NEDO's Technology Development for Liquefied CO_2 Ship Transportation

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1. INTRODUCTION

To realize carbon neutrality by reducing emissions of greenhouse effect gases (GHG) to net zero, development of technologies for carbon recycling by capturing and reusing carbon dioxide (CO_2) as a resource and CCS (Carbon dioxide Capture and Storage) by capturing and storing CO_2 underground is currently in progress, as CO_2 represent the largest part of GHG. The "Strategy for the Promotion of Transition to the Decarbonized Growth-Oriented Economic Structure (GX Promotion Strategy)," approved by a Cabinet decision in July 2023, presented a policy of promoting social implementation of green transformation (GX) through decarbonization, premised on securing a stable energy supply, and development of the technologies necessary to achieve this goal [1]. For CCS, which enables direct sequestration of large quantities of CO_2, Japan intends to develop a business environment for private sector to start CCS businesses by 2030. In line with this, the Act on Carbon Dioxide Storage Business (CCS Business Act), which establishes the permitting system for storage projects, was enacted and promulgated in May 2024. Also, "Advanced CCS projects" are being promoted based on the CCS long-term roadmap [2, 3].

In social implementation of CCS, it is important to construct a "CCS value chain" in which the CO_2 discharged as a result of industrial activities flows through a series of processes consisting of capture, transportation and storage. In Japan, CO_2 emitting areas and storage areas are frequently different, requiring technologies for concentrating CO_2 separated and recovered at multiple emission sources of different scales, and collectively transporting it to distant locations efficiently and economically. Therefore, in 2021, Japan's New Energy and Industrial Technology Development Organization (NEDO) launched the NEDO project "R&D and Demonstration Test of CO_2 Ship Transportation" as one means of transporting CO_2 recovered from CO_2 emission sources to storage or use sites safely and at low cost. In this project, a cargo tank system enabling transportation under liquefied CO_2 temperature and pressure conditions suitable for mass transportation is being developed, and technical study of an integrated marine transportation system for liquefaction, storage, loading/unloading and land transport of the liquefied CO_2 is being carried out. This paper presents an outline of the demonstration test ship "EXCOOL," which is equipped with a tank system capable of loading liquefied CO_2 with various temperature and pressure conditions, and a ship transportation demonstration test conducted in cooperation with land-based facilities located in Maizuru (Kyoto Prefecture) and Tomakomai (Hokkaido).

2. OVERVIEW OF THE PROJECT

2.1 Aims of Technology Development

Liquefied CO_2 is used in a wide range of applications, including welding, beverages, cooling, steelmaking and chemicals, and others. Domestic demand in Japan is around 700 000 tons/year. Liquefied CO_2, which is produced by refining carbonic acid gas generated by petrochemical plants and steel works as the feedstock, is filled into tank lorries or high-pressure gas vessels in a condition of approximately –20 °C/2.0 MPa(abs), which is referred to as medium temperature/medium pressure, and then shipped to users by land transportation. However, since social implementation of CCS will require low-cost transportation of large quantities of liquefied CO_2 to storage locations in Japan and other countries, ship transportation is expected to play a key role in transportation of liquefied CO_2.

One effective means of large-scale ship transportation is transportation under a liquefied CO_2 condition of about –50 °C/0.7 MPa(abs), which is termed low temperature/low pressure. Since this pressure condition makes it possible to reduce the design pressure of the liquefied CO_2 tanks, large-volume and lightweight CO_2 tanks can be used. This means the cargo capacity per ship increases, and as a result, the required number of ships or voyages can be reduced, leading to a reduction in

