The 155k-m^3 Sayaendo: A New Generation LNG Carrier with a Continuous Integrated Tank Cover

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Mitsubishi Heavy Industries, Ltd. (MHI) has received an order for the newly developed 155k-m^3 Sayaendo, a next-generation liquefied natural gas (LNG) carrier with a continuous tank cover integrated with the hull. Sayaendo retains the reliable configuration and sloshing resistance of spherical tanks, while integrating a continuous tank cover to improve the carrier's overall structural efficiency, thus achieving a lightweight and compact design. Furthermore, adoption of a high-efficiency ultra steam turbine (UST) propulsion system enhances operating economy by significantly reducing fuel costs. This article describes the advantages of Sayaendo, including its improved maintainability, compatibility with LNG terminals, and environmental performance.

1. Introduction

The name "Sayaendo," which means peas in a pod in Japanese, comes from the vessel's appearance, featuring spherical tanks ("endo" or "peas") in a continuous cover ("saya" or "pod"). In conventional liquefied natural gas (LNG) carriers, the upper half of the spherical tanks above the ship's deck is covered by a semispherical dome and the lower half under the deck is supported by a cylindrical skirt structure. In contrast, the Sayaendo employs a continuous cover, integrated with the ship's hull, to house all tanks entirely, thus improving the overall structural strength and achieving weight reduction. For the main power plant, the Sayaendo uses the Mitsubishi Heavy Industries, Ltd. (MHI) ultra steam turbine plant (UST), a new turbine plant that achieves higher thermal efficiency through effective use of thermal energy by reheating steam. Together with the weight reduction and improvements in propulsion performance, the new ship achieves more than a 20% reduction in fuel consumption compared with conventional ships. Furthermore, in conventional LNGCs, piping, electric cables, and passages atop the tanks are supported by complex structures. The new design makes such complex supporting structures unnecessary, thus improving maintainability. The continuous cover also improves aerodynamics by substantially reducing longitudinal wind force, which serves as a drag on the ship's propulsion, contributing to reduced fuel consumption during actual operations at sea.

2. Characteristics of the 155k-m^3 Sayaendo LNG carrier

2.1 Development concept and key technologies

The 155k-m^3 Sayaendo has a new-generation hull form designed to achieve significant improvements in long-haul operating economy, operational flexibility and environmental performance, by combining the advantages of key technologies such as the continuous cover, stretched tanks, and UST propulsion plant. Characteristics of the Sayaendo are described in the following sections.

2.2 Improved operating economy

(1) Light weight and compact design

In conventional LNGCs, a hemispherical cover has little effect on the overall strength, which is maintained by other structures. The 155k-m^3 Sayaendo employs a continuous cover to house four spherical tanks entirely, enabling the cover to be used as a hull-reinforcing element,

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resulting in greater overall strength and a reduction in weight. The new design also reduces the depth of the ship (**Figure 1**). Size comparisons with a conventional 147k-m^3 carrier are shown in **Table 1**.

(2) Increased cargo capacity via stretched tanks

The capacity to transport 8,000 m^3 more LNG than a typical 147k-m^3 carrier is achieved without increasing the beam by using vertically stretched spherical tanks that maintain the same tank diameter. Thus, the new design provides a higher cargo capacity while meeting the New Panamax requirements (**Figure 2**).

