Key Technologies of Mitsubishi LNG Carriers – Present and Future –

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CO_2 emission control is recognized as the essential issue related to the greenhouse effect, especially since demand for energy increasing. Use of Liquefied Natural Gas (LNG) must be expanded because it produces less CO_2 emission than any other fossil fuel. Worldwide, approximately 90 million tons of LNG are transported by sea in 1999. Mitsubishi Heavy Industries, Ltd. (MHI) has developed LNG Carriers (LNGCs) since the early 1970s, and has been introducing many technical innovations, such as an insulation system with lower boil-off-rate (BOR), and a sophisticated automation system, in order to enhance their reliability and economy. MHI is building its latest LNGCs with both major containment systems, namely, the spherical tank type and the membrane tank type, and MHI is the No.1 shipbuilder of LNGCs in the World. Given the safe and reliable operation of LNGCs over the past thirty years, the economy of LNG transportation has become a topic of increasing attention for the LNG supply chain. MHI will continue to lead the way by building future LNGCs that incorporate new technical advancements such as size enlargement, standardization and alternative propulsion plants.

1. Introduction

The world's first Commercial seaborne trade of Liquefied Natural Gas (LNG) began in 1964, shipping LNG from Algeria to the U. K. Since then the quantity has been increasing year by year and, approximately 90 million tons of LNG, worldwide, were transported by sea borne trade in 1999. Approximately 52 million tons of LNG were transported to Japan, accounting for about 60%.

The Third Conference of Parties to the United Nations Framework Convention on Climate Change (COP 3) in December 1997 established a new environmental target for CO_2 emissions. To meet this target natural gas has increasingly attracted considerable attention.

The main component of natural gas is methane. It is condensed to about 1/600 of the volume by cooling to below the $-160^{\circ}C$, boiling point, to produce LNG.

LNG has three major characteristics as a seaborne trade cargo: (1) the $-160^{\circ}C$, super-low temperature, (2) a low specific gravity (0.43 to 0.50), and (3) flammability. Up to now, various cargo containment systems designed to handle these characteristics have been put into practical use and about 110 LNG carriers are in service in the world.

In this paper the history of technological development of MHI, application to ships, technical themes for the future, etc. regarding technological trends and the future view of LNG carriers are explained. The whole view of MHI's latest LNG carrier is shown in **Fig. 1**.

2. Cargo containment systems of LNG carriers

Various cargo containment systems having various

Fig. 1 The latest LNG carrier built by MHI
The whole view of MHI's latest LNG carrier is shown.

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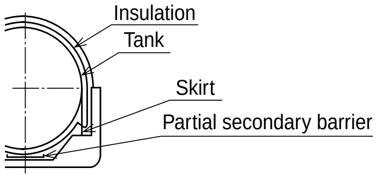
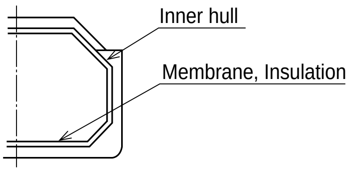
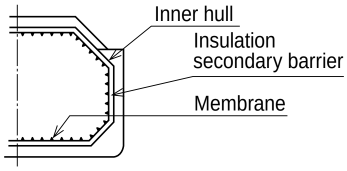
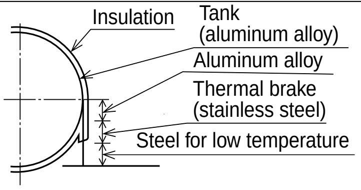
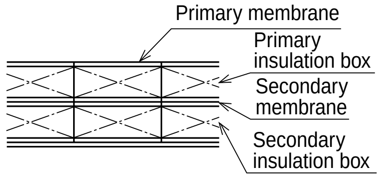
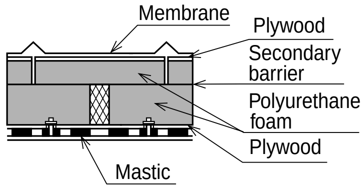
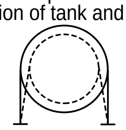
Table 1 Comparison of LNG cargo containment systems

	Spherical tank type	Membrane type	
		Gaz Transport system	Technigaz system
Tank section			
Insulation structure			
Tank material	Aluminum alloy or 9% nickel steel	36% nickel steel (Invar)	Stainless steel
Measures for thermal expansion and contraction	By thermal expansion and contraction of tank and skirt 	(Measures are not required due to very low coefficient of thermal expansion of membrane)	By expansion and contraction of membrane 
Insulation material	Plastic foam	Insulation boxes filled with perlite	Plastic foam
BOR (insulation thickness)	0.15%/d (about 220 mm)	0.15%/d (about 530 mm)	0.15%/d (about 250 mm)
Secondary barrier	Drip pan (partial secondary barrier)	The same as primary barrier	Triplex

configurations, materials and structures suitable to LNG have been proposed and put into practical use. The spherical independent tank type and membrane tank type are adopted mainly at present due to their economy and reliability. **Table 1** shows a comparison of those containment systems.

