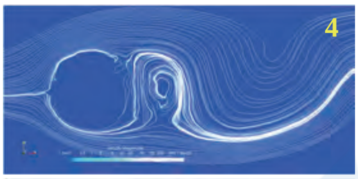
Signs of generation of a vortex on the boundary layer of the cylinder top



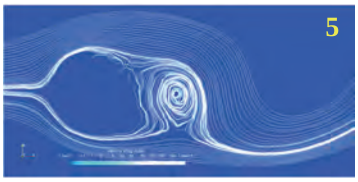
Obvious generation of a vortex at the cylinder top



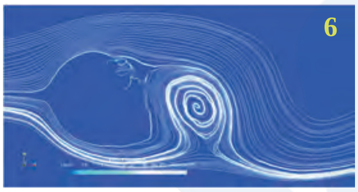
Expansion of the vortex



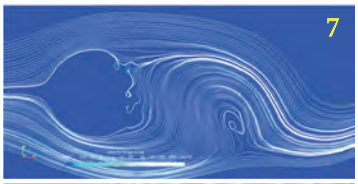
Vortex joins the flow from the cylinder bottom on the opposite side



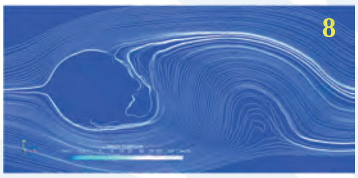
Separation from the cylinder



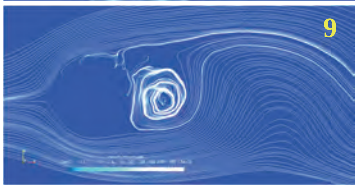
Flows downward as a cylinder bottom flow



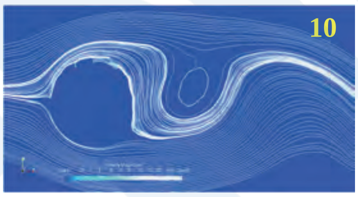
Signs of generation of a vortex on the boundary layer of the cylinder bottom



Expansion of the vortex

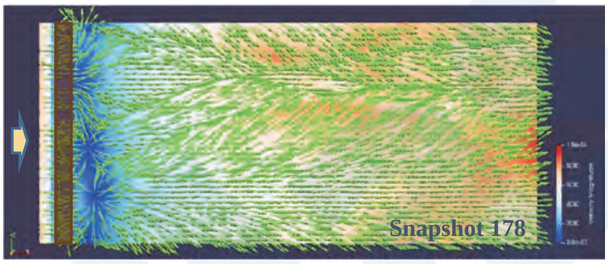


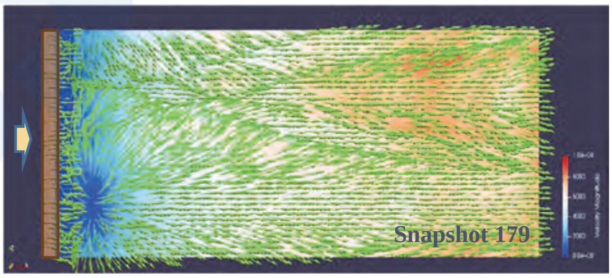
Vortex joins a flow from the cylinder top on the opposite side



Vortex separates from the cylinder and flows down as a cylinder top flow

Fig. 5 Alternating vortex shedding from the cylinder boundary layer [15)]





The above figures concern the flow velocity on a plane formed by the flow direction and the cylinder axis, where the magnitude of the flow velocity is shown by the background color and the direction of the flow velocity is shown by the green arrows. A dead water region is present immediately behind the cylinder (indicated by the brown rectangle) on the left end (right side of the cylinder in the above figure).

If the moving images are observed, when a sufficient time has passed after the flow becomes a Karman vortex, regions of a low-velocity fluid (blue part) and a medium-velocity fluid (light-blue part) appear alternately in the cylinder axial direction and sway quite violently in that direction. Further downstream, the images display a state where a “part in which the downstream flows converge, accelerating the flow velocity” and a “part in which the flows spread, slowing the flow velocity” are arranged alternately in the cylinder axial direction, and temporal wavey undulation, while swinging the flow direction, was observed. This fluid behavior considered to have occurred due to a combination of streams called high-speed streak and low-speed streak, and the effect of a “vertical vortex with a rotational axis in the downstream direction.”

Fig. 6 Vertical vortexes generated in the wake flow of a cylinder [14)]

4.2 Collective Calculation of 16384 Lattice Points with a Vector Core

If all the state quantities representing the state of virtual particles are discretized into a finite number to completely eliminate real-number representations, real number calculation in a time evolution calculation would become unnecessary. If a real computer is to memorize one real number, a 32-, 64- or 128-bit memory is required, depending on the accuracy. Therefore, in order to calculate the temporal change of one real number, it is essential to occupy a 32-, 64- or 128-bit width in the arithmetic circuit. By contrast, if the state quantities of virtual particles are discretized into a finite number for representation, the only requirement would be, for example, to allocate codes such as A, B, C and so on in ascending order to the values of the state quantities, and if the value of the state quantity is B, to memorize a one-bit value of B = 1 instead of memorizing the real value of B itself. If the value of the state quantity is not B, the computer will memorize B = 0. This will realize a substantial saving of storage capacity.

In addition, if two arriving particles having velocities D and E at a lattice point become two starting particles with velocities F and G (D + E ⇒ F + G) due to collision scattering, the two arriving particles with velocity D and velocity E have ceased to exist due to collision scattering, and they no longer have those velocities. Therefore, computation processes D = 1 ⇒ D = 0 and E = 1 ⇒ E = 0 will be performed. Similarly, because two starting particles having velocities F and G are generated through collision scattering, the computation processes F = 0 ⇒ F = 1 and G = 0 ⇒ G=1 will also be performed. In any of these computation processes, the variables D, E, F and G can only take a value 1 or 0. Therefore, in the arithmetic circuit, it is only necessary to always occupy one-bit width. Accordingly, the decision made is to perform calculations of changes D, E, F, G, … at one lattice point constantly corresponding to a certain bit in the arithmetic circuit in sequence. This makes it possible to perform parallel time evolution operations collectively for the same number of lattice points as the number of bits that can be processed collectively using one arithmetic instruction.

The Tohoku University Cyberscience Center vector computer AOBA-A (SX-Aurora TSUBASA, manufactured by NEC), which the author uses, is capable of processing data of 64 bits/word × 256 words/instruction = 16384 bits/instruction per vector processor core by issuing one vector instruction. Therefore, a single vector processor core is capable of performing collective calculations for 16384 lattice points (the capacity of one CPU with 8 cores is 8 times larger).

In addition, as of 2013, it was confirmed that this collective calculation approach can process time evolution calculations for 100 billion lattice points using 64 nodes (512 CPUs, total main storage: approx. 8 TB) of the Earth Simulator (ES2 = SX-9) [16].

In some cases, it is also possible to achieve real-time calculation by using this calculation method. The author was responsible for the startup of operation of the supercomputer “K,” and conducted an analytical evaluation of an air-cooling wind field for supercomputer racks arranged in a computer room with an area of approximately 50 m × 60 m [17]. The conclusion at that time was that a computer with approximately 10 teraflops (approximately one rack of supercomputer K) would be capable of performing real-time simulation of an air-cooling wind field for a large-scale computer if the division of lattice points is approximately 1,024 × 1,024 × 256 ≒ 260 million. There are also cases where real-time simulation is possible simply by the effect of 1 lattice point, 1 bit width operation, provided a certain level of resolution is acceptable.

4.3 Calculating Values for Any Turbulence with No Real Number Calculation

The lattice gas method has an important advantage from the viewpoint of stable calculation of violently changing flows such as turbulence. As described above, all real number representations can be eliminated in time evolution calculations by the lattice gas method, and in this case, no truncation error resulting from floating-point operation will occur. Therefore, arithmetic failure will not occur during the calculation, and it will be possible to stably continue to find some kind of calculation result, regardless of how violent the flow is.

Although turbulent states generally occurs under a large Reynolds number condition, on the other hand, it has been confirmed that this method is capable of expressing not only positive fluid viscosity, but also negative fluid viscosity, as will be described in section 5.3 below. If these mechanisms for expressing viscosity are properly adjusted, it will be possible to simulate even a state with a very large Reynolds number by expressing the positive fluid viscosity of a value extremely close to zero. This method is also considered to be very advantageous for application to turbulence analysis from this viewpoint. For the idea of using “negative viscosity expression” with the lattice gas method for turbulence analysis, please refer to Rothman’s dissertation [18].

4.4 Many-Worlds Probability Bit Operation with a Quantum Computer

The collision scattering calculation in the lattice gas method is a calculation which converts a bit string representing the presence or absence of arriving particles having various velocities to a bit string representing the presence or absence of any starting particle, as described in section 4.2. At this time, the bit string of the starting particle that becomes the output of collision scattering calculation can be generated in any bit string in a physical sense, as long as the sum of the mass and the momentum is conserved before and after the collision scattering. Therefore, multiple starting particle bit strings can generally be output for one arriving particle bit string. In individual calculations, the only requirement is to determine only one starting particle bit string, among the multiple possibilities, according to a certain probability. Such an arithmetic characteristic is simply the arithmetic property of a "gate-based quantum computer," which uses quantum bits (qubits) [19]. In other words, in the world where quantum mechanics is applied, state change progresses concurrently in many-worlds, and a result of change in any one of the worlds is produced probabilistically at the instant it is observed.

Currently, research and development of quantum computers toward practical use is being pursued at major companies, universities, etc. around the world, and their open use has also begun. Although the author considers use of the "gate-based quantum computer" to be promising, the number of qubits that can be interconnected is still small due to the "quantum entanglement phenomenon." However, IBM's Q System [19], which became famous in 2019, when Google demonstrated that a quantum computer could solve a problem in only 200 seconds, which would require 10000 years with the fastest supercomputer, also showed this performance even at 53 qubits. Moreover, the quantum computer also has good compatibility with qubit computation, which is specific to the lattice gas method; for example, "direct transition of the bit operation of the lattice gas method to qubit computation is easy (cf. Fig. 7)" and "the lattice gas method, which finds a physical quantity through a statistically average calculation, can ensure reliability within its own limitations, even though the error rate of the quantum computer is not zero." Thus, the quantum computer is expected to have great potential for use in achieving low-power-consumption, massively parallel computing in the future.

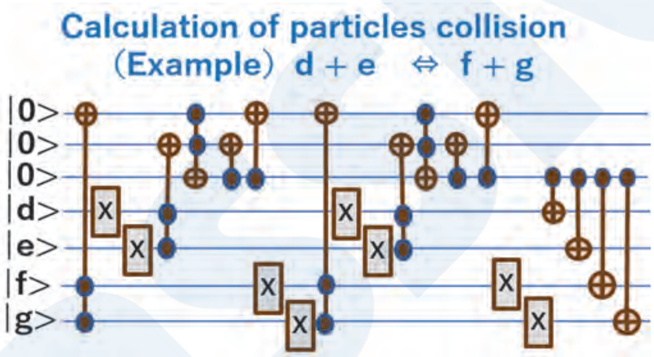


Fig. 7 Image of computation with gate-based quantum computer

[Panoramic perspective] Focus on Brain-Inspired Computing

Among the three cases described in section 2.1, the "ocean energy harvesting vessel" represents the most dynamic movement of the system itself under the influence of the natural environment. Even in such a situation, a human (for example, a master yachtsman) would manage to handle the ship properly in real time. Therefore, the author decided to search for hints in "brain-inspired computing," like that which the human brain performs.

A third artificial intelligence (AI) boom has now arrived. Although the impetus for this boom was the success of deep learning, various studies of AI from diverse angles were conducted long before this boom, but we are still far from elucidating the essential mechanism of expression of the brain functions.

In the meantime, systems which are capable of expressing a property similar to the mechanism of expression of functions in an actual brain have been developed, even though the mechanisms are different, and some of those technologies have developed in scale to engineering applications and have been adopted widely in society. The following focuses on "fuzzy inference" and "multi-layer perceptron learning" as representative examples of those technologies.

5. AIMING AT REALIZING MULTI-PHYSICS COUPLING (Proposal of Simplified Model for Intuiting Physical Behavior)

5.1 Same Calculations for Physics with Different Virtual Particle Pictures

The essence of fuzzy inference is not the fuzzy inference rule itself, but the rough "image model" that an expert in the field draws in their head when deriving that rule. This "image model" is not the real, complex system which is subject of discussion. It is a simple image model that is visual in many cases. However, an expert in the field would be able to derive the actual system behavior intuitively and semi-quantitatively by imagining the behavior of this image model. In other words, the model becomes a "surrogate model" that plays the role of "surrogation," for example for a differential equation that drives time evolution calculation. Therefore, the author considered that **"being a simple image model which makes it possible to infer semi-quantitatively the causality of physical behavior"** should be the primary condition for an AI surrogate model.

In this paper, a "virtual particle picture" is adopted as a specific example of a "simple image model." An image model for "collision scattering" and "translational movement" of a virtual particle that is based on the lattice gas method is itself a general-purpose "virtual particle picture," and is adaptable to various physical phenomena. For example, assume the application of a collision scattering rule which requires that any lattice point group in a certain region should be inverted regardless of the direction of an arriving particle, so that the particle returns in the direction from which it came. Under this assumption, any virtual particle in that region is static on a time average basis in macro terms, and thus can be interpreted as representing a fixed solid region. This is the simplest example showing that the model can simulate both fluid and solid behaviors using the same calculation.

5.2 Achieving Zero Delay Resulting from Coupling by Conducting Solid-Fluid Coupling Analysis

Now, let us consider moving the position of a lattice point, which is subject the collision scattering rule for expressing the characteristics of the solid described above, according to the "magnitude and the direction of an 'impulse' applied to that point by a virtual particle arriving from the surrounding area in the course of collision scattering." If this is adjusted skillfully, it should be possible to simulate even the deformation of an elastic body. In this way, multi-physics physical phenomena are interpreted by a unified "single physics" of interaction between particles, and the time evolution calculation is performed using the same calculation regardless of whether the substance is a fluid or solid. This should ensure that no essential delay will occur in comparison with the calculation time in cases where the entire substance is a fluid.

Currently, the most successful approach for this kind of "virtual particle picture" seems to be the "particle method" [8)]. The approach used in the particle method is to find a solution to how individual fluid masses move according to the lapse of time by solving a motion equation for each fluid mass. Therefore, this method is also capable of simulating "major deformation of a fluid" and "fragmentation of a fluid due to collision." In other words, since the method models substances as an aggregate of small masses, free handling of major changes in the motion or shape of a substances is possible. For this reason, the particle method is extensively applied not only in fluid analysis, but also in structural analysis and solid analysis.

The essential reason why a fluid mass (virtual particle) can move freely in the "lattice method" is because it is a "meshless solver" with no lattice to constrain the positions where virtual particles can exist. By contrast, in the "lattice gas method," the positions where virtual particles can exist are limited to regularly-arranged lattice points. However, this does not mean that the movements of virtual particles are limited in the direction of the lattice axis. For example, in the case of "Teixeira's 54-velocity FCHC model," virtual particles can protrude from each lattice point in 48 different directions, which allows quite large freedom of movement. Thus, if there are successful cases of multi-physics simulation by the "particle method," it thought that the benefits of this method were achieved by direct application of that innovation.

5.3 Controlling Viscosity by the Probability of Entrainment in a Starting Particle Group

A virtual particle in fact represents an extremely large number of real molecules. An "arriving particle" and "starting particle" before and after collision scattering is in fact particle groups consisting of many real molecules acting as a group. In the case of a liquid, the density is not greatly different from that of a solid, and even gases will behave as an incompressible fluid if the Mach number is sufficiently small. In other words, real molecules move while clustering very closely together, and would also move to fill any vacant space that might be created. Expanding this image, it is possible to establish a "fuzzy inference" to the effect that "If there is a virtual particle that starts to move in a certain direction in the previous collision scattering, it will be drawn into the previous starting particle group, and the number of real molecules that are forcibly entrained in that direction will increase, even if virtual particle(s) attempt to fly out in another direction in this collision scattering.” This means that the probability that the starting particle in this collision scattering is synchronized with the direction of the starting particle in the previous collision scattering will increase. Based on many case studies, the author has confirmed that fluid viscosity can be controlled over a wide range by changing this “synchronous entrainment probability” [20] (cf. Fig. 8). In this type of control, care must be taken to ensure that conservation of momentum is maintained on a time average, and it is possible to express negative viscosity (including spontaneous generation of a vortex from a stationary fluid).

In fluidics for manufacturing, if Reynolds numbers ranging from a Reynolds number on the experimental and prototyping scale to a Reynolds number on the real machine scale can be continuously simulated, the reliability of prediction will increase, making it possible to perform engineering design with higher confidence. In this sense, the ability to provide a wide range of fluid viscosities by a simple method is an enormous advantage.

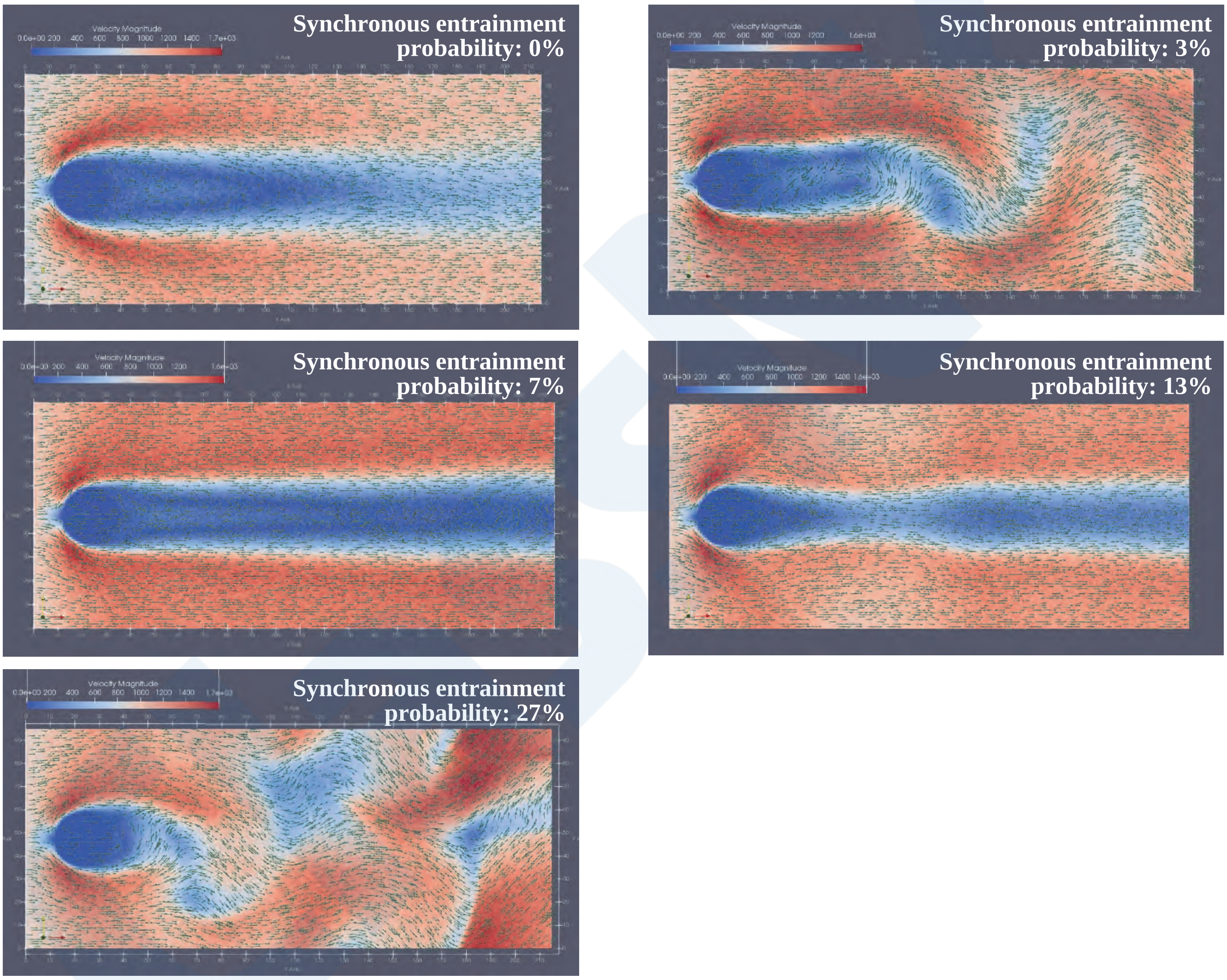


Fig. 8 Viscosity control by changing the probability of synchronous entrainment operation [20]

5.4 Predicting Crack Propagation by Results of the Particle Method

Among the applications of the particle method, simulations are also conducted in dynamic elasticity analysis and crack propagation analysis [8]. Since the small masses that constitute the substance of interest are separated, it is possible to simulate the growth of cracks. In examples of the particle method, it is considered that a particle of a substance will fracture when the von Mises stress (or strain) of the particle reaches the fracture stress (or fracture strain) due to stress concentration. Since stress distribution is no longer possible under this condition, the fractured particle will become the particles that form the crack face. Here, it is sufficient to employ ingenuity to realize a calculation method using the virtual particles of the lattice gas method. In real structures such as windmills, problems caused by the generation of cracks are a frequent occurrence. As this suggests, an analysis which also includes prediction of crack propagation in a fluid-solid coupling analysis would have major practical advantages.

6. AIMING AT REALIZING AN IMMEDIATE RESPONSE TO THE REAL WORLD (Proposal of Simplified Model with Learning Computation)

6.1 No-Delay Learning with a Recurrent Neural Network

The “multi-layer perceptron (hierarchical neural network)” is the type of artificial neural network whose use in society has advanced most. This category also includes neural networks that are capable of performing “deep learning.” The learning function of the multi-layer perceptron is the “error back-propagation method,” which triggered of the second AI boom, and its general theory and engineering applications were already established at that time.