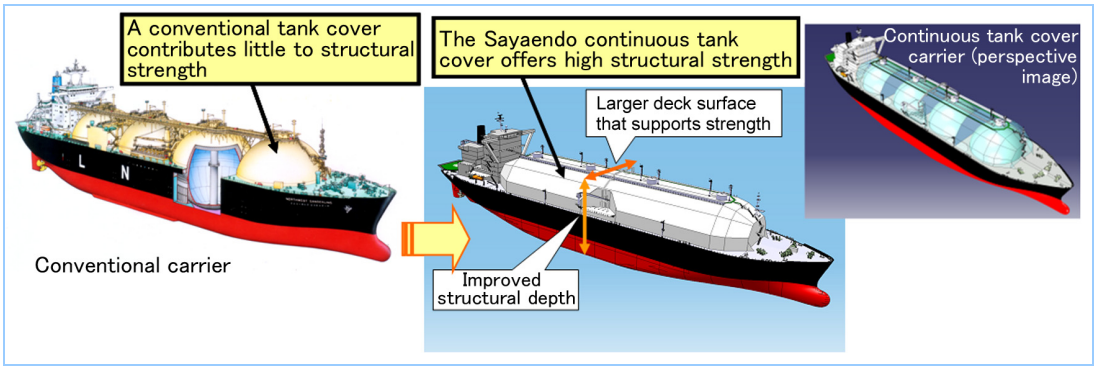

Figure 1 Conventional/continuous tank cover comparison

Table 1 Size comparisons with a conventional 147k-m^3 carrier

	Conventional 147k-m^3 carrier with a spherical tank cover	155k-m^3 Sayaendo with a continuous tank cover
LNG cargo tank type	4 spherical tanks	4 spherical tanks
Cargo tank capacity (m^3)	Approx. 147,200	Approx. 155,300
Loa (m)	288	288
B (mld.) (m)	49.0	48.94
D (mld.) (m)	26.8	26.0
Design draft (mld.) (m)	11.27	11.55
DW (t)	Approx. 71,300	Approx. 75,000
Speed (kt)	Approx. 19.5	Approx. 19.5
Main propulsion plant	Conventional turbine	UST

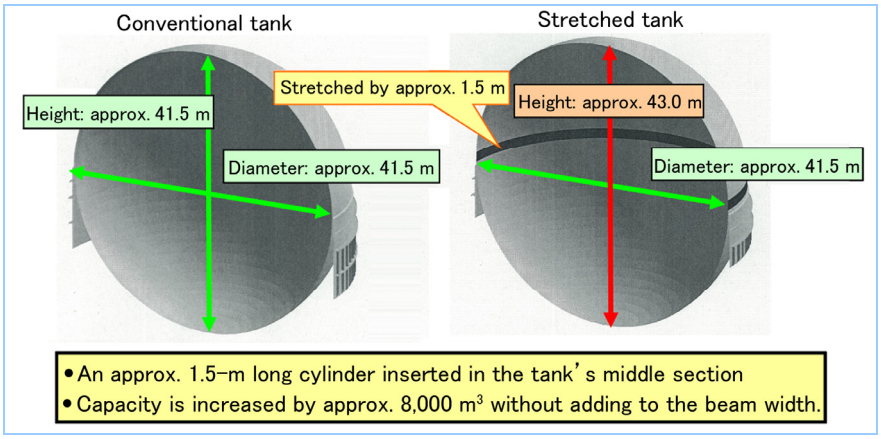

Figure 2 Increased cargo capacity due to stretched tanks

(3) Lower fuel consumption

A significant reduction in fuel consumption is achieved through improvements in ship weight and propulsion performance, as is a reduction of longitudinal wind force with the use of the continuous tank cover and adoption of the high-efficiency UST propulsion plant. With its fuel-selection flexibility (i.e., gas and oil mixture rates), the UST plant provides cost-efficient choices in managing the effects of fuel price fluctuations.

(4) Low boil-off rate (BOR)

By altering the thickness of the thermal insulator thanks to the characteristics of the spherical tank system, the rates of naturally generated boil off gas (BOG), which is caused by heat ingress into LNG storage tanks, can be readily optimized according to operational requirements. Instead of a typical BOR of 0.15%/d achieved in conventional LNG carriers, the

Sayaendo is capable of 0.080%/d, which is even lower than the 0.10%/d adopted recently as the low boil-off rate.

(5) Lower maintenance costs

In conventional hemispherical tank covers, piping, electric cables, and passages atop the tanks are supported by complex structures. The continuous tank cover makes such supporting structures unnecessary, thus significantly improving maintainability.

2.3 Enhanced terminal compatibility

(1) Highly versatile cargo capacity

A larger cargo capacity increases economic competitiveness by lowering the unit cost of operation; however, due to limitations on LNG storage capacity at receiving terminals, LNG carriers that are too large may pose operational difficulties. A total tank capacity of 155k-m^3 offers highly versatile terminal compatibility worldwide.