2.1 Independent tank type

With the independent tank type, the hull and tanks are independent structures and self-supporting tanks are arranged inside the hull. Therefore, deformation due to thermal expansion and contraction is not directly conveyed to the hull. The liquid cargo load in the tanks acts on the self-supporting tanks, not directly on the insulation material, and all loads act on the tank supporting members.

Therefore sufficient strength and insulation performance are required for the supporting structure. Secondary barriers are required to be installed from the viewpoint of hull protection against leakage of LNG in an accident emergency.

At present about half of the LNG carriers in the world are the spherical independent tank type. MHI has improved the spherical independent tank type developed by Moss Rosenberg Verft a.s. (presently Moss Maritime a.s.) and twenty-two LNG carriers have been delivered and/or are being built so far.

In the spherical independent tank type the whole cargo liquid load is borne by the membrane stress of the tank shell in a shell structure tank, therefore stress concentration can be avoided. Also the spherical tank is installed on a cylindrical skirt in the hold and has the feature that deformation due to thermal expansion and contraction of the spherical tank is reasonably absorbed by the bending of the skirt.

Because of the simple configuration and structure of axial symmetry of the spherical tank and cylindrical skirt, high accuracy stress analysis is possible. Therefore the design concept, "No LNG leaks. Even when cracks are generated, progress of the cracks is extremely slow and leakage of LNG is slight." was experimentally and analytically certified and the partial secondary barrier is admitted. The spherical tank type is acknowledged to have the highest safety as tank type B of the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).

2.2 Membrane tank type

In the membrane tank type, the insulation material is installed on inner hull and its surface is covered with a metallic membrane sheet. This containment system aims at reducing the metallic material exposed to low temperatures. The membrane keeps liquid-tightness to prevent cargo leakage, and has no strength against cargo load. The cargo liquid load acts directly on the hull via the insulation material, therefore the insulation structure must have not only insulation performance but also strength. Referring to Table 1, the features of the Gaz Transport system and Technigaz system which are the mainstream membrane types are explained.

A special material having extremely small coefficient of thermal expansion called Invar (36% nickel steel) is used as the membrane for the Gaz Transport system, therefore measures for thermal expansion and contraction are essentially not required. The insulation structure of the insulation boxes filled up with perlite are built like bricklaying. Other feature of this system is that the secondary barrier uses Invar which is the same material as that for the primary barrier. Three LNG carriers of this system are under construction by MHI.

The Technigaz system adopts corrugated stainless steel as the membrane. The stainless steel is corrugated both longitudinally and transversely, and the thermal expansion and contraction is absorbed by the corrugation. As for the insulation structure balsa wood was used in the initial Mark I system, and Mark III system was developed to achieve a lower BOR. In Mark III system, reinforced plastic foam was adopted as the insulation material and Triplex (aluminum foil sheet reinforced with glass cloth) was used as secondary barrier. MHI gained experiences in building a small vessel with Mark I system.

The Gaz Transport system and Technigaz system were developed by separate companies originally. At present these companies have been merged into the Gaz Transport and Technigaz (GTT) and a new system incorporating the advantages of both systems is being developed. The basic idea is that for the membrane will use Invar and reinforced plastic foam for insulation and the secondary barrier is simplified as thoroughly as possible. The study has been made from the above point of view. Attention was given to the new system as a future system.

3. MHI's technical development and characteristics of LNG carrier

3.1 Technical development

MHI built the world's first large refrigerated type LPG carrier in 1962. Since then many LPG and LNG carriers have been built by MHI. MHI is proud of having the rich experiences in building the largest liquefied gas carriers.

The technical introduction of Technigaz membrane system in 1969, Moss spherical tank system in 1971 and Gas Transport membrane system in 1973 were sequentially performed and various improvements for those systems has been developed.

The optimum ship forms had been developed mainly based on model tests. In 1990s, Computational Fluid Dynamics (CFD) technology was established and was put into practical use. At present LNG carriers having good propulsive performance can be developed in a short time.

In the structural design, simulation technique for sloshing loads was established and high accuracy analysis techniques about structural strength and fatigue were developed. MHI's original method to analyze fatigue strength in wave, Discrete Analysis Method (DISAM), was also put into practical use. Structural design of high reliability became possible by these analysis techniques. MHI has been doing the best effort to develop improvement technology to maximize their characteristics . In particular, in the late 1980s MHI held the leadership to develop the large spherical tank type LNG carriers having high transportational economy, the so-called second generation LNG carriers have been developed. The first 125 000 m^3 of 4-tank ship was delivered in 1989 for NWS project and all series ships have been operated smoothly without trouble.