With the lattice gas method, a macro physical property value can be obtained from the sum or statistical average of the masses and momenta possessed by virtual particles in its vicinity. Since the computation of this sum or average can also be represented by the computational structure of a multi-layer perceptron, the hierarchical structure of the neural network that computes the time evolution also contains a “multi-layer perceptron that outputs a macro physical property value.”

If a computed output value which is consistent with the measurement data is desired, the neural network traces back to the cause of the difference between the computed output value and the measurement target value, and corrects the weights of neurons located on that trace-back path according to the procedures of the above-mentioned “error back-propagation method.” By repeating this process, the computed output value can be made to approach the measurement target value, which is the teacher datum. In other words, if a computational structure for recurring the data from the second stage of the multi-layer perceptron to the first stage (recurrent neural network: RNN) is built, a means of “data assimilation” can be acquired automatically. For this reason, the author thinks that **“being a model that can be replaced with the computational structure of a recurrent neural network having a learning function”** is the second condition for an AI surrogate model.

Here, a new weight derived from the difference between the computed output value and the measurement target value at time “t” is reflected in the computation after time “t +⊿t.” It should be noted that the network does not perform the computation by tracing back to the past. Therefore, in this method it is important that “feeding back measurement data to the simulation will not delay the original time evolution computation.”

6.2 Data Assimilation without Stopping Time Evolution Computation

If the method described in the preceding section is applied to a multi-layer perceptron that performs computations in the lattice gas method, data assimilation can be achieved without stopping the time evolution computation. The following shows that in this case all computations of the multi-layer perceptron structure can be performed within a range of very small integers without using real numbers.

First, the lattice points are arranged regularly in a physical space, and each lattice point is considered to contain a multi-layer perceptron (cf. Figs. 9 and 10). In the lattice gas method 54-velocity model, 6 particles are stationary particles and therefore cannot move. This means there can be “arriving particles” from a maximum of 48 (= 54 - 6) lattice points located in the vicinity. Information on their presence or absence at that time, for example, “1” if an arriving particle is present, “-1” if absent and “0” if unknown, is input in the input layer of the “multi-layer perceptron,” and a value (1, -1) calculated by a “sum-of-product threshold computation” of the neural network appears in the output layer. If this information is “1,” a starting particle from the respective lattice point is present, and if it is “-1,” a starting particle is not present.

The macro physical quantity to be observed at a certain location in space is calculated from the total sum of the masses, momenta and energies of the virtual particles in an appropriate vicinity around that location. Therefore, even with a neural network that performs this computation, only very small integers will appear.

Furthermore, if the lattice points where virtual particles can travel are all interconnected, the “entire flow field” can also be represented by the neural network, and a time evolution computation can be performed. In other words, any change in the “flow field” can be considered as the group behavior of the “virtual particles” travelling between a “space lattice containing a neural network (multi-layer perceptron)” and its lattice point (neuron) (cf. Fig. 11).

As described in the preceding section, if measurement data are obtained at several spatial positions in the real world, the “multi-layer perceptron” contained in neighboring lattice points of the respective positions will execute error back-propagation to make the computed output value consistent with the measurement data. At that time, it is assumed that the value of the “weight” by which the input data of the multi-layer perceptron is to be multiplied also can take only a value of “1, 0 or -1.” Learning is performed to adjust the probability of adoption of those weights. In short, rough adjustment is made by selecting an individual weight from "1, 0 or -1," and fine adjustment is achieved through adjustment of the probability of adoption of those weights. If this weight adjustment process is continued, the simulated data can be expected to become consistent with the measurement data to some extent, although this will also depend on the condition of change in the measurement data.

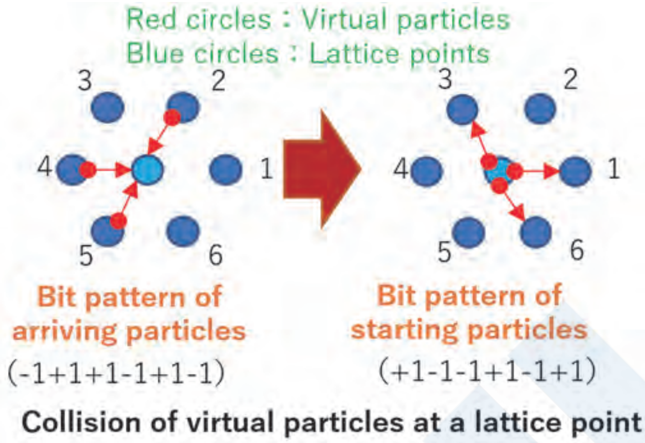


Fig. 9 Change in information on presence or absence due to collision scattering [20]
(in case of a two-dimensional lattice gas method FHP model)

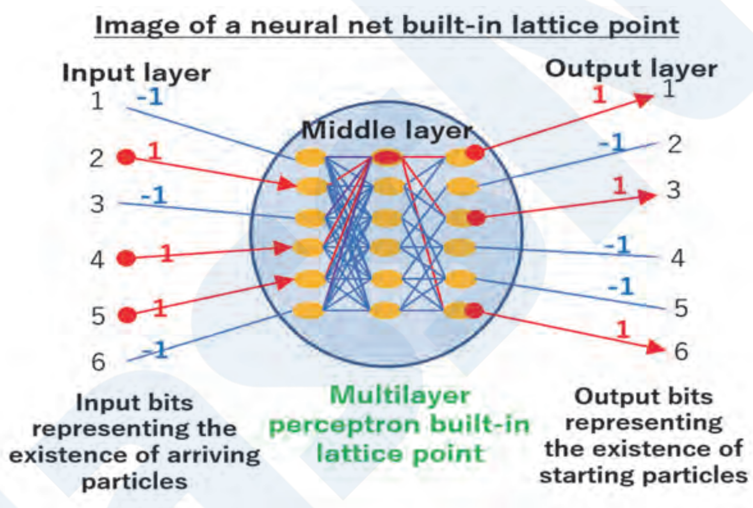


Fig. 10 Multi-layer perceptron for calculation of collision scattering [20]

In Fig. 10, the input layer conveys an input value ±1 as-is to the intermediate layer, and the intermediate layer identifies the input bit string. For example, if a weight of +1 is set for the red line input and a weight of -1 is set for the purple line input on the top red neuron of the intermediate layer, a weight string consisting of purple (-1) → red (+1) → purple (-1) → red (+1) → red (+1) → purple (-1) is formed in that order from the top. At this time, the sum of products is the maximum value (6) only when the input bit string to the input layer coincides with this weight layer. The intermediate layer identifies this by converting the activating function of the intermediate layer neuron to a step function with a threshold of 6. The output of this neuron is connected only to neurons 1, 3 and 6, which are the neurons that should be activated in the output layer. In the neurons in the output layer, the input weights of the connected synapses are all set to +1, and the activating function is converted to a step function with a threshold of -1. As a result of this, if any one of the inputs becomes +1, the neuron will be activated (output = +1). In actual application, these layers must be stacked in multiple stages. Further, if the collision rule is to be probabilistically applied, the number of neurons in the input layer is increased and an input of ±1 is given randomly.

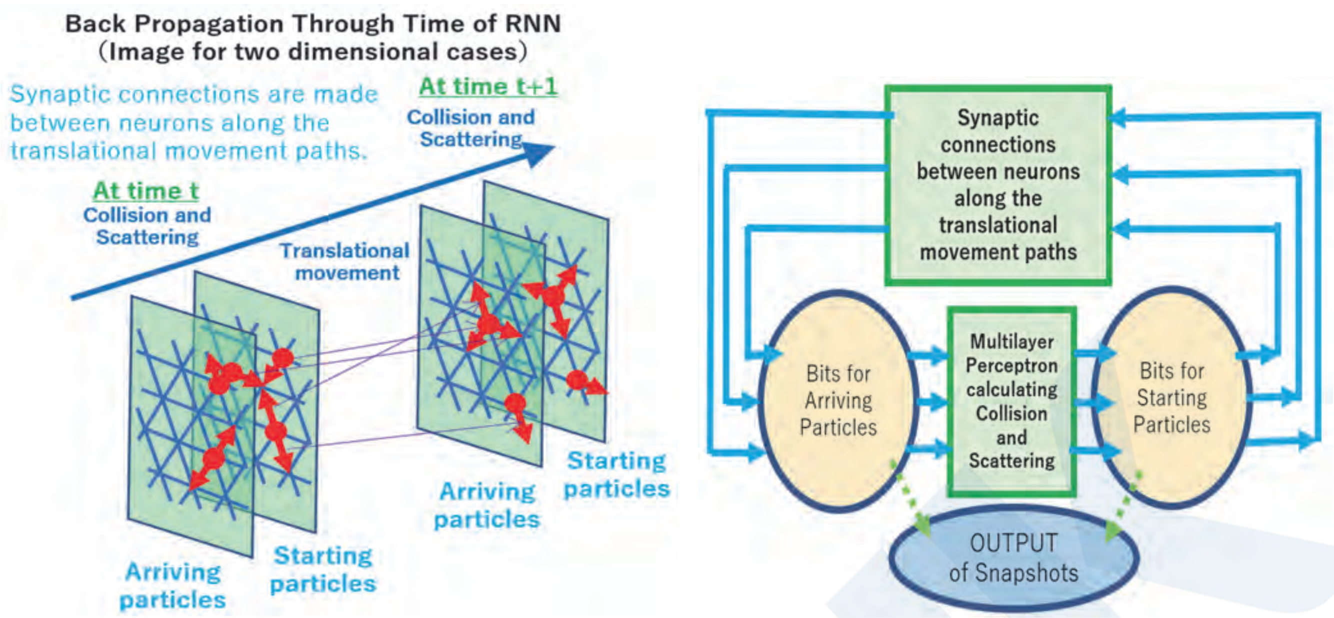


Fig. 11　Example of a neural network across an entire flow field [20)]

6.3　Robust Learning of Even Incomplete Real-World Measurement Data

Actual measurement information which is to be acquired from the real world normally cannot be acquired completely at all boundaries due to factors such as restrictions related to measurement system installation or the occurrence of failures, and thus may contain erroneous data.

The operation of a neural network generally involves repetition of weighted addition of a large number of input values and operation of their thresholds. Therefore, even if a datum that should serve as one input value of one neuron is lost or erroneous information is input, there is a high possibility that its impact will be eliminated in the course of the computational process. Since this type of robustness in a computational process is expected to have a certain effect in cases where the incompleteness of the actual measurement information occurs as temporal-spatial dispersion, this approach is suitable for real-world data processing.

[Panoramic Perspective] Departing from the Differential Equation Solution

The most important point when considering fluidics analysis in the real world is that “it is impossible to predict any future change in the boundary conditions in advance.” Since boundary conditions are subject to the effects of changes in the conditions outside the boundary (i.e., in the outside world), it goes without saying that such changes cannot be predicted in advance unless all environments, including the outside world, are simulated accurately. For this reason, regardless of how accurately the initial conditions conform to reality when a computation is started, it is impossible to continue forever to predict the future state in the real world with high accuracy without feeding back information about the outside world. With this as a major premise, if correspondence with the real world is a priority, the natural idea would be to depart from the conventional approach of “solving a differential equation as accurately as possible,” and substitute a time evolution computation by an AI-based approach, namely, “(having the system) simulate the functions of the human brain and perform prompt feedback correction based on rough, fast inferences and measurement information about the outside world.”

6.4 High-Speed Computation between Distributions of Dimensionally-Compressed State Quantities

When AI is mentioned, the first key phrase that comes to mind today is “deep learning.” Therefore, let us first consider the concept of the “AI surrogate model,” which applies “deep learning” based on ordinary computation fluid dynamics (CFD), and not the lattice gas method (cf. Fig. 12).

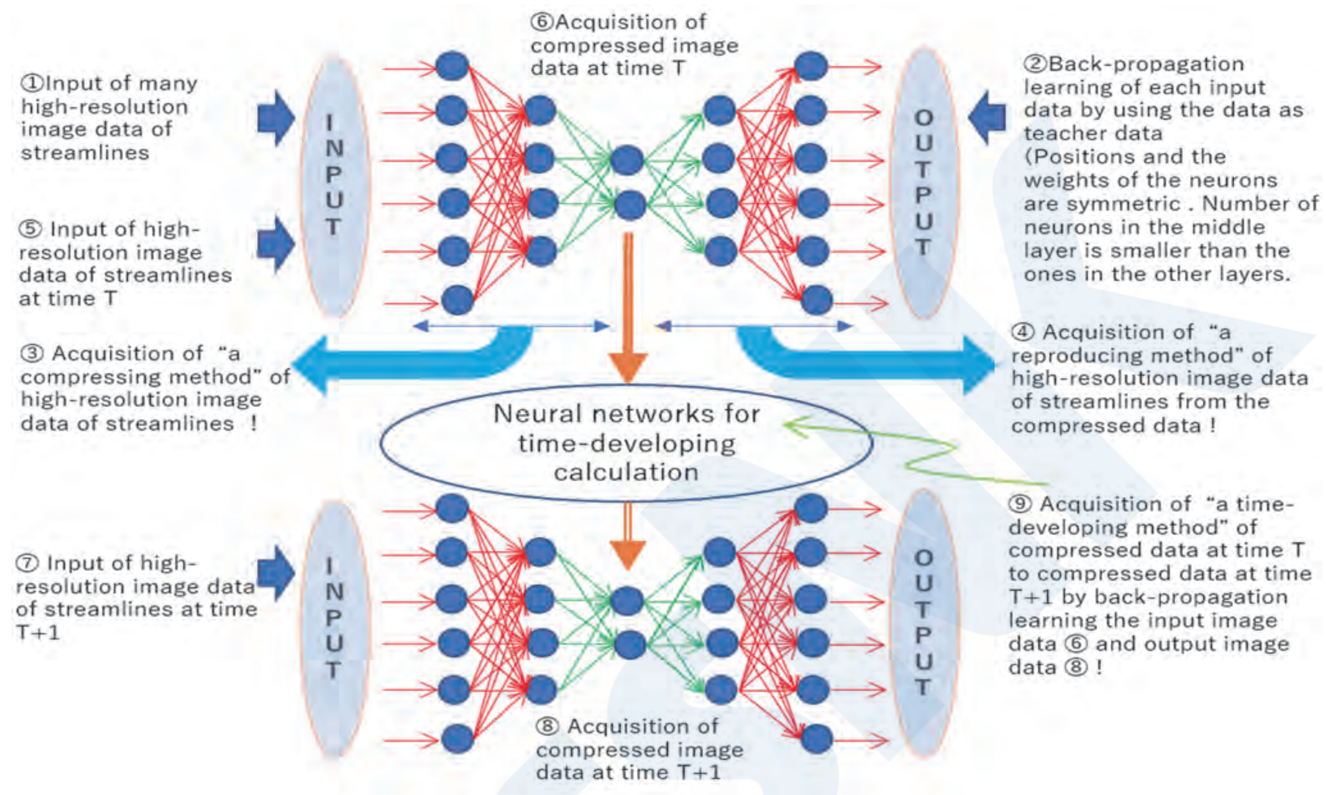


Fig. 12 Information-compressed type time evolution computation

To overcome the challenges of multiscale analysis, the first step is to perform a high-resolution time evolution computation based on the Navier-Stokes equation (NS equation), while utilizing the capability performance of a supercomputer to perform computations on an extremely large scale. This makes it possible to acquire very many sets of “detailed flow velocity space distributions at time t” and “detailed flow velocity space distributions at time t+⊿t”, even in a single computation. The next step is to dimensionally compress the flow velocity space distribution at each time acquired by this computation (huge three-dimensional array of three numeric values representing the respective components of the velocity vector) through deep learning, while utilizing the capability performance of the supercomputer to perform a very large number of parallel computations, provided they are of medium scale. By utilizing dimensional compression, the required storage capacity can be substantially reduced.

However, because the numerical value array obtained by dimensional compression is an array that is mechanically learned through computation by the neural network, a person seeing the numerical value distribution cannot understand its physical meaning by human intuition. The final step is to have the neural network learn a set of spatial distributions of flow velocities at the dimensionally-compressed times “t” and “t+⊿t.” Although the number of input/output datasets is huge, since they are dimensionally compressed, the scale of computation required to learn each dataset does not exceed the medium level.

As a result of the above, the time evolution computation method for the dimensionally-compressed spatial distribution of flow velocities was learned as a computation method of a neural network. This is one of the concepts of the “AI surrogate model,” which substitutes for the time evolution computation using the NS equation.

Incidentally, if a time evolution computation is performed using this “AI surrogate model,” the data obtained directly at the respective times will still be meaningless, dimensionally-compressed data. However, when we want to know the snapshots in the course of the time evolution computation, a physical, a meaningful spatial distribution of flow velocities can be restored at the original high-resolution level at any time by reverse computation of the dimensional compression.

The "information-compressed time evolution computation" described above can also be applied as-is to data obtained by the lattice gas method. This can be considered as a problem of recognition of multi-dimensional images in which one pixel is represented by 54-bit information and information compression. The computation method for time evolution between such information-compressed images leads to the possibility of executing a higher resolution analysis of fluid behavior at a higher speed. Even if the intuitive meaning of the computation method cannot be understood directly at that time, there would be no particular difficulties in the stage of real-time control, unlike the design stage, where trial-and-error study is required.

The need for immediate response to the real world arises during system operation. In this case, a compact independent computer that can be incorporated in the system at the site and can acquire measurement data or an IoT edge computer that can be connected to the Internet, without relying on a supercomputer or the like, would be a more ideal solution. Future AI research might discover an innovative algorithm that will surpass deep learning and have a large impact from both the engineering and social viewpoints. Moreover, a processor capable of executing AI algorithms at high speed might also be developed. In any case, I look forward to seeing the replacement of fluid computations with the computational structure of the neural network, as the results of the future AI research would be immediately applicable.

7. CONCLUSION

The usual approach to numerical simulations in fluidics analysis for manufacturing is to first set the differential equation that governs the physical phenomenon and then compute its time evolution. While this is the most reasonable and reliable approach, a simulation with much higher performance continues to be desired for application in the real world. To realize this dramatic improvement in performance, this paper has examined an "AI surrogate model" that would substitute for the differential equation by departing from the time-honored royal road of "differential equation solution," and has introduced this as one possibility. Since a prosaic style of description was adopted in this paper, the gist of the argument may not be explained clearly in some parts. Finally, therefore, the outline of the paper is summarized as follows.

"AI Surrogate Model" for Manufacturing by Fluidics

(1) EXPANSION OF WIND ENERGY UTILIZATION ANALYSIS IN THE FUTURE
【Present Status】 High-resolution prediction is needed in fluidics for wind energy

(2) SETTING A DREAM TARGET AND ATTEMPTING BACK-CASTING THINKING
【Ambitious Target】 Ideal resolution is a width of 5 to 6 digits per dimension

(3) AIMING AT REALIZING MULTISCALE HIGH-SPEED CALCULATION
(Proposal of a Simplified Model Eliminating All Real-Number Representations)
【Challenging Action】 Operation with One Lattice Point and One Bit Width for Sparse and Dense Lattices

【Direct Results】 Collective calculation of 16384 lattice points with a Vector Core
【Additional Results】 Calculating Values for Any Turbulence with No Real Number Calculation
【Future Expected Results】 Many-Worlds Probability Bit Operation with a Quantum Computer

(4) AIMING AT REALIZING MULT-PHYSICS COUPLING
(Proposal of Simplified Model for Intuiting Physical Behavior)
【Challenging Action】 Same Calculations for Physics with Different Virtual Particle Pictures

【Direct Results】 Achieving Zero Delay Resulting from Coupling by Conducting Solid-Fluid Coupling Analysis
【Additional Results】 Controlling Viscosity by the Probability of Entrainment in a Starting Particle Group
【Future Expected Results】 Predicting Crack Propagation by Utilizing the Achievement of Particle Method

(5) AIMING AT REALIZING IMMEDIATE RESPONSE TO THE REAL WORLD
(Proposal of Simplified Model with Learning Computation)
【Challenging Action】 No-Delay Learning with a Recurrent Neural Network

【Direct Results】 Data Assimilation without Stopping Time Evolution Computation
【Additional Results】 Robust Learning of Even Incomplete Real-World Measurement Data
【Future Expected Results】 High-Speed Computation between Distributions of Dimensionally-Compressed State Quantities

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* This paper is not a paper for presentation at any academic conference, but rather is an exposition. Therefore, the references listed here are explanatory references selected on a preferential basis, rather than original papers.

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Part C "Guidelines for the Safety of Ships Using Ammonia as Fuel" of Guidelines for Ships Using Alternative Fuels

Plan Approval and Technical Solution Division, Technical Solution Department, ClassNK

1. INTRODUCTION

In the international shipping field, regulations for the prevention of air pollution and global warming have been strengthened in recent years, and the use of global environment-friendly alternative fuels instead of petroleum fuels has been actively studied, considering their potential as next-generation marine fuels. As a response to SOx and NOx regulations, introduction of ships using LNG, LPG, methanol/ethanol, and other alternative fuels is progressing. Use of these fuels in place of fuel oil makes it possible to reduce carbon dioxide (CO_2) emissions from ships by 10% to 20%, and ammonia and hydrogen fuels, which do not contain carbon, are expected to be used to achieve zero GHG emissions. Ships that carry ammonia as cargo are equipped with storage and process systems which make it possible to transport ammonia in an appropriate state, and some refrigerated cargo carriers are equipped with systems that use ammonia as a refrigerant. Thus, although ammonia is not yet used as a fuel, ammonia is already handled in the shipping field. Since ammonia also has a higher energy density and is more easily liquefied than hydrogen, it has attracted considerable attention as a decarbonization fuel for ships. Ships using ammonia as a fuel are being developed in various countries and are expected to be commissioned around 2024. To promote widespread use of ammonia as a fuel in ships including oceangoing vessels in the future, development projects for ammonia bunkering vessels are underway at major ports, including Singapore among others. While preparations for the future use of ammonia fuel in ships engaged in international voyages are progressing steadily, international regulations for the use of ammonia as a fuel have not yet been established. In particular, adequate safety measures are required, as ammonia is highly toxic, and contact with the human body, even in trace amounts, can cause serious health damage. To contribute to the development of ammonia-fueled ships, ClassNK (hereinafter, "the Society") specified the requirements for ensuring the safety of ships using ammonia fuel in Part C of its "Guidelines for Ships Using Alternative Fuels."