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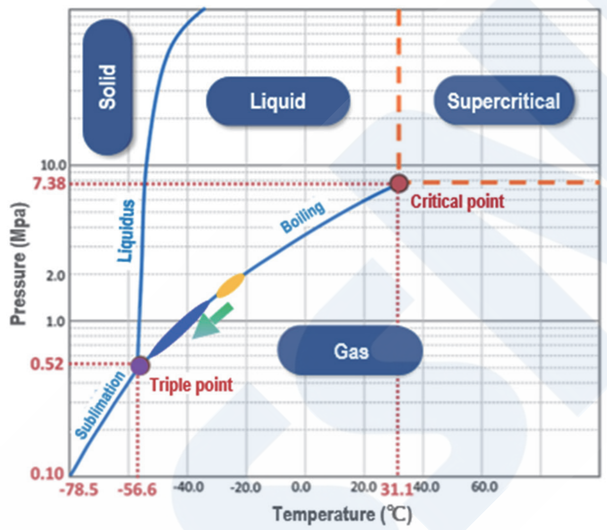
the transportation cost per unit weight of CO_2.

On the other hand, formation of dry ice, that is, “dry-icing” from liquefied CO_2 is a risk. Fig. 1 shows the phase diagram of CO_2. In a liquefied CO_2 tank, the CO_2 exists in the two phases as liquid and gas, and the interface between these two phases is the temperature-pressure condition shown by the “boiling line,” which represents the boundary between the liquid and gas phase. If the temperature-pressure is decreased, the CO_2 will reach the “triple point,” where the solid, gas and liquid phases coexist in equilibrium, at –56.6 °C/0.52 MPa(abs). Below that point, existence as liquid CO_2 becomes impossible, and a phase transition to solid dry ice will occur. If dry-icing occurs in the tanks or piping, it becomes impossible to transport the CO_2, and depending on the case, equipment damage is also a concern. To avoid this problem, in achieving low temperature/low pressure ship transportation of liquefied CO_2, the development of liquefied CO_2 carriers equipped with tanks for loading liquefied CO_2 and an understanding of the behavior of the CO_2 when using land-based facilities for storage and loading under controlled temperature and pressure conditions are essential. Thus, in this project, it is also important to establish a liquefied CO_2 handling technology that ensures safe and efficient marine transportation through demonstration tests of liquefied CO_2 ship transportation through the series of processes consisting of liquefaction, storage, loading/unloading and transportation.



State	Temperature/pressure	Special notes
● Medium temperature /medium pressure	Approx −20 °C/2.0 Mpa	Current transportation and storage condition for liquefied CO_2.
● Low temperature /low pressure	−30 °C/1.5 Mpa to −50 °C/0.7 Mpa	Expected condition in large-volume transportation of CO_2. This condition is near the triple point of CO_2.
● CO_2 triple point	−56.6 °C/0.52 MPa	State where the 3 phases (gas, liquid and solid phases) coexist in equilibrium.

Fig. 1　Phase diagram of CO_2 and transportation conditions

2.2　Project Implementation Method

The key points for establishing a technology for marine transportation of liquefied CO_2 are “Development of cargo tanks for use in ship transportation of liquefied CO_2,” “Securing a stable condition of liquefied CO_2” and “Safety of ship operation and equipment operation.” As efforts to address these challenges, in June 2021, NEDO launched a project called “R&D and Demonstration Test of CO_2 Ship Transportation” with the aim of developing an integrated marine transportation system for shipping, transportation and receiving of CO_2 liquefied under the optimum temperature and pressure conditions. The organizations commissioned with this project and the implementation items are shown in Table 1. Together with study of the physical properties of liquefied CO_2 and stability in handling liquefied CO_2 in ship transportation, construction of a liquefied

CO_2 transportation demonstration test ship called "EXCOOL," which is equipped with a marine cargo tank system for loading liquefied CO_2 under various temperature/pressure conditions, was completed in November 2023 [4)], and efforts related to crew training and liquefied CO_2 handling were begun. In November 2024, land-based equipment for adjusting the temperature/pressure conditions of liquefied CO_2 and unloading it onto the "EXCOOL" was also completed in Maizuru and Tomakomai.