(2) Compact design, comparable to a typical 147k-m^3 carrier

A compact design comparable to a typical 147k-m^3 carrier is achieved through use of the continuous tank cover and stretched tanks, ensuring versatile terminal compatibility. The Sayaendo is also compatible with the size limits for traveling through the Panama Canal after its planned expansion is completed in 2014 (366 m in LOA, 49 m in width, and 15.2 m in draft).

2.4 Environmental performance

With improvements in propulsion performance, a reduction of longitudinal wind force, and lowered fuel consumption via adoption of the UST plant, the Sayaendo is expected to achieve a CO_2 reduction of approximately 25% per cargo unit during actual operations compared with a conventional 147k-m^3 carrier (**Figure 3**). The UST propulsion system also features very low emission of NOx and SOx.

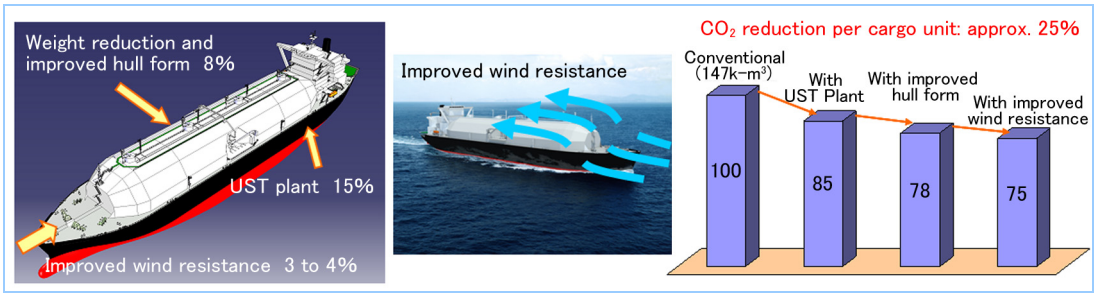

Figure 3 CO_2 reductions per cargo unit

3. Configuration and structure

3.1 Configuration

Figure 4 shows the overall configuration of the Sayaendo. The characteristics of the layout are described below.

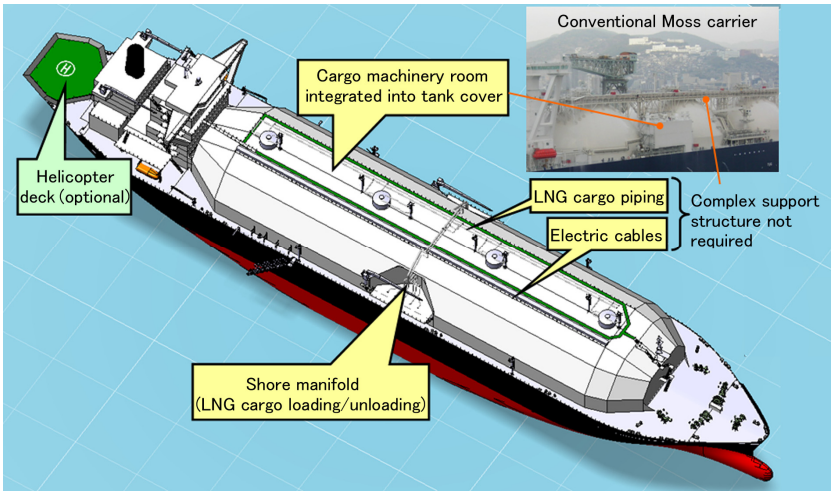

Figure 4 Overall configuration

Four cargo tanks are arranged entirely under a continuous cover, with the inside consisting of four hold areas designated for each tank. Loading/unloading manifolds are placed between the second and third holds where the cover is cut out. Piping and electric cables are located at the flat section on the top of the continuous tank cover, improving accessibility and maintainability. Furthermore, a portion of space between the third and fourth holds under the cover is designated as a cargo equipment room, thus freeing up more space on the flat section of the cover. As a result of consultations with major classification societies with regards to the novel design of Sayaendo, an approval in principle (AIP) has been obtained from LR, DNV, NK, ABS, and BV.