This report presents an outline of the safety requirements for ammonia-fueled ships in the Guidelines.

2. CURRENT STATE OF DEVELOPMENT OF AMMONIA-FUELED SHIPS

2.1 Background of Development of Ammonia-Fueled Ships

The relevant regulations of MARPOL Annex VI which provide for reduction of CO_2 emissions from ships have been in effect since January 1, 2013, and regulations utilizing the Energy Efficiency Design Index (EEDI) for new ships, requiring retention of a Ship Energy Efficiency Management Plan (SEEMP) on board ships and requiring use of the Data Collection System (DCS) for fuel oil consumption of ships have been introduced.

In April 2018, a GHG reduction strategy was adopted by the IMO at MEPC72, requiring a 40% improvement in transport efficiency across the entire international shipping industry by 2030 compared to 2008 as a short-term measure for reduction of GHG emissions. Toward achievement of this short-term target, amendments to MARPOL Annex VI and the relevant guidelines for introduction of the Energy Efficiency Existing Ship Index (EEXI) regulations and Carbon Intensity Indicator (CII) rating system were adopted, and the relevant guidelines for implementation of the CII rating system are being prepared. The IMO GHG reduction strategy sets a mid-term target of improving the transport efficiency by at least 70% and reducing GHG emissions by 50% by 2050 compared to 2008, and a long-term target of achieving zero GHG emissions by the end of this century. As mid- and long-term measures for achievement of these targets, a scheme that would impose charges on the use of fuel oil, an emissions trading system, etc. are also under study.

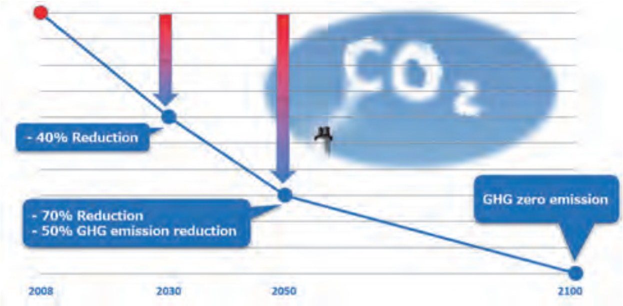

Fig. 1　CO_2 emissions reduction per transport volume of ships in international shipping

The Paris Agreement adopted in 2015 aimed at holding the increase in the global average temperature to below 2 °C above pre-industrial levels, and also included efforts to limit the temperature increase to 1.5 °C. The Inter-Governmental Panel on Climate Change (IPCC) reported that it will be necessary to reduce GHG emissions to net zero by 2050 in order to limit the temperature increase to 1.5 °C, and it has been agreed that the IMO GHG reduction strategy should be reviewed to enhance the targets for reduction of GHG emissions from international shipping specified in the IMO GHG reduction strategy.

With the above background, the use of ammonia as a fuel which does not emit CO_2 when burned is receiving attention as a technology that can realize a substantial reduction of GHG emissions. On land, ammonia is generally used in fertilizers and feedstocks for industrial products. This means that it will be possible to utilize existing technologies in each stage of the supply chain of production, transportation and storage. Ammonia is classified in terms of the production process and the degree of CO_2 reduction as “green” ammonia (ammonia produced from renewable energy), “blue” ammonia (ammonia produced from natural gas and coal materials, with the CO_2 generated in the production process recovered by carbon recycling or CCS) or “gray” ammonia (ammonia produced from natural gas and coal without CO_2 recovery). The current mainstream is gray ammonia, which is available at a cheap price, but emits CO_2 in the production process. Therefore, production of green ammonia and blue ammonia are also expected.

As outlined above, the use of ammonia as a fuel can substantially reduce CO_2 emissions from ships, and in addition, the supply chain for ammonia has already been established throughout the world. In view of these advantages, ammonia is a leading option as an alternative fuel, and the development of ammonia-fueled ships is being actively studied.

2.2　Status of Development of Ammonia-Fueled Ships

As one initiative in connection with ammonia-fueled ships at the world level, multiple ship classification societies issue Approval in Principle (AiP) certification for ammonia-fueled bulk carriers and container ships developed by shipyards, engine manufacturers, etc.

Development of engines is essential for constructing ammonia-fueled ships. MAN Energy Solutions has announced plans for their first delivery of a two-stroke engine in 2024. As an actual ammonia-fueled ship construction project, the development of an ammonia-fueled tanker equipped with Wärtilä Corporation's four-stroke engine, which is to be commissioned in 2024, has also been announced.

Actual construction projects are also underway in Japan, where the development of various ships using ammonia fuel has been announced. These include an ammonia-fueled tugboat equipped with a four-stroke engine developed by IHI Power Systems Co., Ltd., which will be commissioned in 2024, an ammonia-fueled ammonia transport ship with a two-stroke engine developed by Japan Engine Corporation to be commissioned in 2026 and an ammonia-fueled bulk carrier equipped with a two-stroke engine developed by the above-mentioned MAN Energy Solutions.

Fig. 2　Ammonia-fueled ammonia transport ship

2.3　Ammonia Fuel Supply System

The fuel supply systems adopted by ammonia-fueled ships are broadly divided into the following two types.

(1)　System for supply of fuel to a high-pressure two-stroke engine (See Fig. 3): Supplies the required amount of fuel to the engine while circulating liquefied ammonia at the designated temperature and pressure.

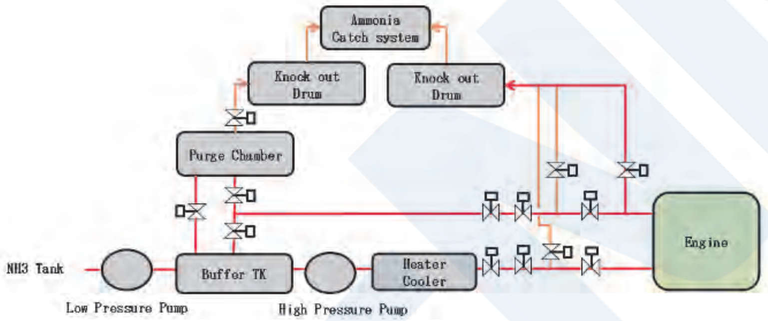

Fig. 3　Fuel supply system for two-stroke engine

(2)　System for supply of fuel to a low-pressure four-stroke engine (See Fig. 4): Gasifies liquefied ammonia and supplies the gasified ammonia to the engine at the designated temperature and pressure.

Fig. 4　Fuel supply system for four-stroke engine

2.4　Types and Characteristics of Gas-Fired Engines

Two types of ammonia-fueled engines are currently under study, as follows:

(1)　Low-pressure four-stroke dual-fuel engine

Low-pressure four-stroke dual-fuel engines use a premixing lean burn system in which a gas fuel is mixed with the air supplied to the engine, and after this lean mixture is compressed, the mixture is ignited by pilot oil. This system has the advantage of a relatively low supply gas pressure because the gas is premixed with the supply air. As disadvantages, a trace amount of unburned gas called "ammonia slip" is emitted, and knocking resulting from abnormal combustion may occur. Control measures to reduce these undesirable effects are required (See Fig. 5).

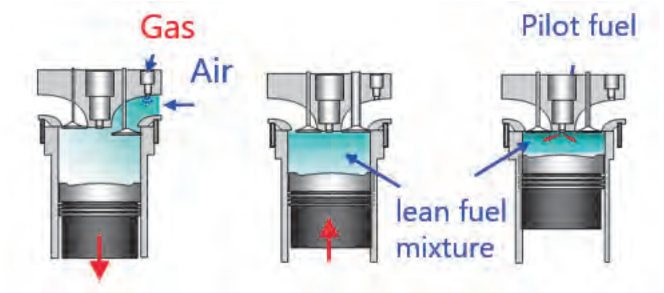

Fig. 5　Combustion system of four-stroke dual-fuel engine

(2)　High-pressure two-stroke dual-fuel engine

High-pressure two-stroke dual-fuel engines use a diffusion combustion system of the type used in oil-fired diesel engines. In this system, after the scavenging process is completed, the ammonia fuel is injected directly into the compressed air and ignited by pilot oil. This system does not cause ammonia slip or knocking and has the advantage of relatively stable combustion. However, as high-pressure ammonia at about 8 bar in a liquid state is supplied to the engine, safety in handling high-pressure gas on board must be considered (See Fig. 6).

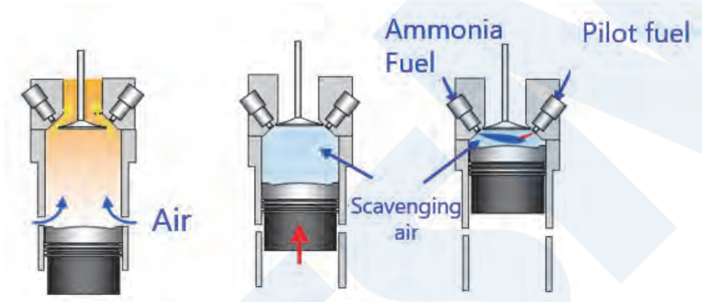

Fig. 6　Combustion system of two-stroke dual-fuel engine

2.5　Ammonia Fuel Tanks

As cargo tanks of ammonia carrier ships, independent tanks as specified in the IGC Code have a record of actual use, and it is thought that similar tanks can also be used for ammonia fuel. The types and characteristics of ammonia fuel tanks are shown in Table 1, and the characteristics of cargo tanks according to the ammonia liquefaction method are shown in Table 2.

Type C independent tanks, which are used as ammonia cargo tanks of the normal temperature pressurized type (in which ammonia is pressurized and carried in a liquid state) and the semi-refrigerated type (in which ammonia is pressurized while being cooled, and ammonia is transported in liquefied form), have a pressure vessel structure. They can be used at high pressure and require no secondary barrier, and they have the advantage of having relatively simple structures and systems. However, their cylindrical shape results in much dead space in the surrounding area when they are installed in spaces in ships. Especially when large ammonia fuel tanks are installed in a large cargo ship, the effect on the cargo carrying capacity and ship size must be minimized. For this reason, it is considered likely that square-shaped Type A and Type B independent tanks, which are used as fully-refrigerated ammonia cargo tanks (in which ammonia is transported at the saturation temperature at atmospheric pressure), will be studied in the future.

Table 1 Types and characteristics of ammonia fuel tanks

Type	Type A Independent tank	Type B Independent tank	Type C Independent tank
Configuration			
Design pressure	<0.07MPa	<0.07MPa	High Pressure
Track record (Gas carrier)	MGC, VLGC	LNGC	LPG/LNG carrier (small size)
Track record (LNG fueled ship)	Nil	Nil	○
Remarks	･Prismatic tank ･Complete secondary barrier	･Prismatic tank ･Partial secondary barrier ･Detail fatigue analysis	･Simple design and structure (Pressure vessel) ･Highly flexible in pressure ･No secondary barrier required

Table 2 Specifications of general ammonia cargo tanks

	Full pressure tank	Semi-pressurized tank	Fully refrigerated tank
Type of tanks	Type C	Type C	Type A, Type B
Design Temp	0°C	Abt.-33°C	Abt.-33°C
Design Pressure	Abt.1.8MPa	0.65MPa～0.85MPa	0.025MPa 0.045Mpa(In harbor)
Tank Volume	～800m³	3,000m³～4,000m³	---
Material	KD500	KL37-M	KL33, KL27

3. PART C OF GUIDELINES FOR SHIPS USING ALTERNATIVE FUELS

3.1 Overview

In August 2021, the Society published "Guidelines for the Safety of Ships Using Ammonia as Fuel" of Part C of the Guidelines for Ships Using Alternative Fuels. Part C-1 of the Guidelines specifies the requirements for the safety of ships using ammonia as fuel except for liquefied gas carriers. The safety requirements for liquefied gas carriers using ammonia fuel are specified in Part C-2 of the Guidelines.

3.2 Process of Developing the Guidelines

The Guidelines for the Safety of Ships Using Ammonia as Fuel were developed in the following three steps:

Step 1 The physical properties of ammonia were investigated, and a gap analysis of conventional fuel oil and liquefied gas fuels was conducted.

Step 2 Based on the provisions for ships using methane as a fuel specified in the IGF Code in Part C-1 of the Guidelines for Ships Using Alternative Fuels, and in Chapter 16 of the IGC Code in Part C-2 of the Guidelines for Ships Using Alternative Fuels, the safety requirements that ammonia-fueled ships should satisfy to ensure safety equivalent to that of methane-fueled ships were provided, considering the investigation results of Step 1.

The IGF Code provides detailed requirements for the use of methane fuel, which is a liquefied gas fuel. As ammonia is also a liquefied gas fuel, the IGF Code was used as a basis for providing the requirements for the use of ammonia as fuel.

Matters requiring special consideration in ammonia-fueled ships were also identified. For example, ammonia has lower flammability and explosion risks than methane, but a higher toxicity risk.

Step 3 The following existing rules and guidelines were investigated and incorporated in the safety requirements as needed.

- IGF Code: Requirements for use of liquefied gas (methane) as fuel
- IGC Code: Requirements for transport of ammonia as cargo

- IBC Code: Requirements for transport of aqueous ammonia as cargo
- Rules for refrigeration installation: Requirements for use of ammonia as a refrigerant
- Part A “Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuels” of the Guidelines for Ships Using Alternative Fuels: Requirements for toxic fuel
- Part B “Guidelines for the Safety of Ships Using LPG as Fuel” of the Guidelines for Ships Using Alternative Fuels: Requirements for use of liquefied gas fuel

3.3 Concept of Part C of Guidelines for Ships Using Alternative Fuels

3.3.1 Basic Policy of General Safety Measures for Liquefied Gas Fuels

As the basic policy of general safety measures for liquefied gas fuels, the underlying concept of the IGF Code was analyzed and the areas of ships where safety measures should be taken were classified into four areas based on the presence or absences of fuels.

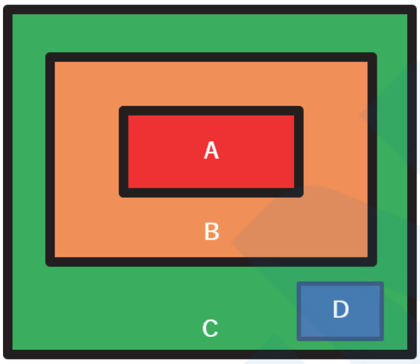

Fig. 7 Classification based on presence/absence of liquefied gas fuels

Area A is an area where fuel is always present (e.g., fuel tanks, piping equipment), and safe containment of the gas fuels inside is required. In this type of area, measures to secure the soundness of the equipment and isolation from any external damage are required. Personnel are not allowed to enter this type of area.

Area B is an area where fuel is not normally present, but is present when leakage occurs (e.g., tank connection spaces, fuel preparation rooms, double-walled pipes and ducts). In this type of area, measures to minimize the effects of fuel leakage are required, including detection of gas leaks, shutting off the fuel supply, containing and removing the leaked fuel and minimizing damage. Personnel may only enter this type of area in case of operational necessity.

Area C is an area where fuel is not present. Area C must be isolated from Area A by two boundaries and from Area B by one boundary. If this type of area cannot be physically isolated, it must be isolated by distance.

Area D is an area in Area C that requires special consideration to ensure that no fuel is present (e.g., accommodation spaces). This type of area must not be in direct contact with Area B.

The physical properties of ammonia that require special consideration in these areas are corrosiveness in Area A and flammability and toxicity in Area B.

3.3.2 Basic Policy of Safety Measures in Consideration of Characteristics of Ammonia

Table 3 shows the differences in the physical properties of methane and ammonia obtained by the gap analysis in Step 1 of the process of developing Part C of the Guidelines for Ships Using Alternative Fuels.

Table 3 Comparison of physical property values of Ammonia and methane

	Ammonia	Methane
Normal boiling point (°C)	-33.4	-161.5
Liquid density (kg/m^3)	682.3	422.5
Gas density (kg/ m^3) @boiling point	0.876	1.820
Gas density (kg/ m^3) @ 20 °C	0.707	0.659
Heat of vaporization (kJ/kg)		510.4
Lower flammability limit (% vol)	15	5.3

Upper detonation limit (% vol)	59.0	13.5
Minimum ignition energy (mJ)	45	0.274
Maximum burning rate (cm/s)	7	37
Quenching distance (cm)	0.064	0.22
Lower heating value (MJ/kg)	18.8	48.0
Self-ignition temperature (℃)	630	537
Toxicity	Yes	No
Corrosiveness	Yes	No
Stress corrosion cracking	Yes	No
Water-solubility (g/100 ml) @20℃	54	2.3

The hazards of ammonia that should be taken into account, as identified by the gap analysis, are described below:

- Toxicity (health hazard)

The typical effects of ammonia on humans include acute toxicity, skin corrosion, severe eye damage and respiratory sensitization. The effects of ammonia on humans by ammonia concentration are as shown in Table 4.

Table 4 Ammonia concentration and effects on humans

Ammonia concentration (ppm)	Effects on humans
5 to 10	Detectable by smell
50	Feeling of discomfort
100	Feeling of irritation
200 to 300	Irritation of eyes and throat
300 to 500	Bearable only for short time (20 to 60 minutes)
2 500 to 5 000	Life threatening in short time (about 30 minutes)
5 000 to 10 000	Respiratory arrest, fatal in short time

- Corrosiveness

Corrosive to copper, copper alloys, mercury, zinc and cadmium.

- Stress corrosion cracking

Causes stress corrosion cracking in carbon manganese steel and nickel steel.

- Low flammability

The lower explosion limit of ammonia is about 15%, which is higher than the limits of existing fuels (1 to 6%), and its minimum ignition energy is 8 mJ to 680 mJ, which is higher than that of methane (0.274 mJ). Accordingly, ammonia is considered to be less flammable than existing fuels such as methane. However, it may generate a flammable gas mixture in semi-closed and closed spaces, and may cause fire or explosion in those spaces.

- Hazard in event of fire

There is doubt about the continuity of combustion of ammonia. In addition, even if ammonia ignites, its calorific value is relatively low compared to those of existing fuels. Therefore, the effect of a fire caused by ammonia on the equipment is expected to be small.

The above-mentioned characteristics of ammonia that should be considered are classified as A) toxicity, B) flammability and C) corrosiveness. The basic policy on safety measures for these characteristics is described below:

A) Toxicity

Ammonia has serious effects on human health, even in small amounts. Therefore, new toxic hazardous areas were set and the safety requirements in the event of a release or leakage of ammonia were defined as follows:

A-1) Isolation of ammonia

Spaces where ammonia is present (Area A and Area B) and spaces where ammonia should not be present (Area C and Area B) are to be separated by physical enclosures or the like, and spaces on open decks where no physical enclosure can be provided are to be separated by distance.

A-2) Control of leaked ammonia

In case ammonia leaks in Area B, the provisions specify that it is to be immediately detected, the ammonia fuel supply to the point where the leakage occurred is to be shut off and the leaked ammonia is to be removed from the space. As in the IGF Code and IGC Code, no special regulations are provided for the release of liquefied gas in an emergency such as leakage into the ship or vent discharge from the pressure relief valves of fuel tanks.

A-3) Response to human exposure to ammonia

To prevent human contact with ammonia, in spaces where ammonia may be present in the event of an abnormality (i.e., Area B), the fact that no ammonia is detected shall be confirmed. If ammonia is detected, personnel wearing proper protective equipment are allowed access to the space. If contact with ammonia occurs, measures to mitigate the effects are to be taken.

A-4) Ensuring Safe Operation

If ammonia is released into the atmosphere in an emergency, places necessary for maneuvering and propulsion of the ship so as to maintain the minimum operation for the ship's safety, and places for performing emergency operations such as fire extinguishing and evacuation, shall be in safe locations.

B) Flammability

Because the lower explosion limit and minimum ignition energy of ammonia are high, ammonia is more difficult to ignite than other fuels. Therefore, there is a comparatively low probability of fires caused by ammonia. The former version of the IGC Code specified that "Because high concentrations of ammonia in confined spaces can be flammable, the provisions of Chapter 10 for flammable products should be applied except in zones on the open deck." Based on these points, no requirements for flammable hazard areas on open decks were provided, and the requirements for thermal insulation, etc. were reduced compared to those for methane fuel.

C) Corrosiveness

Ammonia is corrosive for certain materials and has a risk of causing stress corrosion cracking in carbon manganese steel and Ni steel. Therefore, based on the special requirements for ammonia in Chapter 17 of the IGC Code, the related requirements were provided.

3.3.3 Basic Policy on Release of Ammonia

Ammonia release scenarios were set for emergency conditions and normal conditions. The handling of ammonia in each scenario is described below.

(1) Under emergency situations

The following events are regarded as emergencies, and the release of ammonia into the atmosphere or sea is allowed.

① Retaining ammonia fuel may result in the worst-case situation.

(Example) A fire occurs around an ammonia fuel tank, the pressure in the tank increases and the pressure relief valve operates.

② Events in which it is impossible to retain ammonia fuel.

(Example 1) In closed and semi-closed spaces, the piping system, etc. is damaged and ammonia is to be removed from the space where it leaked.

(Example 2) Leaked ammonia is adsorbed by water from the water spray system at a bunkering station, etc. and released into the sea.

(2) Under normal situations

In normal operation, outboard release of highly concentrated ammonia from spaces where ammonia is present (Area A (tanks, piping systems, etc.)) is not allowed.