An overview of the liquefied CO_2 ship transportation demonstration test integrating this series of facilities is shown in Fig. 2. The marine transportation tests will be conducted with liquefied CO_2 loaded on both the outbound and return routes to enable efficient study of various liquefaction conditions, ship transportation of liquefied CO_2 under actual environments, and cargo-handling technology in order to steadily accumulate know-how related to ship operation. The land bases at Maizuru and Tomakomai were equipped with loading arms, liquid pumping equipment and CO_2 storage tanks to allow both loading and unloading of the liquefied CO_2. In addition, to allow adjustment of the liquefied CO_2 conditions as required by the test items, liquefaction equipment was constructed to produce liquefied CO_2 under various temperature and pressure conditions at Maizuru base. The main navigation route in the liquefied CO_2 transportation test was a round-trip of approximately 1 100 miles (2 000 km) from the land station at Maizuru on the Sea of Japan through the Tsugaru Strait to Tomakomai in Hokkaido. However, ship transportation demonstration tests are also planned in all coastal regions of Japan, not limited to this route, but also including the offshore areas in the Pacific Ocean, Seto Inland Sea, East China Sea, etc.

Table 1 Project consignees and implementation items

Consignees	Items
Japan CCS Co., Ltd. (JCCS) Mitsui O.S.K. Lines, Ltd. Kanden Power-Tech Corporation Mitsubishi Heavy Industries, Ltd.	Technology development of CO_2 liquefaction system Technology development of large-volume liquefied CO_2 storage system Conceptual design of large-scale liquefied CO_2 carrier Construction of shipping terminals Planning/implementation of demonstration tests
Engineering Advancement Association of Japan (ENNA) Ochanomizu University Nippon Ekitan Corporation Nippon Gas Line Co., Ltd. (NGL) *1 Kawasaki Kisen Kaisha, Ltd.	Study of safety in marine transportation of CO_2 Study of specifications of liquefied gas dual purpose carrier Development of marine tank system Planning/implementation of demonstration test of ship transportation Safety management methods for ship operation and cargo-handling
Itochu Corporation	Survey of CO_2 emission sources and CO_2 transportation businesses Study of business model for CO_2 transportation
Nippon Steel Corporation *2	Study of business model for CO_2 transportation (Japanese steel industry)

*1: Reconsignment to ENAA until Nov. 2023, consignment from Nov. 2023
*2 Until Mar. 2024