3.2 Structural configuration and strength

The structural design of the 155k-m^3 Sayaendo follows fundamentally that of a 165k-m^3 prototype carrier.[1] Notable characteristics specific to the 155k-m^3 Sayaendo are described below.

(1) Structural configuration

The Sayaendo is designed with a molded depth of 26 m to support terminal compatibility and maintains the same height from the bow to the engine room as a conventional 147k-m^3 carrier. The front and back ends of the continuous cover are connected to the hull with large scarfing brackets, thus providing sufficient structural continuity.

The continuous cover results in the location of the neutral axis (height from base line) of the hull's longitudinal bending stress being higher than that of a conventional carrier. However, by positioning the height of the tank skirt's lower end near the neutral axis, as with a conventional carrier, the effect of hull flexure on the skirt structure is minimized.

(2) Structural strength and fatigue design

Integrated wave load and strength analysis simulation was conducted using MHI-DILAM,[2] an advanced structural analysis program developed by MHI. It has been verified by a yield and buckling strength analysis with design regular waves and full stochastic analysis for fatigue strength performed on a whole ship model with a continuous tank cover that the hull and the cover have sufficient structural reliability (**Figure 5**).

In addition, with increased longitudinal bending strength because of the continuous cover, the stress ranges at the top of the cover and at the bottom longitudinal stiffeners are reduced by approximately 10% and 30%, respectively, versus a conventional carrier, enhancing structural fatigue reliability.

Stress, buckling, and fatigue strength analyses using a finite element model were conducted on the cargo tanks, skirts that support the tanks, and equatorial ring that connects the two (**Figure 6**).

(3) Vibration control

The continuous tank cover is a novel structure with the Sayaendo. The adoption of stretched tanks has also resulted in a higher deck structure and longer pipe tower inside the cargo tanks compared with a conventional carrier. With these new structural characteristics, an eigenvalue and response analysis was conducted to evaluate vibration of the entire carrier, and confirmed that the level was satisfactory.

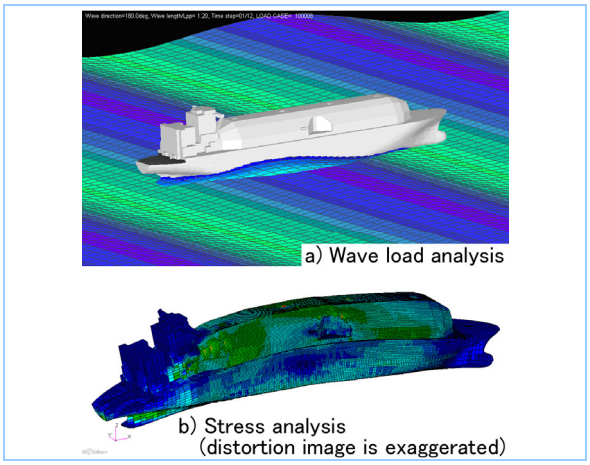

Figure 5 Structural analysis using MHI-DILAM

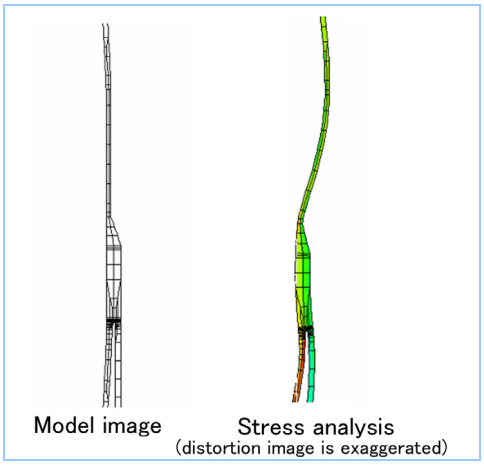

Figure 6 Stress analysis with an axisymmetric solid model (equatorial ring)

4. Propulsion plant and performance

4.1 Improved propulsion performance

By leveraging the advantages of a lightweight hull, combined with state-of-the-art computational fluid dynamics (CFD) technology, MHI developed an optimal hull form to achieve superior propulsion performance at a wide range of speeds, including low-speed operations. The carrier is also equipped with a Mitsubishi reaction fin to further enhance its high performance. Tests conducted in a wind tunnel with headwind confirmed that the wind resistance was substantially reduced, by approximately 20 – 40%, compared with that of a conventional carrier. This improvement translates to a 3 – 4% reduction of total fuel consumption in actual operation. When compared to a 147k-m^3 carrier operating at the same speed, the Sayaendo requires less propulsion power per cargo unit, by 10% or more.