(Example 1) Purging and gas freeing of the ammonia fuel supply system or bunkering lines

(Example 2) Gas freeing of tanks and pipes during docking or undocking

3.4 Major Requirements of Part C of Guidelines for Ships Using Alternative Fuels

3.4.1 Functional Requirements (Chapter 3 of Part C-1)

Part C-1 of the Guidelines for Ships Using Alternative Fuels provides guidelines for design, construction and operation by specifying goals and functional requirements using the goal based approach, which is the basic philosophy of the IGF Code. Chapter 3 of Part C-1 of the Guidelines for Ships Using Alternative Fuels provides the goal and functional requirements of the entire Guidelines. The goal of the chapter is "to provide for the safe and environmentally friendly design, construction and operation of ships and their installation of systems for propulsion machinery, auxiliary power generation machinery and/or other purpose machinery using ammonia as fuel." As functional requirements, 19 items are provided. The main functional requirements are as follows:

- Ships using alternative fuels shall ensure safety and reliability equivalent to those of conventional ships (oil-fueled engine).
- Hazards related to the use of ammonia as fuel shall be minimized.
- Adequate safety measures to prevent a single failure in the fuel systems shall be provided.
- Hazardous areas shall be minimized.
- Unexpected accumulation of fuel shall be avoided.
- Fuel shall not be discharged other than when necessary for safety reasons.
- Measures shall be taken to minimize human health hazards associated with the toxicity of the fuel.

3.4.2 Risk Assessment (Chapter 4 of Part C-1)

In the design of ammonia-fueled ships, a risk assessment is required in order to eliminate or mitigate any adverse effects on passengers and personnel on board, the environment or the ship. Although the scope of risk assessments for ships using natural gas as fuel is limited in the IGF Code, the scope of risk assessment for ammonia-fueled ships is not limited and includes all items related to the use of ammonia as fuel.

3.4.3 Arrangement of Gas Safe Machinery Spaces (Chapter 5, 9 and 10 of Part C-1)

In addition to the concept of gas safe machinery spaces, the concept of ESD-protected machinery spaces is also introduced in the IGF Code. Because ammonia has serious human health effects, even in small amounts, the provisions for ammonia-fueled ships do not permit an ESD-protected machinery space where a single failure may cause a gas fuel release into the space.

Gas safe machinery spaces are defined as spaces that are considered gas safe not only under normal conditions but also under abnormal conditions. Double-walled pipes are to be provided for the ammonia fuel piping in machinery spaces so that a single failure will not lead to a leakage of gas fuel into the machinery spaces.

3.4.4 Material Arrangement (Chapter 7 of Part C-1)

In consideration of the corrosive nature of ammonia, use of mercury, copper, copper alloys and zinc in materials that may be exposed to ammonia fuels under normal use conditions is prohibited. In the future, use of cadmium will also be prohibited.

Because ammonia may also cause stress corrosion cracking in tanks and piping systems made of carbon manganese steel or nickel steel, additional measures were provided based on 17.12 Special requirements for ammonia in the IGC Code. The main requirements are as follows:

- When carbon manganese steel is used for fuel tanks or other pressure vessels, piping systems, etc., it shall have a specified minimum yield point not exceeding 355 N/mm^2 and an actual yield value not exceeding 440 N/mm^2, and is to satisfy any one of the following requirements ① to ④:
  ① Specified minimum tensile strength < 410 N/mm^2
  ② Post-weld stress relief heat treatment
  ③ Carriage temperature of -33°C (less than -20°C in any case).
  ④ Only ammonia containing not less than 0.1% of water shall be carried.
- If materials with a high yield point exceeding the above yield point are used, post-weld stress relief heat treatment is to be applied.
- Carbon manganese steel and nickel steel used for process pressure vessels and pipes are to be given post-weld stress relief heat treatment.
- Use of nickel steel with a nickel content exceeding 5% is prohibited. As Part K of the Rules for the Survey and Construction of Steel Ships specifies that the content of nickel in 5% Ni steel shall be 4.75% to 6.00%, the applicable range in these Guidelines is 4.75% to 5%.

3.4.5 Bunkering (Chapter 8 of Part C)

Since ammonia is highly toxic and has serious human health effects, even in small amounts, ammonia fuel supply piping systems on open decks are to be surrounded with secondary enclosures. However, secondary enclosures are not required for ammonia fuel bunkering pipes, as gas freeing is conducted at times other than during bunkering and the frequency of ammonia in the pipes is low. (In this case, single-walled pipes may be provided.)

In connections at bunkering stations, devices which enable safe disconnection by use of BAC (Break Away Coupling) or ERC

(Emergency Release Coupling) are required in order to prevent bunkering hoses from breaking due to excessive load. If a disconnecting device is activated, a small amount of fuel remaining at the coupling may scatter, and human contact is possible. To reduce this risk, a water spray system is required at bunkering stations.

3.4.6 Hazardous Areas (Chapter 12 of Part C-1)

Because the LEL and minimum ignition energy of ammonia are high, ammonia is considered to have a low risk of causing fire or explosive atmospheres on open decks. Therefore, no flammable hazardous areas are set for open decks. However, there is a risk of ammonia producing a flammable atmosphere in closed and semi-closed spaces, and hazardous areas are set for those spaces, as in the conventional IGC Code and IGF Code. In Part C of the Guidelines C (Ver1.1), hazardous areas are classified as flammable hazardous areas and toxic hazardous areas. In the future, the classification will be changed so that toxic hazardous areas are included in flammable hazardous areas, as in the IGC Code.

3.4.7 Fire Safety (Chapter 11 of Part C)

(1) Open decks

Ammonia fuel tanks must be protected from heat input due to external fire by cooling and fire prevention. Therefore, the exposed parts of fuel tanks located on open decks are covered with water spray systems.

As noted above, it is assumed that ammonia will not cause fires or explosive atmospheres on open decks. Therefore, unlike the requirements of the IGF Code, installation of water spray systems in spaces (accommodation spaces, etc.) that should be protected from fuel tank fires is not required.

(2) Under open deck

Since there is a risk of fire or explosion caused by ammonia in closed and semi-closed spaces, it is necessary to protect ammonia fuel storage systems from machinery spaces of category A and spaces with a high risk of fire by the following methods:

- Installation of A-60 class heat insulation
- Separation by a cofferdam of 900 mm or longer (If Type C independent tanks are not located directly in a category A machinery space or a high fire risk space, the fuel storage hold space may be regarded as a cofferdam.)

3.4.8 Measures Against Toxicity (Chapters 6, 12, 13 and 14 of Part C)

As in the case of flammable hazardous areas, toxic hazardous areas are set for closed and semi-closed spaces but are not set for open decks. However, as safety measures against toxicity on open decks, requirements for distance for separation from places that should be protected, such as places where ammonia release is possible, where personnel are normally present, openings of non-hazardous spaces and inlets/outlets of ventilation systems in non-hazardous spaces, were specified as follows:

① Vent post

Height of vent exits:

- Not less than B’/3 or 6 m, whichever is greater, above the weather deck
- Not less than 6 m from working areas and walkways

Separation distance of vent exits:

- Not less than B or 25 m from air inlets/outlets and openings of non-hazardous spaces, whichever is lower

② Outlets of ventilation systems

Height of outlets of ventilation systems in enclosed hazardous areas

- Not less than 4 m from the weather deck, working areas and walkways

Separation distance of outlets of ventilation systems in enclosed hazardous areas

- Not less than 10 m from air inlets/outlets and openings of non-hazardous spaces

③ Protected areas

The following protected areas (A) to (C), which are defined as areas that should be protected, are to be separated by the distances (a) to (d) specified for the respective places where ammonia may be released.

Protected areas:

(A) Ventilation inlets/outlets and openings of non-hazardous spaces
(B) Escape routes from spaces where personnel are normally present, such as accommodation spaces, control spaces and electrical equipment rooms
(C) Lifeboats

Places where ammonia may be released and separation distances:

(a) A spherical distance of 4.5 m (3 m + 1.5 m) from any fuel tank outlet, gas or vapor outlet, bunker manifold valve, other fuel valve, fuel pipe flange, fuel preparation room ventilation outlet and fuel tank opening for release of a small amount of gas or vapor caused by temperature variation to regulate the pressure in the fuel tank
(b) A spherical distance of 3.0 m (1.5 m + 1.5 m) from any fuel preparation room entrance, fuel preparation room ventilation inlet and other openings of places where fuel may leak
(c) A distance of 4.5 m (3 m + 1.5 m) around and 3.9 m (2.4 m + 1.5 m) above coamings installed around fuel bunker manifold valves to prevent fuel leakage
(d) For fuel storage systems with an exposed external surface except for Type C tanks, a distance of 3.9 m (2.4 m + 1.5 m) from the external surface

3.4.9 Ventilation System (Chapter 13 of Part C)

Ventilation systems are required in the following spaces where gas may accumulate.

- Tank connection spaces
- Fuel preparation rooms
- Double-walled pipes and ducts

In these spaces, exhaust-type mechanical ventilation systems of non-sparking construction having a ventilation capacity of at least 30 air changes/hour are to be installed. In spaces where ammonia-related equipment is installed and personnel enter during operation, an additional ventilation system that can immediately remove leaked ammonia is to be installed and is to satisfy the following requirements:

- The ventilation system shall have a minimum capacity of at least 45 air changes/hour (which may include the ventilation capacity of at least 30 air changes/hour in normal operation).
- When the ammonia gas concentration detected in such spaces exceeds 3 000 ppm, the ventilation system shall start automatically.

Where a bunkering station is not located on an open deck with sufficient natural ventilation, a risk assessment must be conducted to evaluate its safety. At that time, a study of the necessity of installing an appropriate mechanical ventilation system must be conducted, considering the risk of gas leakage especially during bunkering operation.

Ventilation systems for spaces where ammonia may leak shall be independent of ventilation systems for other spaces, and closing appliances are to be installed at air inlets/outlets of spaces where personnel are normally present.

3.4.10 Automatic Shutdown of Ammonia Supply (Chapter 15 of Part C)

In case of abnormal conditions such as leakage of ammonia fuel or stoppage of ventilation system operation, automatic shutoff valves (master valves) for stopping the fuel supply into machinery spaces shall be provided, and in case of abnormality of an engine using gas fuel, double block and bleed valves for stopping the gas fuel supply to the engine must be installed in each engine. Considering the effects of ammonia on the human body, an alarm is given when the concentration of leaked ammonia detected in a space reaches 25 ppm, and when the concentration reaches 300 ppm, the master valves and double block and bleed valves shut off.

3.5 Future Deliberation and Development

International deliberation has been conducted to develop requirements for ships using ammonia as fuel. In September 2021, 27 member states of the EU and the EC submitted a document (CCC7/3/9) proposing the development of safety requirements for ammonia to the Sub-Committee on Carriage of Cargoes and Containers (CCC), 7th session at the IMO. In October 2021, the Japanese government made a proposal on the development of guidelines for ships using ammonia as fuel at the Maritime Safety Committee (MSC), 104th session. In both committees, no deliberation on these proposals was conducted because of time constraints. If the proposal is deliberated and approved at the next MSC 105 (April 2022), study of specific safety requirements for ammonia-fueled ships is expected to start in the Sub-Committee CCC8 (September 2022).

The Society published the Guidelines of safety requirements in order to contribute to the recent demand for the development of ammonia-fueled ships. In the future, we will contribute to discussions on the development of international regulations by using the investigation results, etc. obtained through the development of the Guidelines, and will review the Guidelines at regular intervals in consideration of the most recent status of deliberations in the IMO and the rapid development of new technologies in order to develop guidelines that will be useful for developers.

Overview of Changes and Comprehensive Revision of Part C of the Rules for the Survey and Construction of Steel Ships

Kinya ISHIBASHI*

1. INTRODUCTION

Part C of the Rules for the Survey and Construction of Steel Ships (hereinafter, Part C), which constitutes the technical rules of ClassNK (hereinafter referred to as “the Society”), provides the requirements for the hull construction and equipment of ships except those to subject to CSR (IACS common structural rules), including container ships, ore carriers and liquefied gas carriers, etc., and is a compilation of the technologies and experience related to hull structures that the Society has cultivated over the course of approximately 100 years of ship classification services.

The Society established five basic strategies in the five-year medium-term management plan which started in 2017, and decided to carry out a comprehensive revision of Part C in a manner that corresponds to one of those strategies, “Promoting research and development activities.”

To promote this revision, the Society launched a large number of joint research projects in cooperation with universities and research institutes to conduct research and development of element technologies related to design loads, corrosion and yield, buckling and fatigue strength required in order to develop new structural rules. In addition, the Society also build a dedicated team for simultaneously conducting research, development of rules and consequence assessments, which require an enormous amount of work, with young engineers affiliated with the shipyards and shipping companies along with regular staff participating in this project. In 2019, full-scale discussions on the proposed comprehensive revision were conducted in the Sub-technical Committee, which consists of engineers from related industries as well as scholars and experts, at meetings held by the Society, and finally, the comprehensive revision to Part C was approved at the First Technical Committee meeting held in January 2022.

This report explains the transition of the Society's structural rules since they were first issued in 1921 and describes the positioning of this comprehensive revision from the viewpoint of the transition of the rules to date.

2. CHANGES OF STRUCTURAL STRENGTH RULES

2.1 Issuance of Rules for the Survey and Construction of Steel Ships

The first Rules for the Survey and Construction of Steel Ships, which serve as a basis for the judgment criteria in ship classification surveys, were issued in 1921. When our services resumed after World War II, the new Rules for the Survey and Construction of Steel Ships was issued with contents greatly different from those of the old Rules. Nevertheless, a look at the table of contents of the Rules for the Survey and Construction of Steel Ships issued in 1925 (see Fig. 1) which is the oldest extant version, reveals that many vestiges of the earlier Rules remain in the present Part C. In both the old and the new Rules, the chapters describing the requirements for various structural members such as upper deck and bottom plating are arranged in the order in which those members are constructed according to the construction method used prior to the adoption of block construction, and these chapters make up the greater part of the structural rules. Following the chapters concerning those structural members, the old Rules provided a chapter describing the requirements for oil tankers. Since an oil tanker has a small freeboard, and the loads acting on its structure is relatively large. As it also has a longitudinal bulkhead and its structural type is greatly different from that of a general cargo ship. The rules at that time adopted many empirical formulae using principal particulars such as L, B and D as the parameters, and special formulae for oil tankers which is different from those for general cargo ships were required. Since rivet connections were widely used during that period, the old Rules also described the requirements for the distance of rivets, etc. to prevent leakage of cargo oil.

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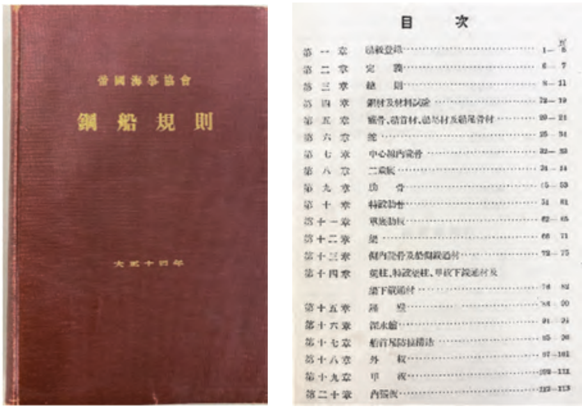


Fig. 1 Rules for the Survey and Construction of Steel Ships by Teikoku Kaiji Kyokai (issued in 1925)

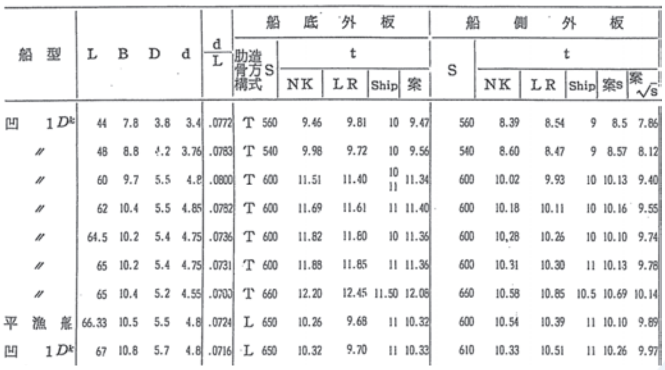
2.2 Transition from Empirical Formulae to Theoretical Formulae

Table 1 summarizes the major revisions related to structural strength made in Part C over the past 70 years. Here, revisions related to rudders, hull equipment, materials and welding were omitted.

In the rules of the 1950s, formulae for determining scantling were used for members that could be regarded as simple beams, such as stiffeners, in the same way as in the current Rules. However, many of the formulae for shell plating, girder plates, etc. were empirical formulae as a function of principle particulars such as L, B and D, that were derived from the actual scantling of the ships built in the past, or comparisons with the rules of other ship classification societies (see Fig. 2). As approaching the present day, more rational scantling formula based on appropriate load and strength capacity models were adopted. (see Table 2).

Table 1 Major revisions of NK rules for structural strength

Time	Content of revision
1921	Issuance of first edition of the Rules for the Survey and Construction of Steel Ships.
1949	First issuance of Rules for the Survey and Construction of Steel Ships by Nippon Kaiji Kyokai (renamed from Teikoku Kaiji Kyokai following World War II).
1959	Introduction of requirements considering slamming load.
1961	Introduction of theoretical formula-based shell plating requirements.
1963	Introduction of buckling strength requirements for girder webs.
1972	Introduction of longitudinal bending moment based on long-term prediction.
1973	Creation of new Chapter 31 “BULK CARRIERS.” (Introduction of grillage structure assessment by equivalent plate panel)
1974	Reorganization of structural requirements into Part C of the Rules for the Survey and Construction of Steel Ships. Introduction of strength assessment method based on direct strength calculation.
1980	Substantial revisions using wave pressure based on long-term prediction.
1983	Creation of new Chapter 32 “CONTAINER SHIPS.”
1987	Partial incorporation of UR S11 (longitudinal strength).
1989	Introduction of requirements for buckling under combined loads.
1993	Creation of new Chapter 29A “DOUBLE HULL TANKER.” (Introduction of fatigue strength requirements for longitudinal stiffeners)
1999	Introduction of bulk carrier safety-related requirements. (Introduction of requirements for strength in event of flooding, etc.)
2001	Issuance of Guidelines for Tanker Structure. (Introduction of net scantling assessment, equivalent design wave method, fatigue strength assessment for girders, Ultimate hull girder strength assessment)
2006	Creation of new Part CSR-B and CSR-T.
2016	Creation of new Part CSR-B&T. Substantial revision of requirements for container ships. (Introduction of requirements considering whipping load)



船型	L	B	D	d	d/L	肋骨構造方式	S	船底外板 t NK	LR	Ship	案	船側外板 S	t NK	LR	Ship	案s	案/√s
凹 1 Dk	44	7.8	3.8	3.4	.0772	T	560	9.46	9.81	10	9.47	560	8.39	8.54	9	8.5	7.86
〃	48	8.8	4.2	3.76	.0783	T	540	9.98	9.72	10	9.56	540	8.60	8.47	9	8.57	8.12
〃	60	9.7	5.5	4.8	.0800	T	600	11.51	11.40	10 11	11.34	600	10.02	9.93	10	10.13	9.40
〃	62	10.4	5.5	4.85	.0782	T	600	11.69	11.61	11	11.40	600	10.18	10.11	10	10.16	9.55
〃	64.5	10.2	5.4	4.75	.0736	T	600	11.82	11.80	10	11.36	600	10,28	10.26	10	10.10	9.74
〃	65	10.2	5.4	4.75	.0731	T	600	11.88	11.85	11	11.36	600	10.31	10.30	11	10.13	9.78
〃	65	10.4	5.2	4.55	.0700	T	660	12.20	12.45	11.50	12.08	660	10.58	10.85	10.5	10.69	10.14
平 漁 艇	66.33	10.5	5.5	4.8	.0724	L	650	10.26	9.68	11	10.32	600	10.54	10.39	11	10.10	9.89
凹 1 Dk	67	10.8	5.7	4.8	.0716	L	650	10.32	9.70	11	10.33	610	10.33	10.51	11	10.26	9.97

Fig. 2 Comparison with other ship classification societies and actual scantling published in NK journal

Table 2 Formulae for determining thickness of bottom shell plating

Period	Rule formula
1960	When L is not less than 110m, $\left\{0.54 + 10.7\left(\frac{L}{100}\right)\right\}\left\{1 + 0.025\left(\frac{L}{11} - D_s\right)\right\}$ (mm) D_S: Depth (above strength deck) of ship
1961	$1.44C_d S\sqrt{L} + 2.5 \ (mm)$ $C_D = 1 + 7\left(\frac{d}{L} - 0.06\right)$ S: Spacing of longitudinals
1974	$3.64CS\sqrt{\frac{d + 0.035L'}{1.66 - f_b}} + 2.5 \ (mm)$ C: Correction coefficient of 1.0 to 1.07 depending on L f_b: Utilization factor of longitudinal strength on ship's bottom

The 1960s was a period when the size of cargo ships, especially tankers, increased dramatically. The NK journal published in 1972, when periodical survey of those large cargo ships in service had begun, contained the following description: "Investigations of the actual damage of ships revealed that damage caused by increased longitudinal bending stress on the ship hull is extremely rare, and in more cases, forces such as the wave-induced force acted on local hull structures, causing damage such as buckling and cracking due to stress concentration." The formulae for longitudinal strength and stiffeners represented by a simple beam model can respond to the significantly larger size of these ships, but the empirical formulae for plate members and girder webs based on actual scantlings of past ships were difficult to deal with. The volume of cargo holds also increased as a result of the increase in ship size, heightening the relative importance of the strength of the girder members in holds, but it became impossible to cope with the deformation and stress generating by the responses of complex indeterminate structures by using the empirical formulae. Therefore, many complex formulae applicable to various indeterminate structures were developed at that time, such as adopting a method for obtaining the burden rate of shear force acting on longitudinal and transverse girders by replacing grillage structures such as double bottom structures with equivalent panels.

2.3 Advent of Long-Term Prediction and Direct Strength Calculation

In the 1970s, strength assessment technologies, which are the most important even today, appeared in Part C. One of those technologies was a design load estimation [4] based on long-term prediction. It then became possible to obtain the maximum expected values for wave pressure, wave-induced longitudinal bending moment, etc. during service life of ships by a technique combining the strip method, which makes it possible to calculate ship motion and pressure acting on the hull, and short-term prediction and long-term prediction based on the science of statistics. The empirical formulae used until that time were replaced by this approach, making it possible to develop more widely applicable and more rational requirements.