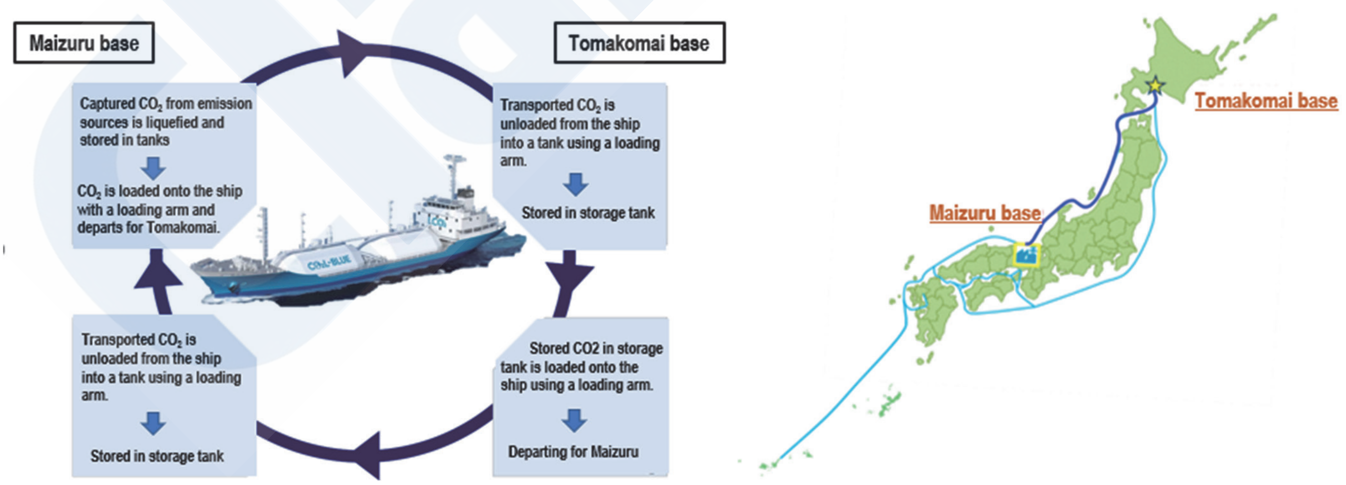


Fig. 2 Overview of liquefied CO_2 ship transportation test and main route

2.3 Liquefied CO_2 Transportation Demonstration Test Ship "EXCOOL"

The liquefied CO_2 transportation demonstration test ship "EXCOOL," which was constructed for this project, is a pressurized liquefied gas bulk carrier with a forecastle and poop. The external appearance and a schematic layout diagram of the ship are shown in Fig. 3, and its principal particulars are given in Table 2. The main hull is of single hull construction and has two cargo holds; one horizontal cylindrical cargo tank (volume: 725 m^3) is installed in each hold. As the propulsion system, a one engine/one shaft type with a variable pitch propeller was adopted, and the vessel has a side thruster at the bow for docking and undocking. The navigation area is coastal waters, and the specifications place few restrictions on changes in the demonstration test area in home waters (non-international) when necessary. As a distinctive feature, the vessel can carry not only liquefied CO_2 (maximum load: 850 tons) at temperature of –20 °C to –50 °C with different specific weights and temperature-pressure, but also propane, butane and other types of liquefied petroleum gas (LPG). It is particularly noteworthy that the “EXCOOL” is the first ship in the world that can carry low temperature/low pressure liquefied CO_2, which is the purpose of technology development in this project [5)].

The ship owners of this ship are NEDO and Sanyu Kisen, and the ship is operated under a bareboat charter by Nippon Gas Line Co., Ltd. (NGL), which provides the crew and performs ship management. In parallel with the operation of the ship, NGL is also responsible for reliable operational management in this project, which includes studying the demonstration test plan and formulating and executing operation plans from the perspective of a shipping line in order to establish safe and efficient cargo-handling plans and solve various problems in ship transportation of liquefied CO_2, such as management of the cargo during transportation.

Fig. 3　External appearance and schematic layout of EXCOOL

Table 2　Ship’s principal particulars

Length overall, breadth overall and draught	72 m, 12.5 m, 4.5 m
Gross tonnage, deadweight tonnage	997 tons, 1,261 tons
Classification society	Class NK
Cargo tank type and capacity	Independent Type-C, 1,450 m^3
Design temperature and pressure	-50℃～+45℃・1.9MPaG
Main loading equipment	Deep well pump, compressor
Other	Gas detectors Sensors and data acquisition equipment

3.　STATUS OF SHIP TRANSPORTATION TEST IMPLEMENTATION

3.1　Loading Tests under Different Liquefied CO_2 Conditions

Liquefied CO_2 transportation tests are being carried out with the “EXCOOL” while changing various ship transportation conditions in steps, including the liquefied CO_2 loading method, amount loaded, temperature, pressure, etc. Table 3 shows the main liquefied CO_2 loading conditions in the ship transportation tests conducted since the ship was completed.

The first loading of liquefied CO_2 on the “EXCOOL” was carried out from lorries used in transportation on land. In this

Truck-to-Ship test, the functional integrity of the cargo tanks and the operability of loading when used with liquefied CO_2 were confirmed, and the technical possibility of loading liquefied CO_2 on the ship, even without a large-scale liquefied CO_2 shipping/receiving terminal, was verified. Thus, provided the port facilities and functions required for liquefied CO_2 loading are arranged, it is considered possible to collect liquefied CO_2 recovered from multiple CO_2 emission sources by ships, and the port can be expected to play the role of a hub & cluster in the CO_2 network necessary for expansion of CCUS (carbon capture, utilization and storage).