3.2 Characteristics of delivered ships

The characteristics of the latest LNG carrier are shown comparing with the first generation LNG carrier.

(1) The tank capacity is enlarged from 125 000 m^3 to 135000 m^3 to decrease transportation cost . In the future the capacity will be further enlarged.

(2) In the spherical tank type ship, a lower BOR became possible due to the development of a thermal brake in the tank skirt. Although a super low BOR of 0.10%/d is possible technically, at present, 0.15%/d is judged to be the most economical from the viewpoint of practical use. Most large-sized LNG carriers have adopted 0.15%/d. The Gaz Transport system attained a BOR of 0.15%/d by thicker insulation in a reasonable range and simplification of the thermal insulation structure.

(3) A higher service speed and decrease of the main engine output and fuel cost were attained at the same time by the optimum design of the hull form and propeller and development of improved heat efficiency technology.

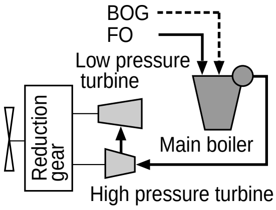
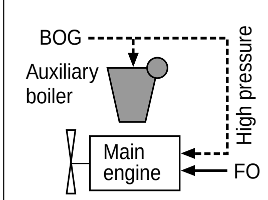
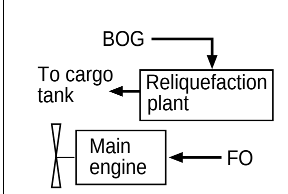
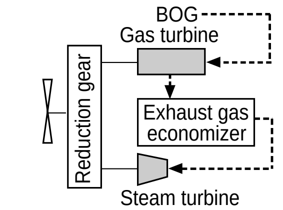
(4) By combination of low BOR and a forcing vaporizer BOG could be used effectively in all service speed range from low load to maximum load, so operational economy could be improved. An environmentally-friendly ship was realized by decreasing the NOx, SOx, etc.

(5) In consideration of long term maintenance full attention was paid to structured layout, material selection, painting specifications, etc in design stage. In particular in the structural design, fatigue strength design is carried out making full use of DISAM.

(6) Simplification of operation and improvement of navigation safety are attained by using extensive automation systems.

Furthermore, the LNG carrier has been developed by introducing new technologies such as automatic ballast water exchange system, measures for CFC refrigerants and these techniques have partly been applied to some building ships.

Table 2 Comparison of propulsion plants for LNG carrier

Propulsion plant		Steam turbine engine	Dual fuel diesel engine	Diesel engine with reliquefaction plant	Gas combined cycle
Plant configuration					
Advantages		•Most LNG ships adopt and reliability is high •100% of BOG can be fired during voyage	•Fuel efficiency is better •BOG can be used as fuel	•Fuel efficiency is better •The cargo part and engine part can be separated	•Fuel cost is better compared with that of the steam turbine engine
Disadvantages		•Fuel efficiency is low	•Exclusive BOG burning is impossible •BOG can not be fired at a low output	•Heavy fuel oil consumption is high •Electric power for driving reliquefaction plant is required	•High quality fuel oil is required •Dual fuel burning is impossible
Economy	Initial investment	100	105	105	104
	Fuel efficiency (fuel)	100 (BOG + HFO)	67 (BOG + HFO)	65 (HFO)	79 (BOG or Gas Oil)
Discharge gases	CO_2	100 (87)	66	77	73
	NOx	4 (3)	100	99	10
	SOx	67 (0)	43	100	0

(Note) Numerals in parentheses are those in the case of BOG exclusive combustion

4. Future view of LNG carriers

Recently in the international meetings such as the International Conference on LNG and GASTECH, the reduction of the LNG transportation cost has become a major topic. In particular various proposals to reduce the LNG chain cost are being discussed. In the background of the discussions on this subject, safety and reliability have already been demonstrated and it is recognized that economy is the most important issue.

Therefore the future view for LNG carriers is explained paying attention to economy .

4.1. Enlargement

The economic merits of enlarging the LNG carriers are that it will reduce the unit transportation cost as same as other kinds of merchant ships. In particular in the LNG project, transport quantity is roughly constant, therefore the number of LNG carriers can be reduced by choosing the larger LNG carriers. Reduction of the number of LNG carriers is connected directly to the reduction of capital and operational costs.

When discussing enlargement, the theme becomes the ship-shore interface with existing LNG terminals, specially the receiving terminals. In the study which have been conducted so far, although regarding main dimensions, mooring arrangements, tank capacities, etc. enlargement is not serious in building ship, it is considered that reconstruction of the receiving facility may be necessary depending on the ship size from the view point of berth strength and cargo discharge rate(1).