Another important technology is direct strength calculation of cargo hold structures by the finite element method, as illustrated in Fig. 3. When rule formulae are used to deal with grillage structures and indeterminate problems such as subjected to forced displacement, the formulae would become too complex and substantial errors may occur in modeling. However, in the direct strength calculation method, the actual structures are replaced by appropriate beam elements and shell elements, enabling assessment with much higher accuracy than in the past. In the case of shell elements, the local stress generated on girders having complex shapes, such as transverse rings, can also be calculated with high accuracy.

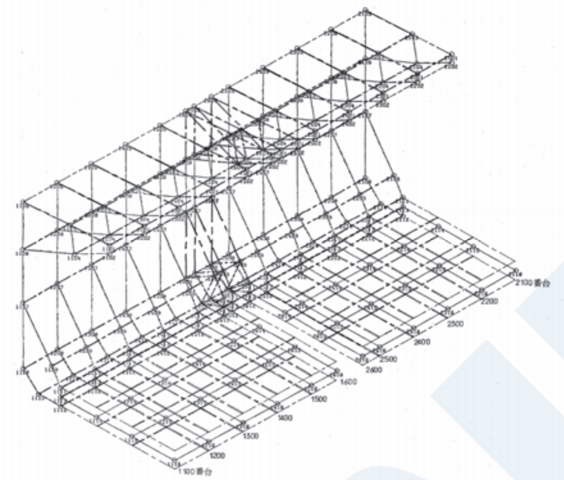


Fig. 3　FE model created in 1970s

2.4　To More Theoretical and Rational Rules

Although it was thought that development of more theoretical and rational rules, which is one of the goal of this comprehensive revision, can be significantly advanced by applying the two above-mentioned technologies, no major revisions had been made since the 1980s, except the revision that wave pressure based on the long-term prediction was applied. On the contrary, since the 1990s, a larger number of revisions have related to structural safety measures introduced by the IMO and IACS, such as the establishment of IACS Common Structural Rules (CSR).

Although there are many reasons why the development of the rules has not progressed, the two problems described below are considered to be large factors.

One of the problems is thought to be the relatively large load values obtained by the long-term prediction method. Fig. 4 shows the results of long-term predictions of the wave-induced vertical bending moment used for longitudinal strength requirements, which served as the technical background for the revision of the Rules in 1972. At that time, it was already known that the maximum expected value during the service life of a ship corresponds to an exceedance probability of 10^{-8} level. However, a formula for deriving the moment corresponding to the exceedance probability of 10^{-5} level was adopted for the reason that it takes into account the effects of weather routing, speed reduction and veering. At the time, some adjustment to actual scantling was necessary because the allowable stress for longitudinal bending stress was taken as approximately 150 N/mm^2 (currently 190 N/mm^2).

From around that time, some ship measurement projects were carried out for the purpose of surveying the actual conditions of ship operation and encountered sea state, but limited data were only obtained from a few ships and it was impossible to see a full picture of the actual conditions.

The second factor was that long-term prediction makes it possible to obtain the maximum expected values of each load component such as wave-induced longitudinal bending moment, wave pressure, accelerationat each position, but the correlation among the load components is completely unknown. In ship design, it is necessary to consider simultaneously-occurring loads combined on all load components. Various studies [5)-7)] were conducted in connection with this problem in the past, and the research results were utilized to develop the equivalent design wave method, which was adopted for the first time in the “Guidelines for Tanker Structures” [8)] issued by the Society, and was also adopted subsequently in CSR.

The equivalent design wave method focuses on the characteristics that the expected value with an extremely low probability of occurrence in the long-term prediction of hull structure response is caused by a very limited number of designated short-term seas (or regular waves of designated wave directions or wave lengths) and using some combined load cases that reproduce those short-term seas to evaluate the strength of hull structures.

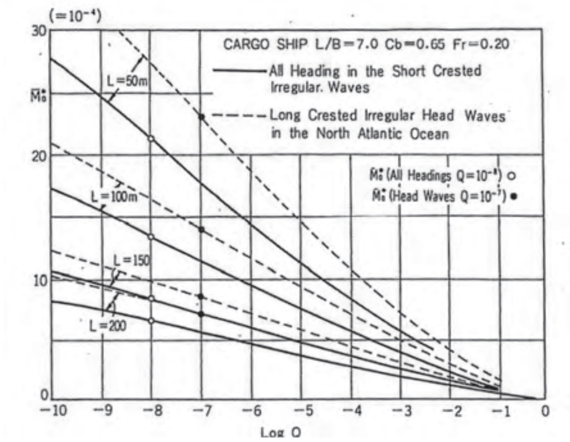


Fig. 4 Long-term prediction results of wave induced vertical bending moment

3. NEW PART C OF THE RULES FOR THE SURVEY AND CONSTRUCTION OF STEEL SHIPS

3.1 Composition of Chapters of New Part C

As previously described in section 2.1, the structure of the chapters of the current Part C has not changed substantially from that of the Rules issued in the 1920s. The chapters specifying the requirements for structural members mainly for general cargo ships make up the greater part of the Rules, followed by exclusive chapters for ship types. At the subordinate level of each chapter for ship type, there are sections concerning structural members such as bottom structures and side structures. Thus, the Rules are composed in a so-called nesting style. This is one factor which reduces the readability of the Rules.

Unlike the period when the original Rules was issued, today long-term predictions of loads and the equivalent design method can be used to indicate the expected load values at various locations and acceleration in long-term prediction and considering the simultaneity of those loads. In addition, generalized strength capacity models can be used not only for the local strength of plates and stiffeners, but also for primary supporting members such as girders and stringers. This means that the necessity dividing chapters by structural members has been reduced.

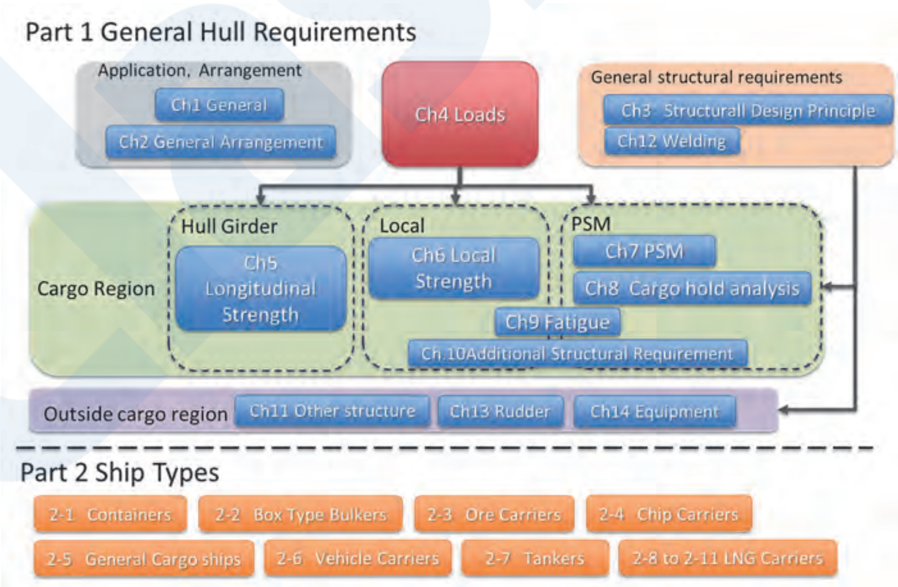


Fig. 5 Composition of chapters of new structural strength rules

Based on these circumstances, considering the readability of the Rules, the ease of understanding for designers familiar with CSR, the new structural rules were developed with the chapter composition shown in Fig. 5.

The essential parts of the Rules are the chapters on the hierarchical levels of structures in terms of strength, such as local strength, strength of primary supporting members and longitudinal strength, and the categories concerning strength assessments such as load and fatigue. The requirements for the cargo types and its loading and additional requirements for structures specific to ship types are specified in Part 2.

3.2 Design Load

In the new Part C, the design load continues to be based on the long-term prediction method and the equivalent design wave concept described previously in section 2.4, and it is now possible to derive more realistic load values by considering the non-linear effect and the effect of operational factor.

In the development of the load formulae, the physically meaningful formulae derived from the two-dimensional potential theory were simplified to obtain more applicable and more accurate estimation formulae [9) 10)]. Furthermore, a wave load analysis was conducted by the 3D panel method, which is best-balanced in terms of estimation accuracy, reliability and calculation cost and is widely used at present, and based on the results, a series of calculations of short-term predictions and long-term predictions was carried out to verify and adjust the developed load formulae.

Nonlinear effects due to changes in the submerged parts of ships in large waves, etc. have been obtained as factors for respective equivalent design waves [11)] from the results of a series of analyses using tank experiments and the nonlinear 3D panel method.

For the effects of operational factor, the long-term prediction values for major hull responses are determined from the wave scatter diagram based on the encountered sea states obtained from AIS (Automatic Identification System) data from several tens of thousands of ships, and the factors [13)] are specified from the ratio of the obtained values to the long-term prediction values derived from the wave scatter diagram defined in IACS Rec. 34 [12)], which had been used from an early date.

By using this factor, it is possible to estimate the load values acting on hull structures more accurately and derive scantlings with less deviation from the actual scantlings.

3.3 Corrosion Additions and Improvement of Accuracy of Strength Criteria

Methods for achieving higher accuracy were targeted not only for design loads, as described in section 3.2, but also for corrosion additions and strength criteria for yield, buckling and fatigue to make it possible to perform strength assessments more in line with the actual phenomena.

For the corrosion additions used in the new structural rules, values corresponding to various corrosion environments were obtained by statistically analyzing enormous volumes of data obtained from thickness measurements conducted at the time of surveys of in-service ships.

Although corrosion additions determined by this method have also been adopted in CSR, in the new Part C, the quality of maintenance in recent years premised on the Enhanced Survey Programme (ESP) was reflected in the corrosion additions by collecting the thickness measurement data for statistical analysis mainly from ships constructed in the 1990s and later. As a result, locations of ship structures such as ballast tanks, where improved maintenance quality has reduced corrosion, and members such as the inner bottom plating of dry cargo ships, where corrosion has not been reduced, are clarified as numerical values.

Efforts were also made to define the strength criteria for yield, buckling and fatigue so as to be more directly related to damage. For example, for the scantling formulae for the lateral pressure of plates and stiffeners, formulae based on the initial yield strength and rigid plasticity theory and the accompanying empirically-defined safety factors had long been used.

In this development, nonlinear FE analyses, in which various levels of pressure were loaded/unloaded, were conducted for plates and stiffeners in order to investigate the level of strength criteria where no residual deformation occurs, and simple formulae for deriving the criteria were developed [14) 15)]. Appropriate safety factors were added to these simple formulae to derive the formulae for scantlings with a clear correspondence to damage.

In buckling strength assessments, while using physically meaningful formulae as much as possible as in the case of the load formulae, an approach that makes it possible to estimate the collapse strength after elastic buckling with high accuracy was adopted [15)]. Requirements that consider the effects of load redistribution after local buckling of a plate panel on surrounding structures in indeterminate structures such as hull structures were also partially incorporated to provide criteria having a higher correlation with actual damage.

For fatigue strength assessments, repeated loading closer to actual conditions was set based on the information on ship courses obtained from the AIS data of several tens of thousands of ships [16)], and requirements with a clear correlation with actual damage cases were adopted, for example, by setting safety factors based on the probability of occurrence of fatigue damage in an entire ship structure.

4. CONCLUSION

The concept of the new Part C is now quite close to the ideal image of structural rules conceived from the time when long-term prediction technology developed in the 1970s, and it may be said the most important factor in its development was the big data obtained from the AIS data and plate thickness measurement data.

As digital twin-related technologies progress and are widely adopted in the future, quantitative measurement and use of the various events that occur while ships are in service will become possible, and it will also be possible to obtain more knowledge in connection with the sea conditions which ships actually encounter and their complex nonlinear structural responses than ever before, allowing an accurate elucidation of the causes of damage accidents, etc.

The new Part C was developed with the aim of enabling strength assessments based on reproduction of the sea conditions actually encountered by ships and the condition of hull structures after ships are commissioned, together with strength criteria based on actual damage. Accordingly, the knowledge revealed by digital twin-related technologies can be reflected relatively easily in the Rules, and further improvement of the safety and rationality of the Rules can be expected in the future.

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Setting Corrosion Additions Based on Latest Thickness Measurement Data

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1. INTRODUCTION

As the corrosion additions to be considered in ships, conventionally, the hull structural rules of the Society, Part C of the Rules for the Survey and Construction of Steel Ships, specify that a thickness of 2.5 mm is in principle to be added to the scantling calculation formulae for structural members, regardless of the corrosive environment [1]. On the other hand, the guidelines for hull structural strength [2) 3)], which summarize hull structural strength assessment methods using finite element analysis, adopt a structural strength assessment method using net scantlings obtained by pre-deducting the diminution value (corrosion addition) expected during the design life (25 years) of the ships from the as-built thickness. This method is also adopted in the common structural rules (Common Structural Rules) of the International Association of Classification Societies (hereinafter, "IACS"), namely, CSR-BC, CSR-OT, and CSR-BC&OT [4)-6)]. Thus, in establishing rational structural rules, it is necessary to estimate appropriately the cumulative corrosion diminution of the structural members in ships over a period of 25 years. Since the corrosion diminution of hull structural members depends on the environment to which the member is exposed and the condition of the anticorrosion coating, a probabilistic model is established for the processes of the initiation and progress of corrosion, in which thickness measurement data accumulated over many years are statistically analyzed by fitting to the model in order to estimate the corrosion diminution. In this report, corrosion diminution is estimated and corrosion additions are specified based on thickness measurement data from relatively new ships, and the obtained corrosion additions are compared with those specified in CSR-BC&OT.

2. TRANSITION OF RULES AFFECTING CORROSION

The corrosion diminution of hull structural members depends on the coating conditions under the environment to which members are exposed and the degree of maintenance. Accordingly, amendments to rules that include coating-related requirements will have a significant effect on corrosion diminution. Table 1 shows the list of the rule amendments on coating and maintenance that may affect corrosion environments.

After the International Convention for the Prevention of Pollution from Ships (MARPOL Convention) [7] came into effect in 1983, oil tankers were required to be equipped with segregated ballast tanks. Until that time, oil tankers had navigated with ballast water in the cargo holds after unloading. Under the newly-introduced requirement, cargo oil tanks and ballast tanks began to be used as purpose-dedicated tanks, and as a result, cargo oil tanks showed a dramatic improvement in corrosion conditions. After a series of accidents resulting in the sinking of aged bulk carriers due to damage caused by deterioration over time, the International Maritime Organization (hereinafter, "IMO") adopted the Enhanced Survey Programme (hereinafter "ESP") [8] for bulk carriers, oil tankers and chemical tankers. Thereafter, the coating condition of ballast tanks was assessed in three levels of ratings: GOOD, FAIR and POOR. If the coating condition of any tank was found to be POOR, the tank would thereafter be required to undergo annual internal inspections. To avoid this penalty, the degree of maintenance of tanks aboard ships after commissioning generally improved. Table 2 shows the judgment criteria for the three levels of coating conditions. Since some of the abovementioned accidents occurred because of corrosion, moves to investigate coating conditions and improve corrosion conditions also gained international momentum. Then, following the adoption of the IACS Unified Requirements (UR) Z7 (Rev. 5) [9], coating conditions were also assessed into three levels, similarly to the ESP. Corrosion conditions significantly improved after these rules came into effect in 1996 and 1998. More recently, the Performance Standards for Protective Coatings (PSPC) [10) 11)] came into force for ballast tanks in 2008 and for cargo oil tanks in 2013. Thus, it is now required that ships be coated with high-performance coatings so as to maintain the GOOD condition until 15 years have passed. In structural rules, the net scantling

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approach is adopted in the ship type-specific guidelines for hull structural strength developed by the Society and IACS CSR to ensure that structural integrity is maintained against corrosion diminution during the design life of the ship.

3. CORROSION DIMINUTION ESTIMATION METHOD

The present report employs a corrosion diminution estimation method based on the statistical approach proposed by Yamamoto et al. Assuming that the occurrence and progress of corrosion can be divided into the three consecutive processes below, Yamamoto et al. introduced a probabilistic model for each process [12):

Phase I: Generation of active pitting point

Time until active pitting points are generated, T_{g}, is assumed to follow the log-normal distribution as given below.

$$f_{T_{\mathrm{g}}}(t) = \frac{1}{\sqrt{2\pi}\sigma_0 t} \exp\left\{-\frac{(\ln t - \mu_0)^2}{2\sigma_0^2}\right\} \qquad (1)$$

where,

μ_0, σ_0 : Mean value and standard deviation of $\ln T_{\mathrm{g}}$, respectively

Phase II: Transition to progressive pitting point

Transition time from active pitting points to progressive pitting points, T_r, is assumed to follow the exponential distribution as given below.

$$g_{T_r}(t) = \alpha \exp(-\alpha t) \qquad (2)$$

where,

α : Inverse of mean transition time

Phase III: Progress of pitting points,

The depth of corrosion pit, $z(t)$, can be expressed as below.

$$z(t) = \begin{cases} 0 & ; \quad t \leq t_0 \\ a(t - t_0)^b & ; \quad t > t_0 \end{cases} \qquad (3)$$

where,

a, : Parameters which govern the characteristics of corrosion progress. a is a random variable which follows the log-normal distribution.

t_0 : Time until progressive pitting points are generated. $t_0 = t_{\mathrm{g}} + t_{\mathrm{r}}$

These processes can be graphically represented as shown in Fig. 1. The parameters of the probabilistic models for Phase I to Phase III are estimated from thickness measurement data by the maximum likelihood estimation method in order to calculate corrosion diminution statistically.

Table 1 Rules related to corrosion environment and maintenance

Title of Rules	Effective since	Published by	Effect on corrosion environment or maintenance
MARPOL	1983	IMO	Corrosion condition of cargo oil tanks improved remarkably as a result of the installation of segregated ballast tanks.
ESP	1996	IMO	Condition monitoring by thickness measurement, coating condition inspection, and improvement of the corrosion condition of hull structures by early-stage maintenance.
IACS UR Z7 (Rev.5)	1998	IACS	
PSPC (WBT) PSPC (COT)	2008 2013	IMO	Improved coating quality in ballast tanks and cargo oil tanks.
Guidelines for Structural Strength	2001 2002	NK	Structural integrity maintained by the net scantling approach against corrosion diminution during design life.
CSR-BC, CSR-OT	2006	IACS	
CSR-BC&OT	2015	IACS	

Table 2 Judgment criteria of coatings

Rating	Judgment criteria
GOOD	Condition with only minor spot rusting. More specifically, condition with spot rusting on less than 3% of the area under consideration without visible failure of coating and rusting at edge or welds, must be on less than 20% of edges or weld lines in the area under consideration.
FAIR	Condition with visible failure of coating at edge or welds, and thin rust over 20% or more of the area under consideration; a condition better than POOR.
POOR	Condition with breakdown of coating on more than 20% of the area under consideration and hard rust scale on more than 10% of the area under consideration.

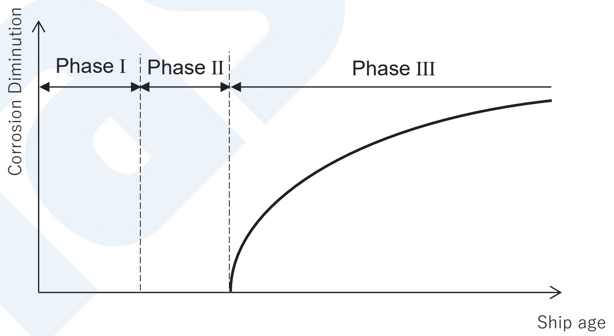

Fig. 1 Consecutive processes of corrosion generation and progress

4. THICKNESS MEASUREMENT DATA

In order to estimate corrosion diminution, it is necessary to collect thickness measurement data. For the present report, the conditions below were set so as to collect as much data as possible from ships commissioned after the ESP or UR Z7 (Rev. 5) came into effect. The thickness measurement data were collected from a total of 211 866 locations on 285 ships. The collected thickness measurement data were obtained during periodical surveys of ships registered to the Society.

- Ships 90 m or more in length (ships subject to Part C of the Rules for the Survey and Construction of Steel Ships)
- Ships classed by the Society since the time of new construction
- Ships subjected to periodical surveys on or after January 1, 2004
- Ships aged 14 years or older at the time of the survey

- Thickness measurement data taken at hull transverse sections

Fig. 2 shows the distribution of ships subject to thickness measurement data collection by year of build. The distribution reveals that much of the data was collected from ships built after the ESP or UR Z7 (Rev. 5) came into effect. No data from ships subject to the PSPC are included because none of the ships had been in service for 14 years or more since the effective date of the PSPC at the time of data collection.

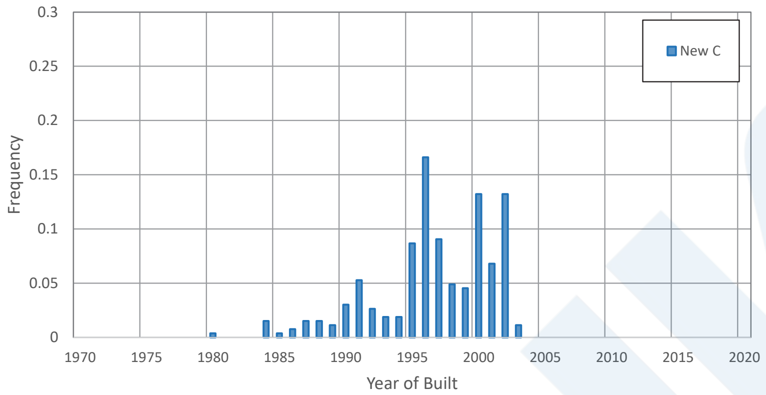

Fig. 2 Built years of ships whose thickness measurement data were collected

5. CORROSION DIMINUTION ESTIMATION RESULTS

Corrosion diminution estimations were made using the approach presented in Section 3 and the thickness measurement data collected as described in Section 4. In principle, corrosion diminutions were estimated for each combination of corrosion environments. More specifically, although the typical plates forming the boundary between a ballast environment and a seawater environment include bottom shell plates and side shell plates, these plates were handled as a single combination of corrosion environments without distinguishing each member type. However, this was not applied where the corrosion diminution of the members differed significantly even under the same combination of corrosion environments. For example, in the case members forming the boundary between a cargo hold environment and a ballast environment, the inner bottom plates were handled separately from the other members.