In handling of liquefied CO_2, as in handling of other liquefied gases, the ship and land sides are connected not only by the liquid piping, but also by return piping that returns the gas phase to the liquefaction plant, in order to balance the pressure between the ship and land sides. Since dry-icing of the liquefied CO_2 was a concern, the loading quantity and temperature-pressure conditions in the loading tests using the loading arm from the land base were adjusted in steps. Low temperature/low pressure conditions were progressively applied to the liquefied CO_2 while confirming the integrity of the ship and land base, and in January 2025, liquefied CO_2 with the target conditions of –50 °C/–0.7 MPa(abs) (0.6 MPaG) was successfully transported from the Maizuru base to the Tomakomai base.

Temperature-pressure adjustment of the liquefied CO_2, large-volume loading in the cargo tanks, (upper limit of 750 tons due to port restrictions), additional loading (completive loading) and other operations were carried out. Coordinated tests involving the ship and land side facilities that realize the low temperature/low pressure condition in the liquefied CO_2 are also being conducted, in which the CO_2 gas (BOG: Boil Off Gas) which evaporates in the ship's cargo tanks is reliquefied by the land base.

During the liquefied CO_2 transportation voyages with liquefied CO_2 loaded under these various conditions, changes in the temperature, pressure, liquid level, etc. of the cargo were constantly monitored by measuring equipment installed on the ships. Ship motion values were also measured during the voyages transporting liquefied CO_2, considering the comparatively high specific weight of the cargo, and the results of those tests were then reflected in an operation manual for liquefied CO_2 ship transportation.

Table 3 Main conditions of liquefied CO_2 loading tests

	Test item	Loading method	Loading quantity (ton)	Temperature (°C)	Pressure (MPaG)
July 2024	First loading / Truck-to-Ship	Truck-to-Ship	85.3	-35.3	1.11
November 2024	Loading from land base	Maizuru base L/A	424.4	-46.4	0.68
January 2025	Loading in –50 °C region	Maizuru base L/A	422.9	-49.3	0.60
April 2025	Loading in –35 °C region	Tomakomai base L/A	446.7	-36.0	1.04
June 2025	Large-volume loading	Tomakomai base L/A	750.0	-41.1	0.88
June 2025	Completive loading to cargo tank	Maizuru base L/A	743.2	-45.6	0.73
July 2025	Coordinated operation with land-side liquefaction facility	Maizuru base L/A	496.8	-47.8	0.64

L/A: Loading arm Quantity, temperature and pressure values are after loading

3.2 Liquefied CO_2 / LPG Dual Purpose Carrier

Since the structure, specifications and composition of the auxiliary equipment of the liquefied CO_2 cargo tank is similar to those of tank used in LPG transportation, the tanks incorporated in the "EXCOOL" were designed and constructed to "dual purpose carrier" specifications, making it possible to transport both liquefied CO_2 and LPG. In this project, liquefied CO_2 and LPG transshipment tests were conducted to clarify the operability of the ship as a liquefied CO_2/LPG combined carrier. Fig. 4 shows the condition of the connection of the loading arm during LPG loading.

In the transshipment test, after first completely offloading the liquefied CO_2 and performing gas replacement with air and N_2, LPG gas replacement, loading, sailing in the loaded condition and offloading were performed. The operation necessary to return again to liquefied CO_2 loading was then carried out through N_2 gas replacement. The quantity of LPG loaded on the ship was approximately 660 tons, which was the full load of the cargo tanks, and a transportation voyage test was made, although only for a short time and distance. No change was observed in the concentration of LPG offloaded from the cargo tanks after docking, and there were no problems with the subsequent gas replacement to CO_2. This test verified the operability of the "EXCOOL" as a liquefied CO_2/LPG dual purpose carrier. Based on these results, ship operation with liquefied CO_2 loaded on the outbound route and LPG loaded on the return route becomes clear, and an overall reduction in ship transportation costs can be expected.