4.2. Propulsion plant

The Sayaendo uses a high-efficiency turbine (UST) plant that uses a reheat cycle while retaining the merits of conventional turbine plants, thus achieving an approximately 15% improvement in plant efficiency. The UST plant offers a level of reliability equivalent to a conventional plant, in addition to high maintainability and flexibility in fuel selection (100% gas, 100% oil, or any mixture of the two). Furthermore, with a structure that enables steam extraction from the main turbine at low loads, the plant efficiency during low-speed operation is equivalent to that of a diesel plant, offering optimal overall operating profitability. The plant also offers excellent environmental performance; when using gas only during low-speed operation in combination with low BOR, the plant delivers an approximate 50% reduction in CO_2 emissions. As for NOx emissions, turbine-powered carriers are already below the Tier III level, and marine gas oil that is in compliance with low-sulfur fuel regulations can be used without any issue. Furthermore, with potential changes in such regulations in mind, the new fuel gas supply system is now capable of gas-only use at all conditions of operation, including when the carrier is in harbors.

4.3 Low BOR and improved fuel efficiency during low-speed operation

On a LNG carrier, BOG is inevitably produced from cargo tanks. BOG is commonly used as propulsion plant fuel. When the high efficiency propulsion plant is applied to the vessel and/or during low-speed operations, BOG exceeds demanded capacity and requires disposal using a boiler or gas combustion unit. In the spherical tank method, rates of BOG can be readily controlled by increasing the thickness of the thermal insulator. As such, the method enables the use of a high-efficiency propulsion plant with an optimal BOR that can be selected according to operational requirements. Instead of a typical BOR of 0.15%/d achieved in conventional LNG carriers, the Sayaendo is capable of a BOR of 0.080%/d, a further improvement over the recently adopted 0.10%/d. The correlation between service speed and surplus BOG is shown in **Figure 7**.

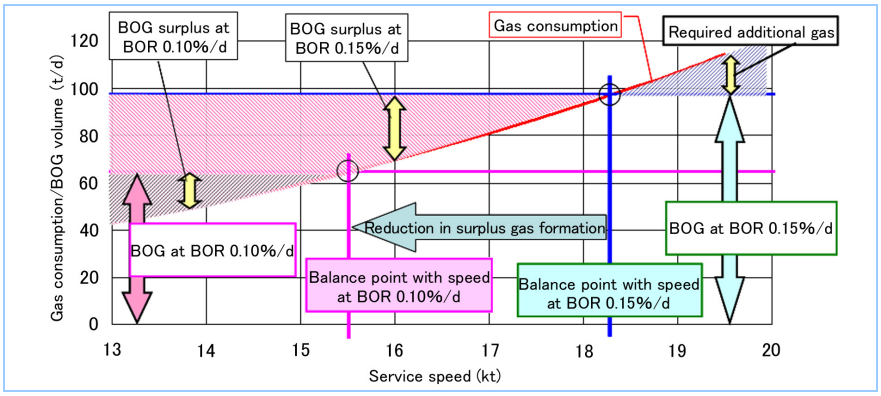

Figure 7 Correlation between service speed and surplus BOG (at full load)
BOG at a BOR of 10%/d and 15%/d and gas consumption by the plant to volume of surplus BOG is shown, using service speed as a parameter.

5. Other technologies

5.1 Wind-tunnel tests

Due to the Sayaendo's unique form, wind force analysis was required to accurately compare the behavioral characteristics of the Sayaendo and a conventional carrier with spherical tanks. The

results of wind-tunnel tests using a detailed model revealed that the wind force coefficient of the Sayaendo was substantially reduced for headwinds due to the effect of the continuous cover, while the coefficient for beam winds was approximately the same as that of the conventional carrier. The Krylov Institute, a third-party research body, also carried out wind-tunnel tests independently and verified the performance improvements (**Figure 8**).