As examples of the estimated corrosion diminution values, Figs. 3, 5 and 7 respectively show the values for members of which both sides are exposed to ballast environments; members between a cargo hold of a chip carrier, general cargo ship or tanker and seawater environments; and members of which both sides are exposed to cargo holds of a chip carrier, general cargo ship or tanker. In these graphs, the horizontal axis is the number of years elapsed, the vertical axis is corrosion diminution, the black dots represent the values of the corrosion diminutions obtained from the thickness measurement data, the red dots represent the mean corrosion diminution by the number of years elapsed and the colored curves represent the values corresponding to the cumulative probabilities for corrosion diminution, corresponding to 50%, 75%, 90%, 95% and mean value, respectively.

In the present report, the values corresponding to the cumulative probability of 90% at the elapsed time of 25 years were used to determine the corrosion additions. This approach is the same as that used in the CSR. The values corresponding to the cumulative probability of 90% at the elapsed time of 25 years were 0.61 mm for members of which both sides are exposed to ballast environments and 0.84 mm for members between a cargo hold of a chip carrier, general cargo ship or tanker and a seawater environment. Many of the members for which the thickness measurement data were collected appear to have a corrosion diminution exceeding the value corresponding to the cumulative probability of 90%. However, a closer look at the corrosion diminution histograms shown in Figs. 4, 6 and 8 for the thickness measurement data reveals that the occurrence frequency of data indicating significant corrosion damage is close to zero. Table 3 shows some of the corrosion environment combinations considered in the present report and the corresponding 90% cumulative probability values at the elapsed time of 25 years.

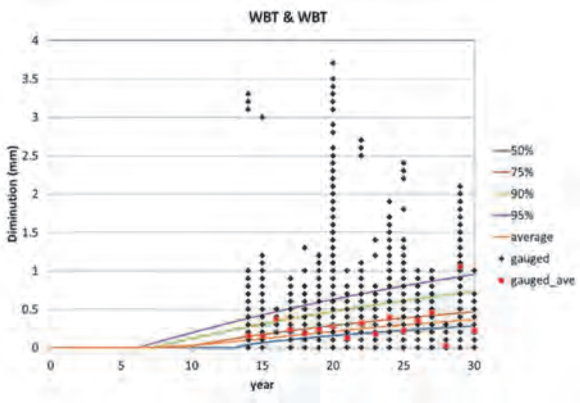

Fig. 3　Estimated corrosion diminution of members of which both sides are exposed to ballast environments

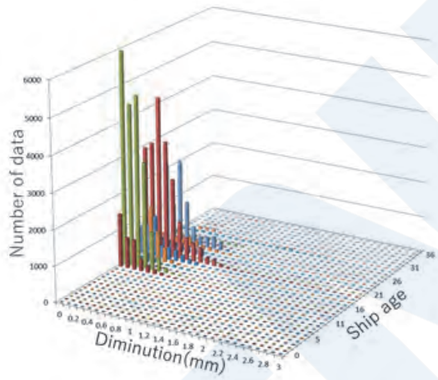

Fig. 4　Histogram of thickness measurement data of members of which both sides are exposed to ballast environments

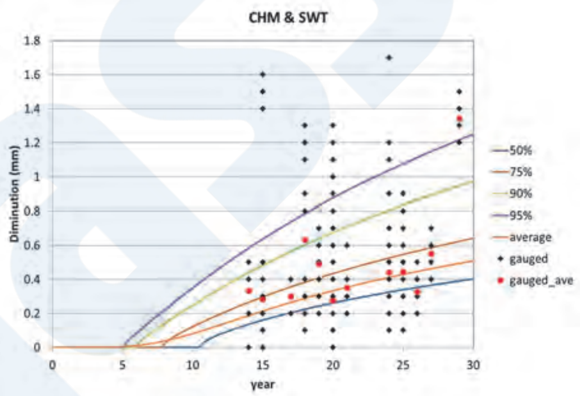

Fig. 5　Estimation of corrosion diminution of boundary members between cargo holds and seawater of chip carriers, general cargo ships and tankers

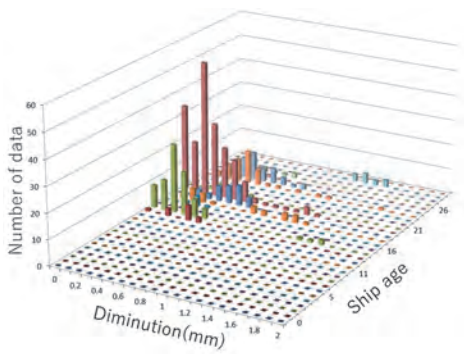

Fig. 6　Histogram of thickness measurement data of boundary members between cargo holds and seawater of chip carriers, general cargo ships and tankers

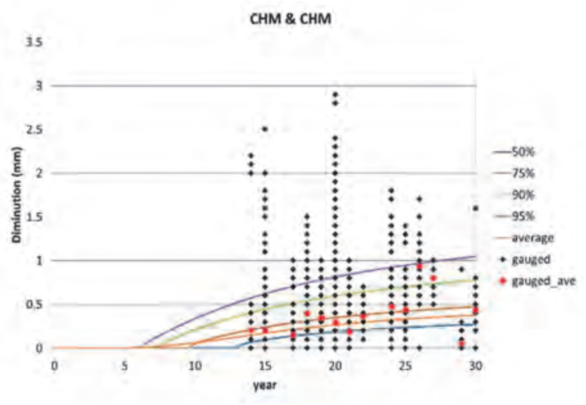

Fig. 7　Estimation of corrosion diminution of members of which both sides are exposed to cargo holds of chip carriers, general cargo ships and tankers

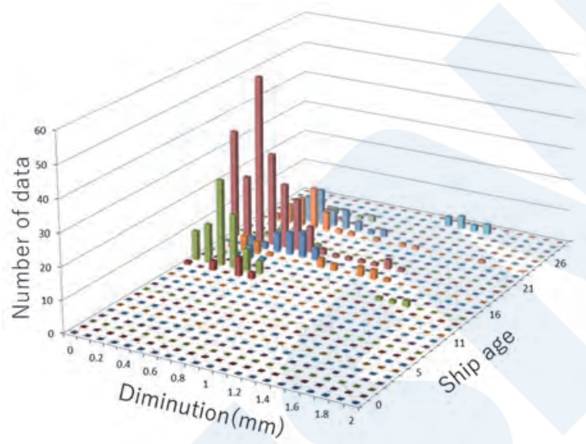

Fig. 8　Histogram of thickness measurement data of members of which both sides are exposed to cargo holds of chip carriers, general cargo ships and tankers

Table 3 Examples of estimated corrosion diminution corresponding to the 90% cumulative probability after 25 years passed for each combination of corrosion environments

Combination of corrosion environments		Corrosion diminution(mm)
Atmospheric environment (high temperature)	Ballast environment	0.67
	Low-temperature cargo hold	0.59
	Cargo hold (other)	1.08
Atmospheric environment (other than high temperature)	Atmospheric environment (other than high temperature)	0.71
	Ballast environment	0.45
	Low-temperature cargo hold	0.46
	Cargo hold (other)	0.68
Fuel oil tank	Fuel oil tank	0.52
	Seawater environment	0.57
	Ballast environment	0.81
Seawater environment	Void environment	0.65
	Ballast environment	0.53
	Cargo hold (other)	0.84
Ballast environment	Ballast environment	0.61
	Cargo hold (other)	0.53
Cargo hold (other)	Cargo hold (other)	0.70
PCC cargo hold	PCC cargo hold	0.45
Ordinary temperature Type C cargo hold	Ordinary temperature Type C cargo hold	0.46
Inner bottom plating in cargo hold (bulk carrier)	Ballast environment	4.20
Inner bottom plating in cargo hold (chip carrier)	Fuel oil tank	4.05
	Ballast environment	3.94
Inner bottom plating in cargo hold (general cargo ship)	Fuel oil tank	3.26
	Ballast environment	3.24
Inner bottom plating in cargo hold (tanker)	Ballast environment	0.47

"Cargo hold (other)" refers to cargo holds of chip carriers, general cargo ships and tankers.

6. CORROSION ADDITIONS

The corrosion addition t_c (mm) is obtained from Eq. (4):

$$t_c = Roundup_{0.5}(t_{c1} + t_{c2}) + t_{res} \qquad (4)$$

where t_{c1} and t_{c2} are the one-side corrosion additions, t_{res} is fixed to 0.5 mm considering the corrosion diminution during the survey interval and *Roundup* means that the value is to be rounded up to the nearest 0.5 mm increment.

The one-side corrosion additions t_{c1} and t_{c2} are derived from the estimated corrosion diminution value for the applicable environment combination found above in Section 5. The derivation of the one-side corrosion additions set as t_{c1} and t_{c2} is conservative to prevent their sum from falling short of the value for the applicable corrosion environment combination in Table 3. The corrosion additions determined herein have been included as specifications in the fully revised version of Part C of the Rules for the Survey and Construction of Steel Ships (hereinafter "New Part C"); their numerical values are presented in Appendix 1. For some members such as chain lockers, it was not possible to collect a sufficient amount of thickness measurement data. The corrosion additions for those members were set referring to the values and approaches conventionally considered in Part C of the ClassNK Rules for the Survey and Construction of Steel Ships or CSR.

7. COMPARISON WITH CORROSION ADDITIONS SPECIFIED IN CSR

The corrosion additions specified in the CSR are also based on the corrosion diminution estimation method discussed in Section 3. Table 4 shows the results of a comparison of the one-side corrosion additions provided in the CSR and New Part C for typical compartments.

Table 4 reveals that, for most of the corrosion environments, the corrosion additions in New Part C are smaller than those in the CSR. For example, whereas the value specified in the CSR for ballast environments is 1.2 mm, the corresponding value in New Part C is 0.5 mm.

The distribution by year of build of the ships subject to thickness measurement data collection for the present report is as shown in Fig. 2. The ships subject to thickness measurement data collection to define the corrosion additions in the CSR were ships built before the effective dates of the ESP and UR Z7 (Rev. 5). Accordingly, it is thought that the improved coating performance of the ships and the improved degree of maintenance resulting from the changes in the applicable rules are factors in the smaller corrosion additions obtained herein in comparison with those specified in the CSR. Moreover, improvements in coating technology per se are also considered to have been a contributory factor.

For inner bottom plating in bulk carriers, no difference was observed in the results of the comparison between the CSR and New Part C. This may be due to the fact that it is difficult to improve the coating condition of this component, since it is expected to be subject to mechanical damage and the corrosion phenomenon is different from the original corrosion phenomenon.

Table 4 Comparison of one-side corrosion additions in CSR and new structural rules (New Part C)

Compartment type	One-side corrosion addition per CSR	One-side corrosion addition per New Part C
Ballast tank	1.2 mm	0.5 mm
Bulk cargo hold (hopper sloping plating, inner bottom plating)	3.7 mm	3.7 mm
Exposed to atmosphere (exposed deck plating)	1.7 mm	0.6 mm
Exposed to seawater (near draught waterline)	1.5 mm	1.0 mm
Fuel oil tank	0.7 mm	0.5 mm
Fresh water tank	0.7 mm	0.5 mm
Void space	0.7 mm	0.5 mm
Dry space	0.5 mm	0.5 mm

8. CONCLUSION

For the present report, corrosion diminution estimations were made based mainly on thickness measurement data from ships built after the ESP came into effect in 1996. The results of those estimations were used to specify the corrosion additions for various corrosion environments. A comparison of the corrosion additions specified herein with those specified in the CSR revealed that the values specified herein are smaller than the CSR values for most of the corrosion environments considered. However, the corrosion addition for inner bottom plating in bulk carriers obtained here was the same as in the CSR. The likely factors in the smaller corrosion additions obtained herein in comparison with those specified in the CSR include improvements in the as-built coating performance, corrosion environments for ships in service and the degree of maintenance as a result of amendments of the rules applicable to ships.

It should be noted that the corrosion additions determined herein do not include the effects of the PSPC. We will conduct a similar study to establish corrosion additions for ballast tanks and cargo oil tanks subject to the PSPC after ships subject to the

PSPC complete their third periodical survey and sufficient thickness measurement data are collected.

The corrosion additions obtained herein have been adopted in the fully revised version of Part C of the Rules for the Survey and Construction of Steel Ships. These corrosion additions are expected to be of assistance in carrying out more rational structural strength assessments.

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APPENDIX

Corrosion addition specified in the new structural rules (new Part C) of ClassNK

Appendix 1 Corrosion additions specified in the new structural rules (New Part C) of ClassNK

Type of Compartment	Details		t_{c1} or t_{c2} (mm)
Ballast tank, bilge tank, drain storage tank, chain locker(Note 1)	Within 3 m vertically below the top plate of the tank(Note 2)		1.0
	Elsewhere		0.5
Cargo hold or cargo tank	Container carriers	Inner bottom plating	1.5
		Elsewhere	0.5
	Dry bulk cargo holds (bulk carriers, ore carriers, etc.) (Note 3)	Inner bottom plating and hopper sloping plating(Note 4)	3.7
		Lower stools slopting plate and vertical plating	1.6
		Transverse and longitudinal bulkheads(Note 5)	1.0
		Other	1.0
	Wood Chip carriers	Inner bottom plating, sloping plating, and vertical plating of hopper and lower stool parts	3.5
		Elsewhere	0.7
	General cargo ships	Inner bottom plating	3.0
		Elsewhere	0.7
	Low-temperature cargo holds (refrigerated cargo ships)		0.5
	Void cargo hold spaces (car carriers)		0.5
	Tankers(Note 6)		0.7
	Hold spaces containing a high temperature cargo tank (for asphalt and the like)		0.5
	Independent tanks for high temperature cargo (for asphalt and the like)		0.7
	Hold spaces containing an independent tank for low temperature cargo (liquefied gas carriers equipped with independent tanks)		0
	Independent prismatic low temperature cargo tanks (liquefied gas carriers equipped with independent prismatic tanks)		0
	Hold spaces of Type C tank liquefied gas carriers (ordinary temperature)		0.5
	Hold spaces of Type C tank liquefied gas carriers (low temperature)		0
	Hold spaces of liquefied gas carriers with membrane tanks		0
	Other cargo holds (including those of ships equipped with a self-unloader(s) in the cargo holds of dedicated cement carriers, etc.)		0.7
Atmospheric exposure	Exposed deck plating		0.6
	Other members		0.5
Seawater exposure	Shell plating between the minimum design ballast draught waterline and the scantling draught waterline		1.0
	Other members		0.5
Fuel oil tank(Note 7) and lube oil tank			0.5
Freshwater tank			0.5
Void spaces(Note 8) and dry spaces(Note 9) (Note 10)			0.5
Accommodation spaces			0
Other than the above			0.5

(Notes)

(1) 1.0 mm is to be added to the plate surface within 3 m vertically above the upper surface of the chain locker bottom.

(2) Only applicable to tanks with an exposed deck as the tank top. The 3 m distance is to be measured vertically from and parallel to the top of the tank. Bilge tanks, drain storage tanks and chain lockers are to be taken as "Elsewhere."

(3) Dry bulk cargo holds include holds intended for the carriage of dry bulk cargoes.

(4) For ore carriers, only applicable to the range within 3 mm vertically above the inner bottom plating. To be taken as 1.0 mm if more than 3 m vertically above the inner bottom plating.

(5) 0.2 mm is to be added to plates used for bulkheads within 3 mm vertically above the inner bottom plating.

(6) 2.0 mm is to be added to the inner bottom plating and suction well in the vicinity of a suction bellmouth within a radius of approximately one longitudinal space from the outer periphery of the suction bellmouth (See Figs. 3.3.4-1 and 3.3.4-2).

(7) For compartments containing a gas fuel tank, the corrosion additions for the hold spaces of the same types of liquefied gas carriers are to be applied.

(8) Void spaces refer to spaces accessible only via bolted manhole openings or spaces not normally accessed, such as pipe tunnels. The internal spaces of pillars with a closed profile are also included.

(9) Dry spaces refer to the internals of machinery spaces, pump rooms, store rooms, steering gear spaces, etc.

(10) 2.0 mm is to be added to the inner bottom plating of the main engine room except if the corrosion protection is carried out with approval by the Society based on prior submitted data.

Evaluation of the Ship Operational Effect Based on Actually Encountered Sea States by Ships

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1. INTRODUCTION

Since ships are operated from various perspectives that include security of lives and hull structural safety, prevention of cargo collapse, protection of the machinery and equipment and energy-saving operation, it is essential to ensure accurate assessment of the actually encountered sea states by ships. Numerous studies have examined the actual tendencies of ship operation in service and the ship operational effect on hull structural strength.[1)-5)] Although the current Classification Rules already take the ship operational effect into consideration implicitly, more rational technical background is required based on the accurate data of the actually encountered sea states.

In recent years, the automatic identification system (AIS) has made it possible to obtain the data of global ship position and timestamp information, while the wave data in ocean can be obtained from wave hindcast. Therefore, the wave data corresponding to the ship position and timestamp information enables the evaluation of the actually encountered sea states by ships. Our previous studies performed a quantitative evaluation of the ship operational effect on roll motion, vertical bending moment amidships and hydrodynamic pressure at the bottom centerline amidships based on the actually encountered sea states in the North Atlantic used AIS data and wave hindcast for a period of 2 years and 11 months to those based only on the natural sea states in the North Atlantic.[6) 7)]

For the Society to complete the comprehensively revision of Part C of the Rules for the Survey and Construction of Steel Ships related to hull structures, it was essential to perform a quantitative evaluation of the ship operational effect regarding to the wave scatter diagram in the North Atlantic Areas in the recommendation No. 34 (hereinafter “IACS Rec. No. 34”)[8)] specified by the International Association of Classification Societies (IACS).

The present study conducted a quantitative evaluation of the ship operational effect on ship motions (heave, roll, pitch) and wave loads (vertical wave bending moment amidships and hydrodynamic pressures at the bottom centerline and waterline amidships) by using of the wave scatter diagrams based on the actually encountered sea states by merchant ships such as bulk carriers, oil tankers and container ships navigating in the North Atlantic and the IACS Rec. No. 34.

2. AIS DATA AND WAVE DATA

The present study was carried out using AIS data from Vessel Tracker.[9)] The AIS data were obtained via satellites and onshore base stations and allowed extraction of the position and timestamp information of the desired ships. Table 1 shows the outline of the AIS data. The AIS dataset used in the study covered a total of 8,456 ships (4,509 bulk carriers, 1,875 oil tankers and 2,072 container ships) that navigated in the North Atlantic during a period of 2 years and 11 months (January 2014 and January 2015 to October 2017). Note that January 2014 was the month when the North Atlantic experienced the most severe sea states during the 25 years period from 1994 to 2018.[10)] In the present study, the AIS data at 0 knots ship speed were excluded, and the AIS data for irregular time intervals were thinned out to an interval of 1 hour.

The wave hindcast from the ERA5 (ECMWF)[11)] and IOWAGA (IFREMER)[12)] datasets were used in this study. Table 2 shows the outline of these wave hindcast. The navigation areas selected for the present study were the same areas used in the IACS Rec. No. 34 shown in Fig. 1 (GWS Areas 8, 9, 15, 16). Both the wave hindcast datasets were validated by comparison with the measured data from buoys and satellites.[10)] Here, the AIS data thinned out to one-hour intervals mentioned above were corresponding to the sea state based on wave hindcast at the nearest timestamp points in the 30 minutes before and after the AIS data. Then, the sea state corresponding to the AIS data is considered as a one-hour-long short-term sea state in this study to be used to constitute the wave scatter diagram with ship operational effect.

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Table 1 Outline of AIS data

Time period	January 2014 and January 2015 through October 2017
Navigation area	GWS Areas 8, 9, 15, 16 (North Atlantic)
Number of ships	8,456 (Bulk carriers: 4,509 / Oil tankers: 1,875 / Container ships: 2,072)

Table 2 Outline of wave hindcast

Data set	ERA5	IOWAGA
Organization	ECMWF	IFREMER
Spatial resolution	0.36 deg	0.5 deg
Time step	1 h	3 h
Wave model	ECWAM	WW3-st4
Wind forcing	Coupled model	NCEP-CFSR

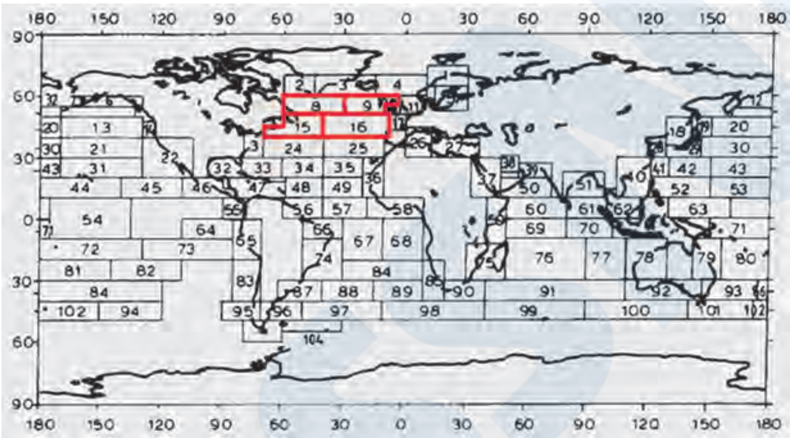

Fig. 1 Definition of the extent of the North Atlantic in IACS Rec. No. 34

3. QUANTITATIVE EVALUATION OF SHIP OPERATIONAL EFFECT

The following steps show the procedure for evaluating the ship operational effect considering the significant wave heights and wave periods actually encountered by ships[6) 7)]:

1) Prepare the following wave scatter diagrams:
   (A) Wave scatter diagrams with ship operational effect (based on AIS data and wave hindcast) respectively for ERA5 and IOWAGA
   (B) IACS Rec. No. 34
2) Use the wave scatter diagrams mentioned above in 1) to calculate the long-term prediction values at the probability level 10^{-8} for heave, roll, pitch, vertical wave bending moment amidships (VBM), hydrodynamic pressure at the bottom centerline amidships (Pcl) and hydrodynamic pressure at the waterline amidship (Pwl) by a linear strip method. As an example, Fig. 2 shows the exceedance probability distributions of long-term prediction of vertical wave bending moment amidships (VBM) for a Panamax bulk carrier.
3) The ship operational effect $F_{op\_rec.No.34}$ as the ratio of the long-term prediction value at the probability level 10^{-8} based on the scatter diagram with ship operational effect respectively for ERA5 or IOWAGA to that based on the IACS Rec. No. 34 was calculate by the following formula:

$$F_{op\_rec.No.34} = \frac{long-term\ \ prediction\ \ at\ \ 10^{-8}\ (with\ \ ship\ \ operational\ \ effect)(\mathrm{A})}{long-term\ \ prediction\ \ at\ \ 10^{-8}\ (\mathrm{IACS\ \ Rec.No.34})(\mathrm{B})}$$

Table 3 shows the outline of targeted ships (22 bulk carriers, 27 oil tankers and 26 container ships) used in a series of calculations, while Table 4 shows the analysis conditions for the long-term predictions. It should be noted that the targeted ships in Table 3 are different from the ships with the AIS data in Table 1.