As technical issues related to operation as a liquefied CO_2/LPG dual purpose carrier, time and costs are required for adjustment and monitoring of the flowrate, temperature, pressure and concentration in the gas replacement operation, and operation by workers who possess expertise at the work site is also necessary. Other issues include loss of CO_2 and LPG as a result of gas replacement. Therefore, one aim of this project is to improve the efficiency of the liquefied CO_2/LPG transshipment method. Study of the integrity of the cargo tanks and auxiliary equipment in operation as a liquefied CO_2/LPG dual purpose carrier and the balance of the hull during transportation of LPG are also planned.

Fig. 4　Loading arm connection during LPG loading (sign indicates loading of flammable hazardous material)

3.3　Changes in State of Liquefied CO_2 during Voyage

Although the cargo tanks used in the liquefied CO_2 carrier have a heat-insulated structure, some of the CO_2 evaporates due to the effects of thermal conduction from the outside air and seawater and hull oscillation. Since the “EXCOOL” is a small-scale demonstration test ship, it is not equipped with reliquefying system, but so long as the tank pressure does not exceed the design pressure (1.9 MPaG) of the cargo tanks, transportation of CO_2 in the gas phase is possible by pressure accumulation, without releasing BOG.

Fig. 5 shows an example of the results of measurements of the pressure rise in the cargo tanks and the temperature rise of the liquefied CO_2 during transportation. In this transportation test, the ship sailed a round-trip route of approximately 1 900 miles (3 500 km) from Maizuru Port in Kyoto Prefecture to Hirara Port on Miyakojima Island in Okinawa Prefecture in July 2025, assuming long-distance transportation under severe weather conditions. Although the ship docked at Hirara Port for about 50 hours, cargo-handling of the liquefied CO_2 was not performed, and BOG was not vented including the voyage. Therefore, there was no change in the cargo weight (496 tons), and the transportation test was carried out with no change in the full amount of CO_2 stored in the cargo tanks.

At the start of the outbound route from Maizuru Port, the temperature and pressure of the liquefied CO_2 were –47.8 °C and 0.64 MPaG, respectively, and the temperature and pressure upon docking at Hirara Port after approximately 90 hours, including offshore anchorage, were –44.9 °C and 0.74 MPaG. Thus, the rates of increase of the temperature and pressure were 0.032 °C/h and 0.0011 MPaG/h. On the other hand, the temperature and pressure on departure from Hirara Port on the return route were –43.5 °C and 0.79 MPaG, and the temperature and pressure on arrival at Maizuru Port after a voyage of approximately 73 hours were –41.1 °C and 0.86 MPaG, showing rates of increase of 0.033 °C/h and 0.0010 MPaG/h, respectively. Since these changes were within the assumed ranges of the insulation design of the cargo tanks, and were also similar to the rates of increase of the temperature and pressure (0.028 °C/h and 0.0010 MPaG/h) while moored for approximately 50 hours at Hirara Port, it can be inferred that the influence of ship motion while sailing on the evaporation of the liquefied CO_2 (i.e., increase in BOG) is minimal.