4.2 Standardization

Because the LNG project requires a great initial investment, the facilities have been developed based on long term contracts between producers and consumers. Therefore LNG carriers were optimized as special exclusive ships for the project and the fundamental requirements such as ship size and ship speed etc., were decided accordingly.

On the other hand a contract may possibly be concluded between any of producers and consumers of LNG like general seaborne commodities. Since some of LNG is being traded in the spot market, the trade using standard ships will be expected to be general manner.

From such a background, the standardization trends are considered from a different aspect of size enlargement.

The present standard ships have been enlarged in general from 125 000 m^3 to 135 000 m^3. As described above, there may exist some LNG terminals where enlarged ships are difficult to enter. Therefore when the standard ships are planned, it will be most important to have the flexibility in operation. The relationship between ship size and ship speed is that 18 kn for 145000 m^3 and 19.5 kn for 135 000 m^3 are roughly the same transport quantity.

4.3 Propulsion plant

On LNG carriers, BOG is lighter than the atmosphere and inflammable, therefore BOG is permitted to be used as fuel in the engine room. Consequently BOG is utilized as a fuel for the main boiler of the steam turbine engine as same as in the past. However, from the stand point that BOG is considered to be cargo, various plants are investigated aiming at effective use of BOG economically.

In this paper the "steam turbine engine," " dual fuel diesel engine," "diesel engine with reliquefaction plant" and "gas combined cycle (gas turbine engine + steam turbine engine)" are compared and evaluated. **Table 2** shows the plant configuration, characteristics, economy, etc. of each plant. As you can see from the comparison table, any plant can be put into practical use from the viewpoint of reliability and safety.

The steam turbine plant has been adopted to most LNG carriers and its reliability is high. Both BOG and heavy fuel oil are combustible as fuel for the main boiler and give the advantage of dual fuel burning, etc. In particular emission gas from BOG exclusive combustion is the most clean. However, the steam turbine plant has the disadvantage of inferior fuel efficiency and high fuel cost.

In the dual fuel diesel engine the dual fuel burning of BOG and heavy fuel oil is possible and fuel efficiency is better, but the high pressure injection is required when BOG is introduced to the engine. Also a disadvantage is that fuel for pilot burning is necessary and flexibility is inferior because BOG exclusive combustion is impossible and moreover in the diesel engine a large quantity of nitrogen oxides is discharged due to the high combustion temperature.

In the diesel engine with a reliquefaction plant, since BOG is reliquefied and can be directly returned to the tanks, the propulsion engine and the BOG handling can be perfectly separated. The main engine is a normal diesel engine as used on conventional merchant ships, and the fuel efficiency is better. However, initial investment for a reliquefaction plant is necessary and consumption of heavy fuel oil increases due to additional driving electric power for reliquefaction. Also more nitrogen oxides and sulfur oxides than those in the other plants are discharged due to the heavy oil fired diesel engine[(2)].

In the gas combined cycle, BOG is fired in the gas turbine and at the same time a steam turbine is driven by steam generated by the exhaust gas energy from the gas turbine. This plant is similar to the land combined cycle system and fuel efficiency is better than that of the conventional steam turbine.Emission gas is clean, the same as that of the steam turbine, but the disadvantages are that a high quality petroleum fuel is required and duel fuel combustion is impossible. In the future this system may be planed with an electric propulsion plant .

5. Conclusion

MHI as a pioneer of the liquefied gas carrier, established the technology through building the world's first large refrigerated type LPG carrier in 1962. Also the key technology of the spherical tank type and the membrane tank type LNG carriers were introduced from 1969 to 1973, thereafter various technologies such as low BOR, forcing vaporizer, automation and other systems have been developed to improve safety, reliability and economy and applied to ships delivered. At present, MHI has the world's best building records of LPG carriers and LNG carriers and is proposing the latest liquefied gas carriers meeting the customers' demand.

Moreover in recent years on the consensus that safety and reliability in the seaborne trade of LNG have been proved, further improvement of economy is being a big issue. MHI is developing most economical ships introducing such technologies as enlargement, standardization, technical development of various propulsion plants and proposal for tank improvements to meet the future needs of the customers.

Cooperation of the parties concerned such as the charterer, owner, licenser, classification society, company staffs has been indispensable. Special thanks are given to the valuable external support the authors have had to date. Future cooperation is expected to realize the next generation LNG carriers having high safety, reliability and economy.

References

(1) Ishimaru, J. et al., Designing LNG Carriers for 21st Century with Emphasis on Economical and Safe Operations, Gastech94 (1994)
(2) Yuasa, K. et al., Economics and New Technology of LNG Carriers, The 8th Annual Meeting of Japan Institute of Energy (1999)