Fig. 3 shows the statistics (mean value ± 2 standard deviations) of $F_{op\_rec.No.34}$, while Fig. 4 to Fig. 9 show the ship operational effect $F_{op\_rec.No.34}$ of heave, pitch, roll, VBM, Pcl and Pwl regarding ship lengths for both the wave hindcasts ERA5 and IOWAGA regardless of the ship types. The range of the mean value ± 2 standard deviations of $F_{op\_rec.No.34}$ shown in Fig. 3 is from 0.75 to 0.84. From Fig. 4 to Fig. 9, the significant variation could not be confirmed in $F_{op\_rec.No.34}$ for the different wave hindcasts, different ship lengths and different ship types used in the series of calculations.

Table 3 Outline of targeted ships used in the series of calculations

Ship type	Bulk carrier	Oil tanker	Container ship
Ship length [m]	110 to 285	110 to 320	110 to 350
Number of ships	22	27	26
Loading condition	Full load		

Table 4 Analysis conditions for the long-term predictions

Program	Linear strip method
Parameters	Heave, Roll*, Pitch, Vertical bending moment amidships (VBM), Hydrodynamic pressure at bottom centerline amidships (Pcl), Hydrodynamic pressure at water line amidships (Pwl)
Ship speed	5 knots
Wave direction	All headings

*Excluding container ships

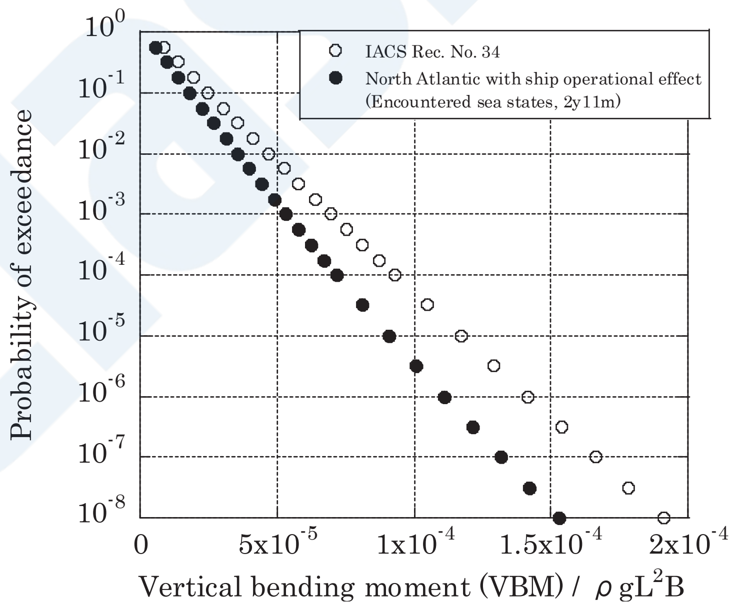

Fig. 2 Example of the exceedance probability distributions of long-term prediction of vertical wave bending moment amidships (VBM) based on the wave scatter diagram with the ship operational effect (ERA5) and IACS Rec. No. 34

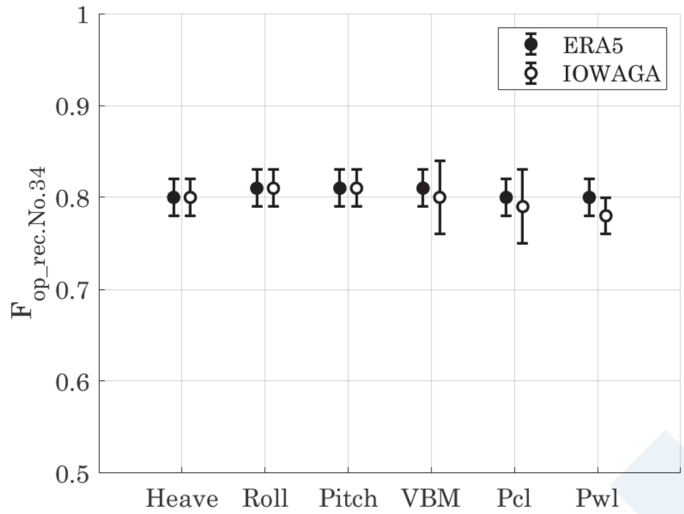

Fig. 3　Summary of the ship operational effect $F_{op\_rec.No.34}$ for heave, roll, pitch, VBM, Pcl and Pwl depending on each wave hindcast

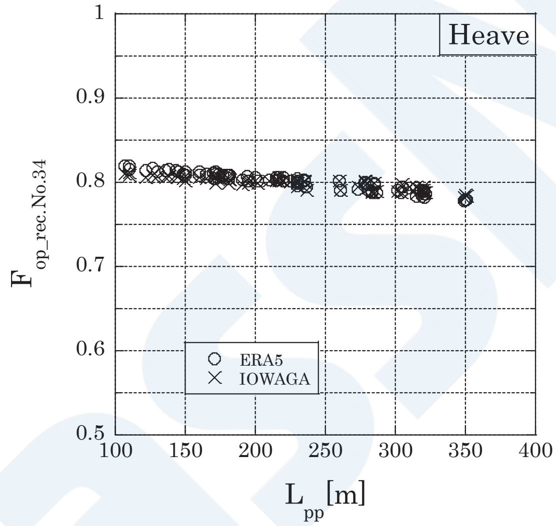

Fig. 4　Ship operational effect $F_{op\_rec.No.34}$ of heave depending on ship length

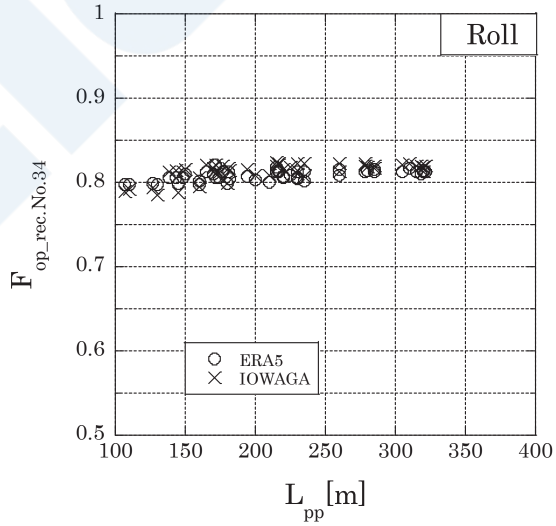

Fig. 5　Ship operational effect $F_{op\_rec.No.34}$ of roll depending on ship length

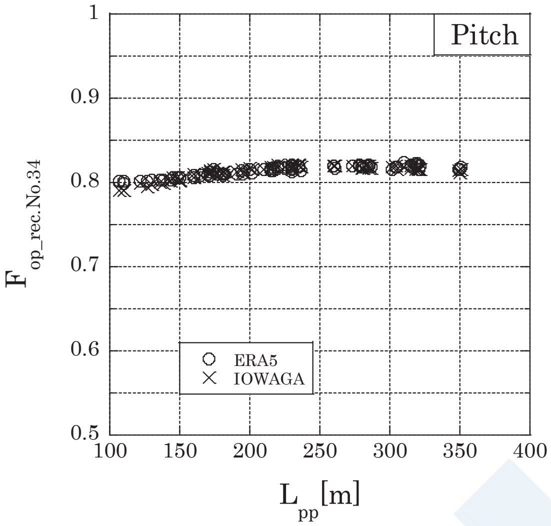

Fig. 6　Ship operational effect $F_{op\_rec.No.34}$ of pitch depending on ship length

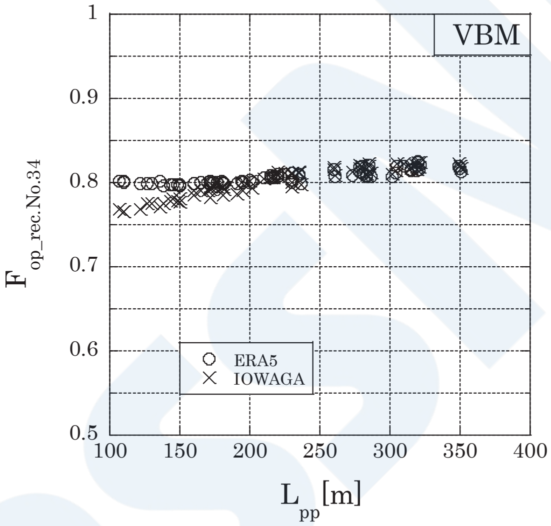

Fig. 7　Ship operational effect $F_{op\_rec.No.34}$ of vertical wave bending moment amidships (VBM) depending on ship length

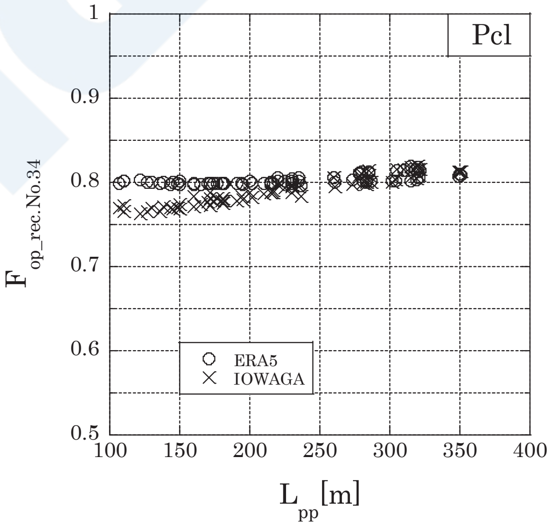

Fig. 8　Ship operational effect $F_{op\_rec.No.34}$ of hydrodynamic pressure at bottom centerline amidships (Pcl) depending on ship length

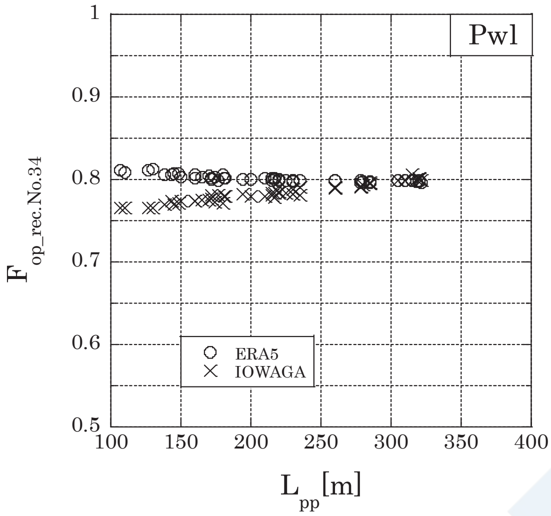

Fig. 9 Ship operational effect $F_{op\_rec.No.34}$ of hydrodynamic pressure at waterline amidships (Pwl) depending on ship length

4. CONCLUSION

In the present study, the authors performed a quantitative evaluation of the ship operational effect which is a gap between the wave scatter diagram constituted by the actually encountered sea states in the North Atlantic Areas by merchant ships and the wave scatter diagram in the IACS Rec. No. 34 in order to contribute to the comprehensively revision of Part C of the Rules for the Survey and Construction of Steel Ships related to hull structures. Considering the actually encountered sea states by merchant ships (bulk carriers, oil tankers and container ships) in the North Atlantic, we performed a quantitative evaluation of the ship operational effect for heave, roll, pitch, vertical wave bending moment amidships (VBM), hydrodynamic pressures at bottom centerline amidships (Pcl) and hydrodynamic pressures at waterline amidships (Pwl). The following conclusions were obtained:

1) The range of mean value ± 2 standard deviations for the ship operational effect $F_{op\_rec.No.34}$ based on the IACS Rec. No. 34 is from 0.75 to 0.84.
2) The significant variation could not be confirmed in $F_{op\_rec.No.34}$ for the different wave hindcasts, different ship lengths and different ship types used in the series of calculations.

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CBM Life Cycle Maintenance

— Marine Equipment Condition Monitoring and Evaluation Technologies —

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1. INTRODUCTION

IACS Unified Requirement (hereinafter, UR) Z27 specifies the scheme for certification of Condition Based Maintenance (hereinafter, CBM), and it is implemented uniformly in IACS from January 2020. In line with this UR, ClassNK also began full-scale promotion of CBM certification. Because CBM technologies enable remote monitoring, assessment and prediction, these technologies are needed in fields with a high demand for automation. The benefits of application CBM to can be summarized as follows:

1) Optimization of maintenance
   Monitoring of the degree of deterioration makes it possible to identify locations that require maintenance, thereby leading to reductions in the burden and cost of surveys.
2) Rationalization of surveys
   Some parts may last longer than the predetermined survey interval, while others may develop abnormalities before the next surveys. Stable survey that is according to the operating condition of each equipment can be achieved by CBM.
3) Standardization of surveys
   Because surveys tend to depend on the experience of surveyors, variations in survey accuracy may occur. Standardization of evaluation techniques based on quality-assured sensor data can easily enable uniform survey comparable to that of skilled surveyor.

However, while CBM practices provide the above benefits, challenges also remain:

1) Initial and running costs
   Installation of sensors and analysis instruments increases the initial cost, and the cost of maintaining that equipment also increases. In particular, monitoring via ship-shore communication requires consideration of additional cost, like communication costs and monitoring cost etc.
2) Reliability of measured values and analysis methods
   Without application at appropriate locations within the range in which sensor accuracy is guaranteed, the results will lack reliability. Therefore, appropriate measurement method and an analysis method for the measurement results are essential.
3) Acquisition of judgment criteria
   Seafarers and surveyors must possess the knowledge to identify data configurations that are judged to be anomalous and determine whether survey is necessary or not.

Because CBM is positioned as an important step toward developing advanced automated and autonomous ships in the future, advancement of onboard data accumulation technologies and technologies related to sensor accuracy is foreseen. Accordingly, the NK Research Institute also expects a further expansion of CBM applicable ships, and will proceed to develop rational equipment monitoring and analysis methods and revise and establish the relevant rules.

2. CBM RULES OF ClassNK

In adoption of CBM for marine equipment, the open-up examinations in Table 1 can be performed based on the CBM Scheme upon application by the shipowner (ship management company) and approval by ClassNK:

* MTI Co., Ltd.
** Japan Engine Corporation
*** Research Institute, ClassNK

Table 1 Open-up Surveys of Machinery and Equipment

Items	Examinations
1. Reciprocating internal combustion engines	- Cylinder covers, cylinder liners, pistons, crosshead pins and bearings, connecting rods, crank pins and bearings, crank journals and bearings, camshafts and camshaft driving gears, turbo chargers, scavenge air pumps or blowers, air intercoolers, attached essential pumps
2. Steam turbines	- Turbine rotors together with bearings, turbine casing, turbine and reduction gear couplings, nozzle valves and maneuvering valves
3. Power transmission systems and shafting systems	- Reduction gears, reversing gears, clutch gears, flexible couplings, intermediate shafts, thrust shafts and their bearings
4. Auxiliary engines	- Auxiliary engines driving generators, auxiliary machinery essential for main propulsion and auxiliary machinery for manoeuvring and personnel safety
5. Water jet propulsion systems	- Hydraulic pumps for steering actuating systems, lubricating oil pumps, coolers, etc.
6. Azimuth thrusters	- Gears, gear shafts, shaft couplings, bearings and clutches for propulsion and for steering, hydraulic pumps and hydraulic motors, lubricating oil pumps, coolers, etc.
7. Auxiliary machinery	- Air compressors, blowers, cooling pumps, fuel oil pumps, lubricating oil pumps feed pumps, condensing pumps, drain pumps, bilge pumps, ballast pumps, fire pumps, condensers, feed water heaters, coolers, oil heaters, fuel oil tanks, air reservoirs, cargo piping systems, deck machinery, distilling plants, etc.

Application of CBM is possible to an overall equipment basis or an individual part basis. The final decision on adoption is made based on factors including administrative costs, the degree of burden on seafarers and technological potential. ClassNK has also established PROCEDURES FOR THE APPROVAL OF PMS/CBM MANAGEMENT SOFTWARE (Annex B9.1.3-4). In 1.3.3-1(3), Annex B9.1.3-4, these Procedures require that measurement data trends and limit values be exhibited for diagnosis of operating conditions to ensure equipment safety. However, determining condition anomalies is extremely difficult given the complicated parameters involved, such as engine load and performance, weather conditions and other external factors and fuel properties. Accordingly, the key points for implementation of CBM include efforts to pursue reliability, data accumulation and effective use to suit anomaly detection technologies developed by the equipment manufacturers and corporate shipowners (ship management companies) concerned.

3. ABOUT THE PRESENT STUDY

The present study is joint research conducted on the basis of the above items by a corporate shipowner, an equipment manufacturer and a classification society aiming at “damage assessment by main bearing Lubricating Oil (hereinafter, LO) outlet temperature monitoring” toward CBM implementation. The results have been incorporated in ClassNK’s CBM Guidelines (Ver. 2.0).

In this study, we grasped where and how failure occur in ship’s main engine plants, what effects failure have, and what to do on the ship to prevent that, and a risk assessment method was used to examine alternative methods that conventional methods are replaced by the data monitoring methods. This risk assessment method uses Fault Tree Analysis (FTA) to analyze the causes of failure and to determine the parameters that can be measured the actual condition. As the results of the risk assessment, a method to monitor the main bearing LO outlet temperature was selected for the main engine main bearing to which the CBM method is applied in this study.

We also evaluated the feasibility of identifying bearing damage by monitoring the main bearing LO outlet temperature. In addition, whether the damage can be properly identified using measured actual ship data was also examined. In order to verify the validity of the technique, a land-based test was conducted to simulate the installation conditions, and the feasibility of CBM application was examined.

3.1 Actual Ship Onboard Monitoring

A temperature measuring resistor was installed through the base saddle as shown in the as-installed view in Fig. 1 to collect the main bearing LO outlet temperature as continuous data on a real ship and investigate the effectiveness of the data analysis technique.

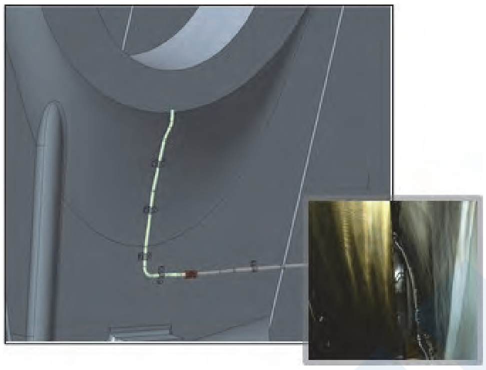

Fig. 1 View as-installed on real ship

The following Fig. 2 shows the main bearing LO outlet temperatures measured in December 2019 (vertical axis = temperature [°C]; horizontal axis = time [days]; black plot = main bearing No. 2; red plot = main bearing No. 4). In the portions enclosed in the circles, the corresponding temperatures were increased by adding +1 °C to the measured data. The possibility of instantaneous temperature rise was examined to verify the effectiveness of the analysis.

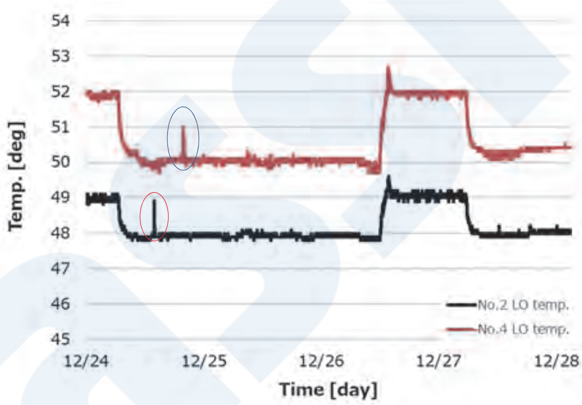

Fig. 2 LO outlet temperatures of main bearings No. 2 and No. 4 (December)

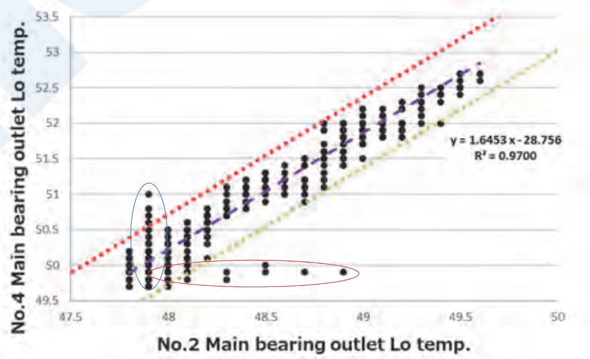

Fig. 3 Correlation plot chart for LO outlet temperatures of main bearings No. 2 and No. 4 (December)

As shown in Fig. 3, the main bearing LO outlet temperatures have an identical gradient. Therefore, when a correlation is taken between the outlet temperatures of main bearings No. 4 and No. 2, with the former and the latter on the vertical and horizontal axes, respectively, a regression line can be drawn as shown by the blue dashed line in the above figure. Most of the resultant data fall within the ± 0.5°C range defined by the parallel red and green dotted lines above and below the regression line. The plot portions encircled in red and blue in Figs. 2 and 3 show that the data for the instantaneous temperature rise in main bearing No. 2 spreads horizontally in the rightward direction, while the plot for instantaneous temperature rise in No. 4 extends vertically upward. This means that abnormal values can be judged clearly by setting a temperature range corresponding to this correlation. It is considered appropriate to check the raw measurement data in order to confirm the time of occurrence when using the analysis method presented above for anomaly determination.