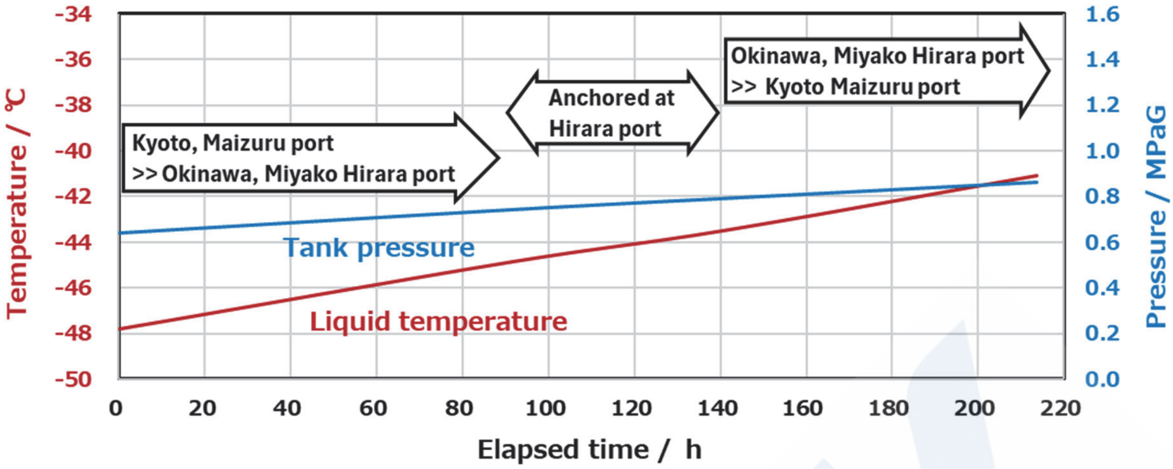


Fig. 5 Change over time in temperature and pressure of cargo tanks during transportation of liquefied CO_2

4. FUTURE PLANS FOR DEMONSTRATION TESTS

In this project, there are plans to obtain knowledge concerning the handling of liquefied CO_2 and acquire data leading to the development of ship transportation technology for liquefied CO_2 by conducting demonstration tests with linkage between ship and land-based facilities. In the cargo tanks of the "EXCOOL," multiple thermometers have been installed at different heights, considering the temperature gradient due to the liquid level, and surface thermometers are provided to measure the temperature of the tank surface and saddle parts. Many thermometers and pressure gauges have also been installed in the cargo-handling piping before/after points where pressure loss is assumed to occur, allowing measurements of the flow rate, load condition of the cargo pumps, and vibration and distortion of the piping during cargo-handling. Instruments for measurement of acceleration and angular velocity are also arranged near the center of the ship's center of gravity. Collecting, analyzing and evaluating ship data assuming various types of ship motion by using these instruments will contribute to the development and demonstration of technologies for safe, efficient, low-cost ship transportation of liquefied CO_2.

In social implementation of CCS, large amounts of liquefied CO_2 will be transported in one shipment by large ship sizes. For efficient, economical cargo-handling work in the loading and unloading processes, the liquefied CO_2 must be handled at a high flow rate, by adopting large-diameter cargo-handling piping and a high liquefied CO_2 flow velocity. In particular, increasing the liquefied CO_2 flow velocity has the potential not only to shorten the cargo-handling time, but also to reduce equipment requirements, for example, by reducing the number of manifolds and loading arms, which is expected to reduce the total cost of ship transportation of liquefied CO_2. Therefore, as part of the study of operability in liquefied CO_2 transportation, plans call for demonstrations of high-speed pumping of liquefied CO_2, in the targeted low temperature/low pressure condition, both onboard the ship and at land bases. High flow velocity (4 m/s) liquid transfer tests using the two cargo tanks installed on the "EXCOOL" and the piping and cargo pumps connecting them has already begun [6]. In conjunction with this, equipment for evaluating high flow velocity liquid transfer of liquefied CO_2 is being installed at the Tomakomai base [7], and safe, sure enhancement of technologies for cargo-handling between ships and land is planned.

5. CONCLUSION

Since CCS can realize decarbonization, even in fields where CO_2 discharges are unavoidable, by electrification and conversion to non-fossil energy such as hydrogen, etc., it has become an essential technology for simultaneously achieving a stable supply of energy, economic growth and decarbonization. In social implementation of CCS, when efficient, low-cost collection of CO_2 from multiple sources is demanded, ship transportation of liquefied CO_2 is a technology that can play a significant role. Global warming and the reduction of GHG emissions have received international attention, but when they are perceived not as "problems," but as "opportunities for achieving future technological innovation," it will be important to promote effective efforts for realizing carbon neutrality as innovation based on a broad technological and social perspective.

The NEDO project "R&D and Demonstration Test of CO_2 Ship Transportation" is being carried out safely and steadily, taking full advantage of the high technological capabilities of the project participants based on their extensive knowledge and experience, with the understanding and cooperation of the related government agencies, local governments, ships and ports, and all local stakeholders. We look forward to future efforts in the field of CCS utilizing the technological results of this project and the liquefied CO_2 carrier.

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