5.2 Maneuverability simulation and mooring analysis

Maneuverability in harbors is an important factor in the operational safety of LNG carriers. Due to the Sayaendo's increased lateral windage area compared with that of a conventional carrier, a detailed analysis was conducted to verify its maneuverability.

The maneuverability analysis was commissioned to Japan Marine Science, Inc., a third-party institute. Applying the wind force characteristics confirmed by the wind-tunnel tests and the influence of tides, several simulations were conducted, including ship berthing and unberthing simulation by a shipmaster license holder using a simulator and computer simulation of turning by tugs and course keeping in a strong wind. The results confirmed that the Sayaendo had a maneuverability equivalent to that of a carrier with conventional tank covers. **Figure 9** illustrates the simulations. Furthermore, based on the analysis of the Sayaendo's wind force characteristics, optimal mooring arrangements at terminals have been determined.

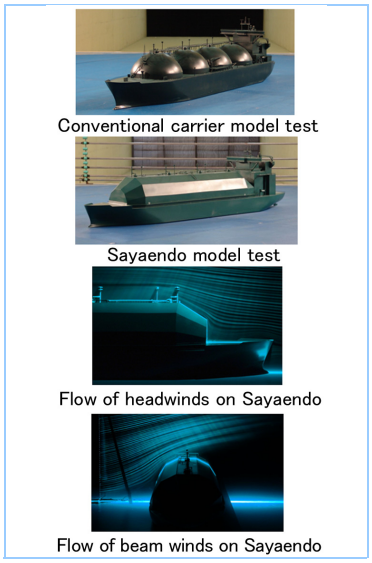

Figure 8 Wind-tunnel tests

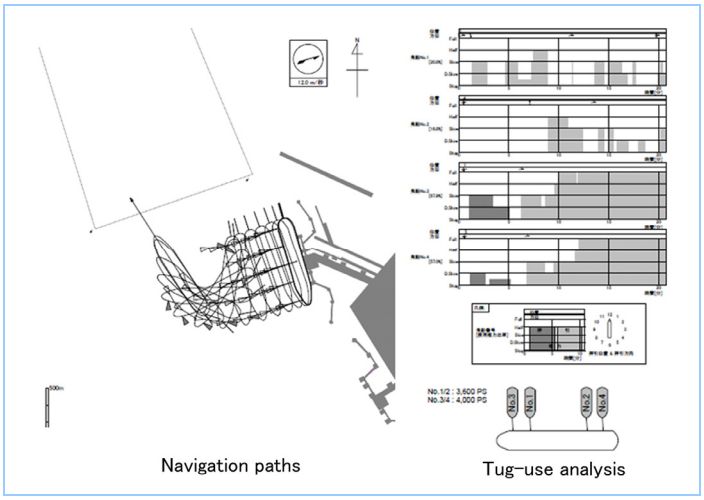

Figure 9 Maneuverability simulations

6. Conclusions

Presently, as part of efforts to prevent global warming, improvements in energy efficiency are being vigorously sought in the area of international marine transportation. In response, MHI is actively developing "eco-ships" with improved environmental performance. In this article, various advantages of the 155k-m^3 Sayaendo are described in detail. With the integration of a continuous tank cover with a hull that leverages the structural reliability of spherical tanks, the Sayaendo was developed, incorporating MHI's state-of-the-art technologies, such as advanced hull form designing, sophisticated structural analysis, and high-efficiency turbine plant system. Following various methods of technical analysis that confirmed its advantages, including environmental performance, the Sayaendo is now available for commercial operations, and MHI has secured an order for construction of the carrier. Positioning eco-ships as one of the key high-value-added products in the company's Shipbuilding and Ocean Development business sector, MHI aims to expand its product line and to further its pursuit of eco-ship development and customer expansion.

References

1. Hiramatsu, S. et al., Sayaendo - New Generation LNGC with Continuous Integrated Tank Cover -, Mitsubishi Heavy Industries Technical Review Vol. 47 No. 3 (2010) pp. 19 - 24
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