Fig. 4 shows part of the measurement results obtained from main bearings No. 2 and No. 4 in June 2020 (vertical axis = temperature [°C]; horizontal axis = time [days]). The sensor for No. 4 malfunctioned, causing part of the continuous data to represent partial fluctuations.

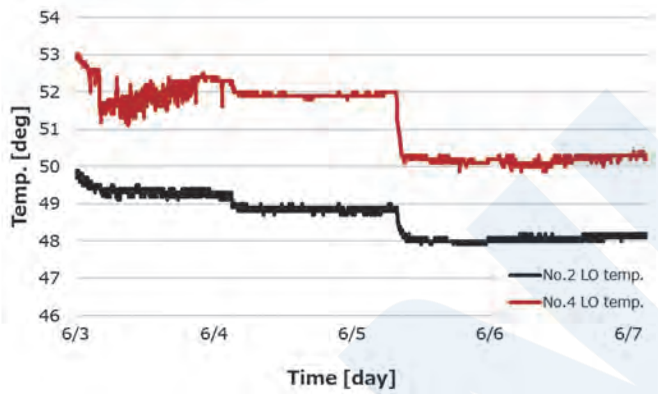

Fig. 4　LO outlet temperatures of main bearings No. 2 and No. 4 (June)

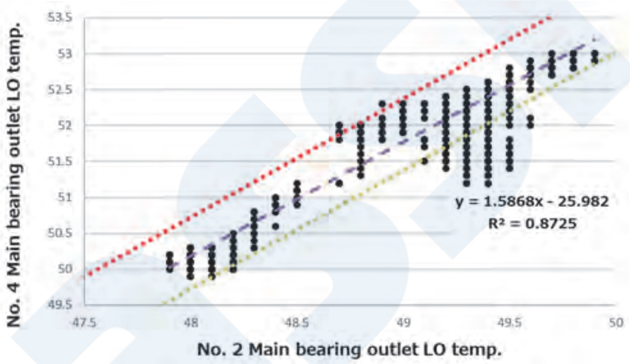

Fig. 5　Correlation plot chart for LO outlet temperatures of main bearings No. 2 and No. 4 (June)

Fig. 5 shows the results of a similar analysis for the situation in which fluctuation occurred in No. 4. Here, a cluster of data points falls outside the parallel lines representing the temperature range of ±0.5 °C. During the fluctuation phenomenon on the No. 4 bearing side, the No. 2 bearing side temperature changed slightly, causing some data to fall outside the ±0.5 °C range and spread horizontally. In this analytical approach, interpretation of the plotted data became more difficult as the number of data falling outside a set range increased. Hence, this approach is suitable for analyzing short-term measurement results and requires a concurrent raw data check.

3.2　Simulation Test

When adopting equipment condition monitoring, the effectiveness of the technology must be examined. In the present study, bearing damage modes were analyzed to investigate the effectiveness of bearing damage monitoring by bearing LO outlet temperature monitoring. Fig. 6 shows the wear modes of a slide bearing. After installation, a bearing is subjected to run-in for a better fit to the shape of the contact face. During this run-in period, the bearing becomes smoother while undergoing greater wear than during normal operation. During the subsequent normal operation, the bearing gradually wears under cyclic loads until it reaches the abnormal wear phase due to such factors as wear growth and absence of oil film, resulting in eventual burnout or breakage.

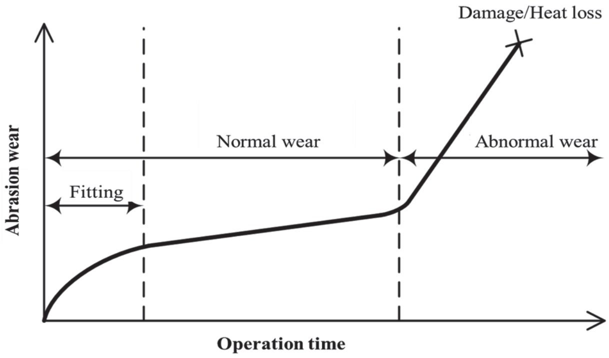

Fig. 6 Wear of slide bearing

In addition to the abnormal wear mentioned above, fatigue fracture also occurs in bearings. The main causes of fatigue fracture are excessive overall or local contact pressure on the bearing or excessive thinning of the oil film thickness, etc. In addition to the above-mentioned abnormal wear and fatigue fracture, other causes of bearing damage include corrosion due to the use of a lubricating oil with poor properties, and other forms of erosion such as cavitation and galvanic corrosion. However, since these other causes only account for a small portion of the causes of bearing damage, they are not included in the present study.

A simulation test assuming real onboard conditions was conducted to collect data on anomalies and investigate the correlation between the occurrence of anomalies and measured values. Fig. 7 shows the confirmation test results for seizure (vertical axis = temperature [°C]; horizontal axis = time [days]).

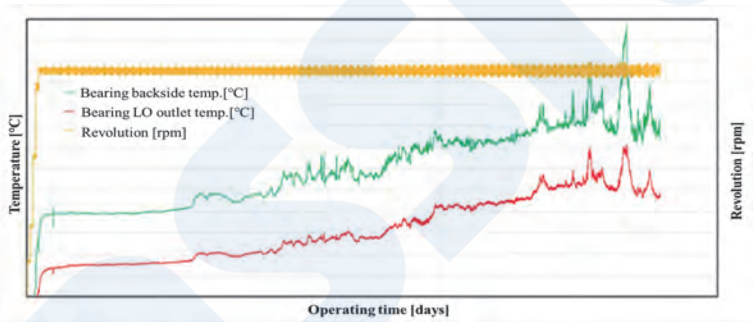

Fig. 7 Results of confirmation test for seizure

In a condition in which damage was caused intentionally by applying a high load and high rotation speed, the initial damage phase was detected by an increase in the LO outlet temperature. Subsequently, the LO outlet temperature rose at almost the same time as the bearing backside temperature increased, and after seizure occurred, more remarkable temperature changes were observed. Fig. 8 shows the appearance of the bearing surface after the completion of the test.

Fig. 8 Bearing metal surface after simulation test

A test was conducted under the same conditions to confirm the damage steps during the initial phase. After the initial-phase temperature rose, as in Fig. 9, the test was stopped and the specimen was checked.

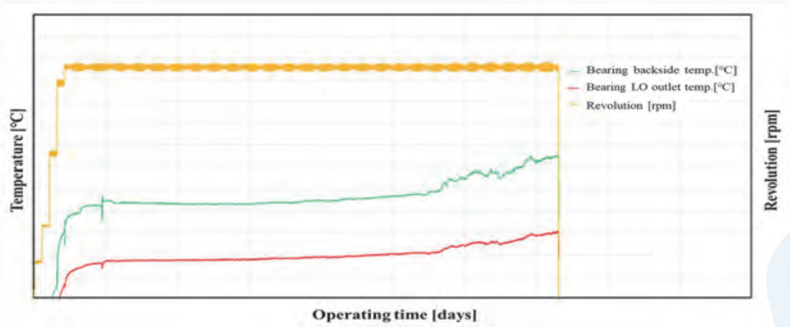

Fig. 9　Results of confirmation test for seizure

As a result, the damage shown in Fig. 10 was observed.

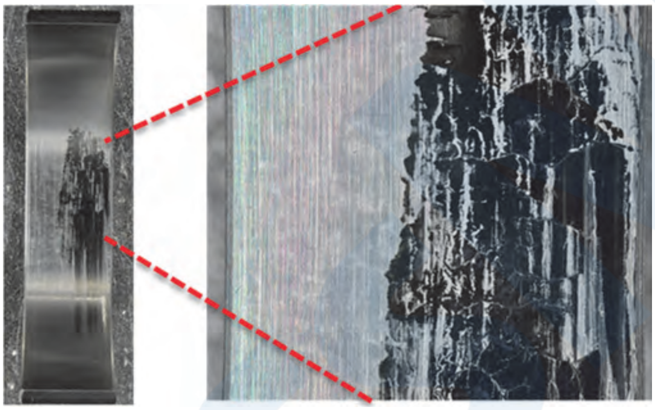
Fig. 10　Bearing metal surface after seizure confirmation test

Thus, this test demonstrated that the main bearing LO outlet temperature reflects the bearing metal temperature, as the outlet temperature gradually rose, and metal damage can be detected by monitoring the outlet temperature.

4.　CONCLUSION

The purpose of this study is to contribute to the industry with new efficient and reliable methods of CBM. The current CBM is still limited, as diagnostic technologies have not yet been established for many areas, and there will be stronger needs for pass/fail judgment by condition diagnosis at the level of individual equipment parts.

ClassNK provides validation of new survey techniques to facilitate smooth survey by condition anomaly monitoring. This paper presented a study of assessment of the damage of bearing metal by monitoring the main bearing LO outlet temperature. The results of an actual ship onboard test demonstrated the effectiveness of main bearing LO outlet temperature monitoring as a more accurate anomaly determination method through proper data analysis. In addition, the results of a simulation test showed that it is possible to understand the condition of bearing damage based on initial-phase anomaly conditions by main bearing LO outlet temperature monitoring.

Thus, this study confirmed that bearing damage monitoring is feasible by measurement, monitoring and analysis of main bearing LO outlet temperature.

We will continue exploring new CBM technologies and publish the progress of those efforts in order to contribute to the maritime industry as a whole.

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Recent Topics at IMO

— Outline of Discussion at IMO Committees —

Rule Development and ICT Division, External Affairs Department, ClassNK

1. INTRODUCTION

This article introduces recent topics discussed at International Maritime Organization (IMO). At the previous issue, a summary of the topics discussed at 76th Marine Environment Protection Committee (MEPC 76) held in June of 2021 was provided.

This article provides a summary of the decisions taken at 77th Marine Environment Protection Committee (MEPC 77) held from 22 to 26 November 2021 and 104th Maritime Safety Committee (MSC 104) held from 4 to 8 October 2021 as below.

2. OUTCOMES OF MEPC 77

2.1 Greenhouse Gases (GHG) Emission Reduction Measures

Measures to reduce GHG emissions from international shipping have been deliberated at IMO and the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP) and the Data Collection System for fuel oil consumption of ships (DCS) have been introduced so far. Further, the Initial IMO Strategy on reduction of GHG emissions from ships, was adopted at MEPC 72 held in 2018, which includes the emission reduction targets and candidate measures to reduce GHG emissions from maritime.

2.1.1 Short-Term Measures for Reduction of GHG

The initial IMO Strategy on the reduction of GHG emissions from ships specifies the short-term target by 2030 for improved transportation efficiency of at least 40% compared to 2008. To achieve the short-term target, at MEPC 76, the amendments to MARPOL Annex VI were adopted to implement Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) as well as the related Guidelines were also adopted. Further, a Correspondence Group (CG) was established for the implementation of CII framework to develop/update Guidelines on SEEMP and DCS, correction factors for certain ship types for the CII calculations.

An interim report of the CG was submitted at this session and followings were agreed. For finalization of the above-mentioned Guidelines, CG will continue its work and final report of the CG will be submitted to MEPC 78 held in June 2022.

(1) in cases where a ship holds multiple load line certificates, deadweight and/or gross tonnage to be used for calculation of the CII should be specified in DCS verification guidelines

(2) the correction factors should be applied in the calculation of the attained CII, and the CII value after correction should be used for rating purposes

(3) the attained annual operational CIIs as well as the parameters to calculate the correction factors etc. should be reported to IMO

2.1.2 Mid/Long-Term Measures for Reduction of GHG

The initial IMO Strategy on the reduction of GHG emissions from ships specifies the middle-term target by 2050 to pursue the efforts towards the CO_2 reduction of 70% per transport work and to reduce the total annual GHG emissions by at least 50% as well as the long-term target within this century to aims to phase out GHG emissions as soon as possible.

At this session, proposals for mid/long-term measures to achieve the above target were submitted, such as cap-and-trade system, carbon levy etc. These proposals will be further considered at future session.

2.1.3 IMRF and IMRB

At MEPC 75 held in November 2020, to promote research and development of low and decarbonized technologies, it was proposed to establish the International Maritime Research Fund (IMRF). As a result of the discussion, MEPC 77 agreed to continuously consider this proposal at the future sessions.

2.1.4 Review of Initial IMO Strategy on the Reduction of GHG Emissions from Ships

In order to keep the Paris Agreement temperature goals which would limit temperature to well below 2 ºC, preferably to 1.5 ºC, the recent reports of the Intergovernmental Panel on Climate Change (IPCC) emphasize the urgency of tackling the climate crisis and reinforce that all emissions must peak now and a zero GHG emissions level must be achieved for all sectors by at least 2050.

At this session, recognizing the need to strengthen the ambition of Initial IMO Strategy, MEPC 77 agreed to conduct a revision of the Initial IMO Strategy, with a view to finalization at MEPC 80 to be held in Spring 2023.

2.1.5 Wind Assisted Propulsion Systems on EEDI

At MEPC 65 held in May 2013, Guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI (MEPC.1/Circ.815) was approved to incorporate the effect of innovative technologies into the calculation of EEDI values.

At this session, the amendments to MEPC.1/Circ.815 were approved to reflect the effect of the Wind Assisted Propulsion Systems (WAPS) to EEDI/EEXI calculation.

2.2 BWM Convention

2.2.1 Commissioning of Ballast Water Management Systems

At MEPC 75 held in November 2020, the amendments to the BWM Convention were adopted to specify the requirements to conduct a commissioning test of Ballast Water Management System (BWMS) including sampling and analysis. This amendment will enter into force on 1 June 2022.

At this session, a Unified Interpretation was approved to interpret that the commissioning testing of individual BWMS should be conducted if the initial or additional survey is completed on or after 1 June 2022.

2.2.2 Ships Operating at Ports with Challenging Water Quality

Proposals on application of the BWM Convention to ships operating at ports with challenging water quality was made due to concerns on operation of BWMS at port area where certain water qualities, such as high level of turbidity, high level of total suspended solids or low salinity, are identified to exceed the operational limitation.

At this session, it was agreed to treat the cases where ships operate at ports with challenging water quality as contingency measures specified in BWM.2/Circ.62. MEPC 77 also agreed to further consider the matter at next session to develop the guidance for ships operating at ports with challenging water quality.

2.2.3 Experience-Building Phase

At MEPC 71 held in October 2017, MEPC resolution was adopted, which stipulates a work plan during the experience-building phase (EBP) to gather data and analyze the concerns for implementation of the BWM Convention and to facilitate the implementation of the Convention by classifying EBP into three stages as follows.

Stage 1: data gathering to collect the concerns over the implementation of the Convention
Stage 2: data analysis
Stage 3: review of the requirements of the Convention

At this session, the extension of EBP was proposed due to the delay in the data gathering caused by the pandemic of COVID-19. As a result of the discussion, MEPC 77 agreed to consider a possibility of the extension at next session, in which the result of data analysis based on the gathered data will be reported.

2.3 Air Pollution

2.3.1 Guidelines for Exhaust Gas Cleaning System (EGCS)

Regulation 14 of MARPOL Annex VI prescribes requirements of sulphur content of any fuel oil used on board ships, for reduction of SOx emission from international shipping, and alternative compliance method can be applied with acceptance of the Administration in accordance with regulation 4 of Annex VI. Under the circumstances that the Exhaust Gas Cleaning System (EGCS) is used as alternative compliance methods, EGCS should be in line with EGCS Guidelines (MEPC.289(68)), which stipulate the technical standards and verification procedures.

At this session, based on the reports from PPR Sub-Committee, amendments to the EGCS Guidelines, which include new definitions for technical terms and revision of technical standards, etc., were adopted. The guidelines will be applied to EGCS installed on ships the keels of which are laid or which are at a similar stage of construction on or after 1 June 2022; or exhaust gas cleaning systems installed on ships the keels of which are laid or which are at a similar stage of construction before 1 June

2022 which have a contractual delivery date of EGCS to the ship on or after 1 June 2022 or, in the absence of a contractual delivery date, the actual delivery of the exhaust gas cleaning system to the ship on or after 1 June 2022; or amendments, as those specified in paragraphs 4.2.2.4 or 5.6.3 of the 2021 EGCS Guidelines, to existing exhaust gas cleaning systems undertaken on or after 1 June 2022.

2.3.2 Failure of EGCS

At MEPC 74, the Guidance on recommended actions to take in the case of the failure of a single monitoring instrument and the EGCS fails etc. was adopted. The Guidance specifies the procedures that a short-term temporary emission exceedance due to the system response should not be considered as a breach, and the system malfunction that cannot be rectified within one hour is regarded as a breakdown. Also, any EGCS malfunction that lasts more than one hour or repetitive malfunctions is required to be reported to flag States and port State's Administration to determine the appropriate action. At their discretion, the Flag State could take such information and other relevant circumstances into account to determine the appropriate action to take in the case of an EGCS malfunction.

At this session, amendments to the Guidance were approved to require additional communication with the relevant port State to decide on appropriate action in accordance with the Convention, to continue on its intended voyage in a non-compliant condition.

2.4 Others (Marine Plastic Litter)

With a view to tackling the problem of plastics in the oceans, MARPOL Annex V prohibits discharge of plastics from vessels. However, it was often pointed out that this prohibition regulation was not effective and that some additional actions were needed at IMO level to reduce plastic pollution in the marine environment. To solve this problem, it was agreed to conduct IMO study on marine plastic litter from ships to estimate the contribution to marine plastic litter by all ships.

At this session, MEPC resolution on Strategy to Address Marine Plastic Litter from Ships was adopted, which includes vision of aims to strengthen the international framework and compliance with the relevant IMO instruments, endeavouring to achieve zero plastic waste discharges to sea from ships by 2025.

3. OUTCOMES OF MSC 104

3.1 Adopted Mandatory Requirement

Mandatory requirement was adopted at MSC 104 as follows:

(1) Amendments to 1988 LL Protocol and IGC Code

Amendments to 1988 LL Protocol regulation 27(13)(a) with the relevant parts of IGC Code were adopted, in order to clarify the condition of watertight doors on cargo ships to be considered for stability criteria at any stage of flooding.

3.2 Ad Hoc Midterm Amendment Cycle for SOLAS and the Associated Codes

Amendments to SOLAS normally enter into force every four years. SOLAS also stipulates that the minimum period between adoption and entry into force of amendments is 18 months. Therefore, amendments adopted less than 18 months before the end of a four-year cycle of entry into force should enter into force at the end of the next four-year cycle.

The COVID-19 pandemic has delayed finalization of draft amendments for approval and adoption, the entry into force of which had originally been planned within the current four-year cycle, i.e. by 1 January 2024.

Considering above circumstances, the Committee endorsed ad hoc midterm amendment cycle with an entry into force date of 1 January 2026 for the draft amendments to SOLAS adopted before 1 July 2024.

3.3 Modernization of the Global Maritime Distress and Safety System (GMDSS)

Due to the fact that requirements and standards related to the GMDSS have not been updated for long time, modernization of the GMDSS has been discussed at IMO.

At this session, the draft amendments to SOLAS II-1, III, IV and V, and the appendix (Certificates), the 1988 SOLAS Protocol, the 1994 and 2000 HSC Codes, the 1983 and 2008 SPS Codes and the 1979, 1989 and 2009 MODU Codes, were finalized and approved. The relevant performance standards, guidelines and guidance were also approved. Provided with adoption of these draft amendments at MSC 105, the amendments would be entered into force on 1 January 2024. The main points of the amendments are shown as follows:

(1) Definition of “Sea area A3” are modified to “a recognized mobile satellite service supported by the ship earth station carried

on board" from "an Inmarsat geostationary satellite".

(2) The provisions in SOLAS regulation III/6 related to two-way VHF radiotelephone apparatus and search and rescue locating devices (SART) have been relocated under SOLAS IV.

(3) The performance standards for the reception of maritime safety information and search and rescue related information by MF (NAVTEX) and HF, shipborne VHF radio installations, shipborne MF and MF/HF radio installations, Inmarsat-C ship earth stations, simplified voyage data recorders (S-VDRs)/VDRs, etc. were amended.

3.4 New Output on Remote Survey

The recent years' COVID-19 pandemic situation has hindered or restricted physical attendance of surveyors to ship onboard surveys. To address the situation, ship surveys have been partially implemented by remote means utilizing ICT technique in lieu of physical attendance of surveyors.

At this session, it was agreed to consider developing guidance on assessments and applications of remote survey with a target completion year of 2024. Discussion will be started at next III Sub-Committee in July 2022.

3.5 New Output on Safety of Newly Built Ships Using Ammonia as Fuel

To achieve GHG reduction target, utilization of alternative fuel is essential and demand for design and/or construction of ammonia-fueled ships are emerging. Under these circumstances, it was proposed to develop non-mandatory guidelines for ships using ammonia as fuel at MSC 104.

Due to time constraint, the proposal was not discussed at this session. It would be discussed at MSC 105 in April 2022 and then the consideration of safety measures for ships using ammonia as fuel would be initiated at CCC Sub-Committee in September 2022.